INVITED PAPER

Smart Grids and Beyond: Achieving the Full Potential of Electricity Systems

This paper deals with present trends and some future expectations and discusses the barriers to implementation of the smart grid, and how each sector of the field from supplier to consumer is approaching these barriers.

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ABSTRACT | This paper explores how electricity systems may evolve in the 21st century. The paper focuses on some fundamental challenges facing the utilization of electricity today and for years to come. Paralleling the challenges, several directions of how new solutions may emerge are suggested. In this context, some new approaches to manage power system development and deployment are outlined.

KEYWORDS | Battery storage plants; carbon economy; electrical vehicles; power engineering; power industry; renewable energy resources; transportation

I. INTRODUCTION

This paper documents trends and proposed ideas on how to integrate legacy and future power system developments and utilize them to achieve full benefits of electricity in the years to come. It provides a few ideas and assumptions that seem rather imminent today and supplements them with a few visionary thoughts with intention of giving the reader an opportunity to continue the thinking in their own space of ideas and assumptions.

Several new trends are already shaping changes in the electricity infrastructure including the expansion of the existing grid with microgrids and megagrids, and new apparatus exploring new materials and concepts ranging from superconductivity and nanomaterials to highly flexible control and energy storage. Additionally, extensive sensors, communications, data processing, visualization tools, and infrastructures are being deployed. This is leading to smart grid concepts that primarily explore the integration issues between new and legacy solutions and infrastructures, which are the most demanding issues to resolve. The most prominent and complex integration issue is the full use of variable renewable generation, the electrification of the transportation sector, and interaction of the previous two factors with the electricity grid. As a result, new economic, policy, environmental, and societal goals are being proposed [1], [2].

The challenge of future grid development is to spur innovation and provide a framework for how global issues affect local developments and *vice versa*. An example of such a consideration is the attempt to develop interoperability standards that would be embraced worldwide and will not inhibit new ideas from being developed and implemented [3]. Another challenge is the environmental concern that is not equally shared around the world now but may have to be coordinated through common goals [4]. Other issues of interest include customer engagement in different economic, cultural, political, and policy frameworks issues. New solutions require not only technical innovation but also behavioral ingenuity by customers and

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researchers in guiding future electricity use and infrastructure development.

This paper focuses on some emerging technologies projected to be widely used in the years to come. Examples of such technologies are residential/commercial/industrial energy efficiency solutions, smart meters, synchrophasor systems, energy management systems, condition-based maintenance, EVs, sustainable energy generation solutions, and energy storage [5]. Many of these emerging technologies are influenced by government subsidies. The application of these technologies to demand side management, distribution and transmission automation, variable generation interfacing, risk-based asset management, planning under uncertainties, and interfaced electricity and carbon-based markets are also discussed [6].

The paper also discusses planning alternatives and a new planning paradigm that will give the direction for future development of the power grid that will assure that the grid expansions are sustainable, cost effective, resilient, safe, and environmentally friendly [7]. To illustrate some of the future expansion options, the paper surveys some existing trends and points out the relationship to the promising and fast evolving smart grid technologies [8].

A background of the current goals set for smart grids and a set of prevailing barriers are identified first. Next, some possible approaches to addressing these barriers, many in their infancy, are mentioned. Finally, the paper ends with examining economic impacts and uncertainties, as well as possible paths forward. Conclusions and references are given at the end.

II. GOALS, CHALLENGES, AND BARRIERS

A. Smart Grid Goals

The Energy Independence and Security Act (EISA) of 2007, particularly with article XIII, started the era of an official use of the term "smart grid" to designate future expansion of the electricity grid [9]. In the meantime, many other terms were used to designate future grid development strategy such as Perfect Power Grid, Intelligrid, and EmPowered Grid [2], [5], [6]. An attempt was made to characterize some key features of future grid development, such as the introduction of extensive communication, computational and sensing capabilities. The preceding factors, combined with pervasive use of renewable generation, will make the future grid smarter, more intelligent, and more empowering for its users. Particular emphasis was also placed on expanding the ability of humans, whether in the role of grid operators or users of electricity, to be able to receive new information concerning grid conditions and to respond to this additional information with various actions at their disposal. As the attributes of the new grid were expanded, it became more difficult to capture all of this in simple terms; thus many interpretations of what smart grid really means have emerged.

Through the National Energy Technology Laboratory (NETL), the U.S. Department of Energy (DOE) funded a study to characterize the key smart grid attributes [8]:

- self-healing from power disturbance events;
- enabling active participation by consumers in demand response;
- operating resiliently against physical and cyber attacks;
- providing power quality for 21st century needs;
- accommodating all generation and storage options;
- enabling new products, services, and markets;
- optimizing assets and operating efficiently.

Due to continued smart grid interest, many research and development organizations, vendors, and consultancy firms in the United States and globally started elaborate programs with respective stakeholders for the development, demonstration, and deployment (3-D strategy) of various smart grid aspects. The most widely pursued are smart metering projects, followed by a variety of projects in customer smart appliances, distribution automation, wide-area monitoring for improved awareness in transmission systems, and distributed renewable generation and microgrids. The investments in such projects were boosted in the United States by the American Recovery and Reinvestment Act (ARRA) of 2009, and by significant matching investments from private sources. It was quickly evident that most of the projects in the United States were focused on the 3-D strategy rather than elaborate research programs [9]. In some other regions of the world such as Europe, China, and Korea, the governments decided to invest large sums in exploring many particular research issues. In the United States, several academic institutions, together with the Electric Power Research Institute (EPRI) and DOE National Labs are involved in R&D through several National Science Foundation (NSF) and DOE funded centers [6], [10]–[12].

B. Challenges and Barriers

One key short-term challenge is the attempt to achieve these various goals while facing the classic engineering cost-benefit issue. Each metric can be improved, but almost always, only with a tradeoff elsewhere. For example, residential level solar photovoltaic (PV) is relatively expensive (at least when unsubsidized) and intermittent, but it is also considered clean, and its solar source of energy is abundant and sustainable. Installing residential "smart meters" has an upfront cost; however, there are future potential benefits from improved system reliability and efficiency. A key barrier to achieving these metrics results from different stakeholder groups having vastly different priorities and, therefore, having vastly different procedures to evaluate and weigh these metrics. Education is also a key challenge, since widely held perceptions about cost-benefit tradeoffs do not always match the reality, which is often determined by quickly evolving technology.

A fundamental longer term barrier for energy is the extent of reliance on fossil fuels, particularly petroleum, coal, and natural gas as the main raw energy resources. There are two engineering-related reasons why this reliance must decrease: depletability and CO_2 emissions (there is also a political reason, to decrease dependence on foreign energy supply). Depletability may be quantified in terms of reserve to production ratios (RPRs) which approximate remaining years if proven reserves are depleted at current production levels. World RPRs for petroleum, coal, and natural gas are estimated to be 42, 118, and 59 years, respectively [13]. (These values change as new reserves are identified and production varies; in addition, region or country-specific RPRs can vary widely.)

Data from [14] for 2008 show that of all energy produced in the United States, 67% is used in the electric and transportation sectors, while these two sectors combine to produce 73% of all anthropogenic CO_2 emissions. These observations lead one to conclude that significant reductions to U.S. CO_2 emissions must effect changes to the electricity and transportation sectors. Data provided in [14] also indicate only 16% of U.S. energy comes from non-CO_2 emitting energy resources, with nuclear, biomass, and hydro being the only such resources playing significant roles in 2008.

An obvious approach to CO_2 emissions reduction emerges: shift electric generation to non-CO_2 emitting resources while electrifying a significant component of the transportation system. However, several key questions remain.

- What infrastructures should be built, when, how much of each, where, and at what ratings and costs?
- How to interconnect added infrastructure to achieve good solutions in terms of cost, emissions, and other environmental impacts, resource depletability, and system resilience?

III. INTEGRATING VARIABLE GENERATION

A. Control of Power Production

For conventional generation, megawatt (MW) output is controlled at four levels. The first level is the only level that is not centralized; it is local to each generator and regulates MW output in response to transient deviations in shaft speed from its reference (synchronous) speed. The second level, also called automatic generation control (AGC), provides regulation and load following and is centralized for a designated region of the network called the balancing area (BA); it regulates power production of all units in the BA, typically pulsing units every 4 s, in response to steady-state deviations in frequency, and tie line power flow to neighboring BAs. The third level typically operates every 5 min to set each generator's basepoint power production level to optimize the BA's economic objective via an algorithm called the security-constrained economic dispatch (SCED). The SCED forms the basis of the real-time electricity markets. The fourth level operates daily to provide next-day 24-h power plant schedules in terms of their hourly interconnection status (up or down) and approximate dispatch via another optimization algorithm called the security-constrained unit commitment (SCUC). The SCUC forms the basis of the day-ahead electricity markets. All control levels are motivated by the need to provide continuous power balance, with levels one and two also providing frequency control and levels three and four also providing economic optimization.

In the nine electricity market systems of North America, electric energy is bought and sold where input data for levels three and four optimization algorithms SCED and SCUC are provided by participants making offers to sell and bids to buy energy, resulting in solutions that provide participant allocations in terms of locational marginal prices (LMPs) and quantities. Within the same optimization framework, a set of ancillary services are also bought and sold, including regulation, spinning reserve, and nonspinning reserve. Regulation and spinning reserve markets provide resources used by control levels two and three to provide regulation and load following.

Variable generation (VG), which includes wind and solar-photovoltaic, is not as controllable as conventional generation, since the primary energy resources cannot be controlled. This reduced control capability endows VG with two attributes which inhibit its integration into the power system: variability and uncertainty.

B. Generation Variability

Power from a wind or solar generator can be controlled, albeit to a lesser extent than conventional generation. This control is currently used to maximize energy production. Generation owners prefer not to control output for any other purpose unless revenues for the provided service exceed those obtained when maximizing energy production.

Conventional generation must compensate for VG, which has two important implications for conventional generators, both of which are played out in the second level of control (AGC). First, increased levels of conventional generation are required to participate in meeting the variability. If the variability is large enough, base-load power plants (plants held at almost constant power), e.g., combined cycle natural gas, coal, and nuclear plants, may need to participate. The so-called "cycling" of these plants increases maintenance, forced outage rates, and emissions and it decreases lifetimes, which result in additional costs imposed on plant owners. Second, the portfolio of generation which will meet this variability must have increased response capabilities, e.g., portfolio average response capability of 5%/min may need to increase to 7%/min, where the percentage is of a machine's rated power production capability.

There are various ways to meet the additional variability imposed by VG, including deploying combustion turbines, demand control, and/or storage technologies, or increasing the size of the BA. A final approach is to enable VG control away from its maximum energy extraction point. Ramp-down capability is available if the VG is online and generating, but ramp-up capability is only available if the VG is generating below its maximum energy extraction point. Today, much attention is focused on identifying the most cost-effective array of investments to address increased variability imposed by VG.

C. Generation Uncertainty

Although market participation rules for VGs vary by system, most systems permit, but do not require, VGs to participate in day-ahead markets [15]. One market operator has recently proposed dispatchable intermittent resources as new mechanism to allow VG participation in day-ahead markets [16]. VGs that participate in both real-time and day-ahead markets settle deviations at real-time prices. VGs that participate in only real-time markets receive real-time prices for energy provided. Day-ahead VG offers depend on the 24–48-h ahead VG resource forecasts, and real-time VG offers depend on 5–60-min ahead VG resource forecasts. The error associated with these forecasts causes uncertainty in VG schedules.

Most systems do not penalize VGs for deviating from schedule, but some do and likely more will as intermittent penetration levels grow. Deviations in VG schedules affect scheduling of the conventional generation, resulting in less efficient system economic performance. Therefore, both VG owners and market operators have strong incentive to obtain accurate VG forecasts for day-ahead, hour-ahead, and 5-min intervals. Extending SCED and SCUC from deterministic to stochastic models is an area of interest.

D. Frequency Regulation

Frequency has been traditionally controlled tightly to avoid activation of under frequency load shedding (UFLS) relays following contingencies. The approach gives margin for frequency deviation before it hits the UFLS set points. To avoid such frequency-induced load interruptions, frequency-based reliability standards have been created by the North American Electric Reliability Corporation (NERC). These control performance standards require balancing areas to meet targeted frequency control performance in terms of metrics based on frequency error statistics. Increasing VG penetration levels degrades this performance. Adjustment of future frequency performance standards may be considered as the penetration level of VG increases. Also, the ability of wind turbine generators to emulate the inertia of traditional generators is an interesting frequency regulation impact to explore.

IV. CONSUMER ENGAGEMENT

A. Smart Homes, Business, and Industrial Parks

Unlike other areas, smart grid development in the consumer domain is in full swing. Smart appliances, which are equipped with controllers to maximize efficiency, are widely available. These appliances have various portal interfaces to select from and users can set the energy savings programs from a centralized location, such as residential or business premises. As of now, the use of smart appliances is reduced to the energy savings in a given locality or premise. More futuristic approaches envision smart appliances participating through various aggregated programs directly in the electricity market as dispatchable loads. Other views are also being investigated, e.g., where the appliances turn themselves on and off as the frequency in the system deteriorates/improves making the appliances act as an automated controller for demand control.

Building energy management systems have been in use for many years but the level of sophistication they offer now makes them rather complex and effective. They are not only focused on energy use, but also on managing information about carbon footprint, aggregation with other buildings in directly controllable building clusters, and on online monitoring of the ventilation, lighting, and water and fire systems. To allow building managers to utilize the full benefits, several vendors have recently introduced the new concept of dashboard information integration and sharing for building energy management control.

Further extension of the smart grid concept that encourages expansion of the customer owned electricity infrastructure leads to what is widely known as microgrids [17]. The main feature is local grid development with various means of generation, energy storage options, and multiple load types all optimized for local energy efficiency and capable of autonomous as well as integrated operation with the main grid. Such solutions are often found on various types of campuses such as universities, hospitals, industrial parks, military bases, and shopping centers where a large number of buildings or other loads are concentrated in a relatively small geographical area, and local electricity generation is also available for full integration in such a local grid for supply of the loads.

B. Options for Aggregation and Market Participation

To facilitate the interest of individual customers to engage in commercial arrangements to actively help with the utility needs or participate in the ancillary services market, an aggregation concept has been developed in several forms.

Typical utility aggregation programs were aimed at grouping customers on a given feeder or combination of feeders to allow the utility to perform load control for peak "shaving," load shifting, and load reduction. Such programs have been known around the world for a long time,

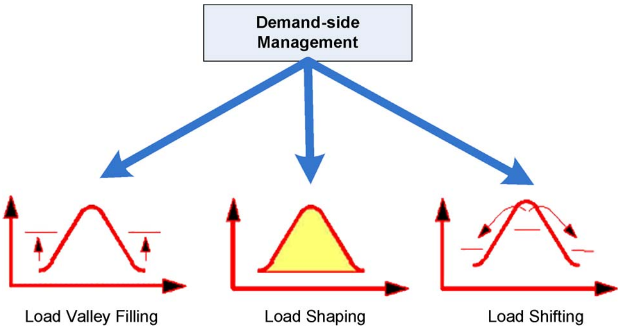

Fig. 1. ***Load management through utility programs.***

where they are often used with multitariff incentives or through direct load control means. Typical load curve changes achieved with such programs are given in Fig. 1. Such programs are now becoming much more versatile and sophisticated, where they may include a variety of options such as advanced energy storage technologies [18].

Another type of aggregation is done by independent aggregators, very often electricity retailers. Popular programs in this area, which are expected to grow in the future, include aggregation of distributed renewable generators installed by homeowners to offer load-as-a-resource capabilities and aggregation of fleet electric cars to offer value added services from controlled charging. Another aggregation option is for individual customers or asset owners to directly participate in the electricity markets through paid ancillary services such as regulation and spinning reserve. Such programs are relatively new, and have different requirements for the minimum level of aggregation needed to qualify for market participation. In the United States, and in most regions, the level is 1 MW.

V. DISTRIBUTION AUTOMATION

A. Ownership and Utilization of Customer and Utility Data

One of the major developments in distribution automation is deployment of smart meters as a gateway between the utility and customer. With such capabilities the smart meter becomes not only a point of measurement of consumed kWh but also a controller capable of bidirectional communications with both the customer and utility. In this capacity, the meter may become a key energy management component of the future by interfacing the customer with the utility.

At the meter, the issue of data ownership and privacy becomes a focal point. The research into the legal issues surrounding the use of customer data, as well as the means for protecting the data, has been gaining a lot of attention lately. With opportunities for multiple uses of data, a number of issues arise when such data are to be used by utilities and also by the customer or by third parties. In an ideal case, such data are expected to be freely available in real time to all parties. However, both privacy and cybersecurity constraints may impose limits on how widely such data may be used in the future. In such cases, data collected from meters are used to estimate future uses so that plans for interaction between customers, utility, and aggregator may be tailored to the needs and benefits of each party.

B. Interfacing Customer Assets, Distributed Resources, and Microgrids

One of the major developments in smart grid deployments is the change in the power flow direction. With the connection of distributed renewable generation, microgrids, and customer energy storage assets, the traditional paradigm of the radial power flow directionality from the utility bulk transmission to loads along the feeders has been already challenged. In the future, the distribution system may look more like a loop or meshed system that is fed from all generation points and supplies electricity to all user points. An example that shows how the network connections at the customer level may look like in the future is depicted in Fig. 2.

In this context, traditional standards that were designed to sanction current utility practices, e.g., IEEE Standard 1547, will have to be changed. New standards will need to accommodate all types of power flow control interaction where each participant in the interconnection is equally entitled to participate in the generation or consumption of electricity.

C. Enhancing Interaction Between Distribution Automation and Bulk Energy Transmission Systems

The states of the power system at both the transmission and distribution level may have to be available and

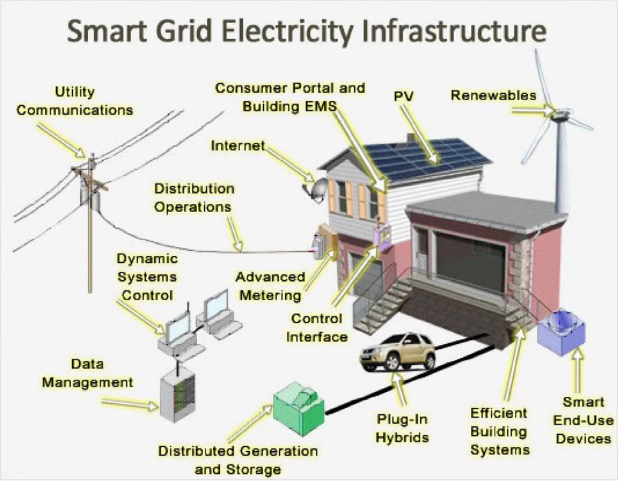

Fig. 2. ***Future grid expansion at the customer site.***

integrated to accommodate power system model aggregation in support of large-scale introduction of variable distributed generation. In that case, the nodal information about the voltage and frequency may have to be accurately reflected for the entire system across both distribution and transmission. Such a state estimation approach is being widely considered by the vendors; they are already exploring the energy management system (EMS) designs that will encompass both transmission and distribution networks under one control solution.

While the traditional radial feeders were protected with various overcurrent protection schemes, the new systems will be protected with directional, differential, or distance protection schemes typically used at the transmission levels today.

Synchrophasor technology aimed at addressing the monitoring, control, and protection issues in the transmission systems is also going to be deployed in the distribution system for a variety of applications. Some may be used to determine contingencies in the bulk supply affecting the distribution, and some may be exclusively used to enhance performance of the distribution monitoring, control, and protection.

VI. TRANSMISSION AUTOMATION

A. Wide-Area Effects of Power Outages

In large-scale electric grids such as those in North America, Asia, and Europe, the transmission grid consists of many tens of thousands of kilometers of wires that hold thousands of generators and millions of individual loads together, presenting some of the largest machines ever created.

Such a large-scale transmission grid provides two primary benefits: reliability and economics. An interconnected transmission grid with thousands of generators means that when even the largest generator fails, the lights stay on. From an economic perspective it also means that electric grid participants can trade electricity, taking advantage of lower cost generation that may be more than 1000 km distant. Since the grid operates at high voltages, the total losses in the transmission system are actually quite modest, averaging about 3% of total generation in a tightly coupled network like the North American Eastern Interconnect, and about 6% in the less dense North American Western Interconnect (WECC).

But this high degree of connectivity has a detrimental side effect: if something goes wrong the effects can quickly be felt over a large area. The August 14, 2003 blackout, which affected more than 50 million people in eight U.S. states and the Canadian province of Ontario provided ample evidence that wide-scale blackouts are not just a part of the distant past. A blackout affecting a similar number of people just one month later in Italy (September 29, 2003), and the November 2009 Brazil–Paraguay blackout, affecting more than 80 million, indicate that large-scale blackouts are a worldwide concern.

B. Local and Wide-Area Protection

Almost since its inception more than 100 years ago the transmission grid has been automatically controlled, at least to some degree. The first key technology of such type of control is system protection.

As transmission automation moves forward, relays will continue to play an important role since they can respond far faster than any human operator. Initially, electromechanical relays were used for detecting system faults, but over the last several decades these devices are gradually being replaced by digital relays. An important advantage of digital relays is that their settings can be modified dynamically. If relay settings can be modified dynamically, this could allow for more flexible system operation through introducing adaptive digital protection. This resulted in a new approach where adaptive protection, heavily investigated some time ago, became practical and highly desirable [19]–[21].

As the digital relaying technology became widely used, new trends of developing all-digital automation systems for substations became a visible trend that is expected to continue in the future. Supported by strong standardization captured by International Electrotechnical Commission (IEC) 61850, which allows interoperability between vendors, the substation automation systems have seen significant progress through introduction of the concepts such as digital process bus, merging units, goose massaging, etc., all aimed at faster processing, more integration among substation automation functions, and expanded interfacing with the supervisory control and data acquisition (SCADA) and other enterprise systems in the utilities responsible for asset management, outage management, operations, and reliability oversight [22]. In addition, the concept of wide-area relaying where the local relaying functions get coordinated with a centralized system protection controller has been enabled with advances in fast communications [23].

C. SCADA and Energy Management Systems

A second key technology that is driving transmission automation is improved power system sensing. Relays primarily rely upon local (i.e., substation) voltage and current measurements, with dedicated communication links sometimes used to provide limited real-time information from other locations, such as at the far end of a transmission line. For decades, SCADA systems have been used to scan system analog values every few seconds, providing voltage and current magnitudes, and complex power values to the control center. While SCADA data have been, and continue to be, quite important in maintaining reliable power grid operation, a key disadvantage has been the inability to determine from SCADA the voltage and current phase angle differences across an interconnected system. The reason is whereas the magnitude of the underlying alternating current (ac) signals is easy to determine, phase angle differences can only be determined with time-synchronized (less than 1 ms) measurements.

In the past, such time synchronization was quite difficult to achieve, but with the recent widespread availability of global positioning system (GPS) clocks, devices known as phasor measurement units (PMUs) are being rapidly deployed in substations around the world. In North America this effort is being coordinated by the North American SynchroPhasor Initiative (NASPI), which also maintains a repository of PMU-based tools [24]. One likely PMU application is to enhance system integrity protection schemes (SIPSs), also referred to as remedial action schemes (RASs) or special protection systems (SPSs) [24]. They are defined as being an automatic protection system designed to take corrective action beyond that associated with the traditional relay operation of isolating faulted components. An example of SIPS action would be automatically reducing generation when one or more of the generator's outlet transmission lines is tripped. PMUs, with an appropriate trustworthy communication network, could expand SIPS actions to look at system angle separations, allowing for closer to real-time control during transient and voltage stability events. Use of SIPS as defense systems for low probability contingencies is appropriate. Overreliance on SIPS, particularly for single-element outages, avoids investments cost in new transmission, but increases complexity and risk.

D. The Role of Operators

While automatic transmission system control will undoubtedly improve in the future, the complexity of large-scale, interconnected power grids means that the human operators will continue to be in the loop for at least decades into the future. Routine events, such as normal generation control, the switching of shunt capacitors, and changing the taps on load tap changing (LTC) transformers are rapidly being automated. But for emergency system operations, such as when a blackout threatens, the human operator is critical.

The causes of the August 14, 2003 blackout were lack of appropriate situational awareness and oversight on the part of several organizations. Hence, a key challenge is to provide the humans in the control room with the appropriate level of information about the real-time condition of the power grid. This is a situation in which "more" is definitely not "better." The approach should not be to overwhelm the operators with raw data from SCADA and PMUs, or with gratuitous background graphics that tend to camouflage desired information, or even with unprocessed outputs from analysis programs such as contingency analysis. Rather, a deliberate design process is needed in which human factor aspects play an integral role. Such a human-factor-centric approach was used in the design of the ISO New England Control Room, shown in Fig. 3. As information technology continues to advance, and the transmission grid becomes more automated, the visual analytics necessary to keep humans integrally "in the loop" will be a research and development challenge for decades to come.

Fig. 3. ***ISO New England Control Room, circa 2009; source ISO New England photo.***

VII. GENERATION EXPANSION PLANNING

A. Short Term

Short-term generation options, those likely to be effective within the next 5–15 years, focus on zero- or low-emission generation technologies that can be built quickly, at relatively low cost, and with relatively low public resistance. The two most promising such technologies are onshore wind and natural gas combined cycle plants. Significant onshore wind resources in the Midwest, Texas, New York, and the West coast are economically viable. Although natural gas prices have been historically volatile, recent technologies to access shale gas are likely to stabilize those prices in the short term. High penetration levels of wind will require heavy investment in local transmission as fossil-fire plants are retired in favor of high-capacity transmission, since many of the most cost-effective wind resources are typically distant from load centers. The least cost means of handling the increased variability imposed by wind will be addressed initially by combustion turbines and demand-side control of thermal-electric loads (air conditioning, space heating, and water heating) and energy-intensive manufacturing processes such as aluminum smelting [25]. As the light-duty vehicle market share of pluggable electric and pluggable hybrid-electric vehicles grows, aggregators will develop control and coordination means to harness their charging flexibility and storage capability. Storage devices (flywheels, sodium-sulfur batteries, molten salt, ice cooling, compressed-air storage, and pumped hydro storage) will also play a role, as long as they have a discharge time at rated power exceeding the 5-min market clearing time [26] so that they can bid into the regulation market. Investment in demand-side efficiency improvements and conservation offers effective short-term approaches to reduce both energy supply and capacity needs.

B. Long Term

Long-term generation options, those likely to be effective within the next 15–30 years, must focus on diversification of supply to increase system resilience while continuing to embrace cost-effective and sustainable solutions. Unless significant amounts of new reserves are discovered, electricity production from *natural gas* may begin to decrease its presence during this period. *Onshore wind* will likely continue its growth as tower heights increase, enabling deployment of wind in regions previously less cost effective for wind development. *Offshore wind* will begin to grow, particularly in the Atlantic and Gulf coasts where ocean depth is less than 60 ft and wind resources are fruitful. Although the 2011 Japanese accident at Fukushima may have damped public receptivity to expanding *nuclear energy*, this proven cost-effective, zero-emissions resource will add much needed diversification and should be a significant part of future energy portfolios provided a solution for the waste storage is found and any significant safety risks due to natural disasters and sabotage are addressed. With very large world and U.S. coal reserves [13], [27], clean use of this resource will be important. Integrated gasification combined cycle (IGCC) plants convert coal into synthesis gas (syngas), following which CO_2 and other undesirable components may be captured via chemical absorption, a precombustion process that is less expensive than the postcombustion processes used in pulverized coal plants. Thus, IGCCs may offer less costly energy than pulverized coal plants, under the condition that carbon capture is required for both types of plants. Although a number of demonstration-grade IGCCs have been built [28], their investment costs are on par with nuclear but have much higher operational costs [7]. Finally, power production from *enhanced deep-well geothermal energy* is thought to have the potential to reach 100 GW of installed capacity in the United States by 2056 with modest R&D investment [29]. Because the cost of geothermal largely depends on the depth necessary to reach high underground temperatures, well depths of 10 000 ft can be economic in the western United States, whereas the 30 000-ft well depths required in the eastern states are less competitive.

Power generation from PV and concentrated solar power (CSP) requires relatively high investment costs [7]. Although these costs have recently decreased, they will need to decrease further for large dedicated solar plants to play a significant role. However, it is likely that distributed PV will grow in solar-rich urban areas, such as the cities of the southwestern United States, where the use of rooftops incurs no opportunity costs, and transmission costs are avoided.

C. Major Uncertainties

There are six classes of uncertainties that are expected to have a dramatic influence on future evolution of energy and transportation infrastructure systems.

Governmental policies: The single most influential uncertainty is whether emitters of CO_2 will be charged, either through a cap and trade program, similar to that which exists for SO_2, or a tax. The potential for such a development depends on perspectives of the populace, orientation of the existing government, and climate change forecasts. Related policies are defined by state- and national-level renewable portfolio standards (RPSs) (there are 30 states with RPSs, but no federal policy) and the extent to which government subsidizes and facilitates (mitigate impediments to) chosen technologies, including renewables, nuclear, national high-capacity transmission, and electrified highway and rail transportation. The two-year reelection cycle at the state and federal levels, an essential part of U.S. democracy, adds to the uncertainty through the potential for significant policy swings. This situation may be quite different in the countries such as China where the policy changes are not driven by short-term elections but by the long-term planning and associated political agenda of the ruling party.

Fuel prices: Sustained and significant price shifts for petroleum, natural gas, coal, and biofuels will deeply influence the extent to which they and, consequently, other resources are used to provide energy.

Technology maturation: The rates at which different technologies mature (called breakthroughs when the rate is very high), in terms of decreasing investment costs and increasing efficiency and reliability, will have a dramatic influence on their growth. Technologies that are likely to show high maturation rates would have great impacts if they include:

- energy supply: IGCC with carbon capture and sequestration, offshore wind, solar PV and CSP, deep-geothermal, ocean thermal, wave, and tidal energy, and biofuels;
- energy carrier: power handling capabilities of semiconductor devices for high voltage direct current (HVDC) transmission, superconducting transmission, and hydrogen production, transport, and utilization;
- energy consumption:
  - transportation: electrified rail, pluggable hybrid electric vehicles (PHEVs), electric vehicles (EVs);
  - demand-side management: smart houses, distributed microgeneration, two-way metering, and control;
- energy storage: batteries, fuel cells, flywheels, compressed air, and thermal storage.

The cost of capital: Discount rates, adjusted for inflation, vary greatly with a region's economic health and have large influence on planning decisions. Economic downturns are strong inhibitors to technological change, as they tend to simultaneously decrease the need for new capacity and the ability to obtain capital. Long-term energy plans must account for them.

Demand growth: Electric demand in megawatt hours, commodity transport demand in ton-miles, and passenger transport in person-miles vary with many factors including economic growth, population growth, and price of electricity and transportation fuels. There is significant scope for efficiency improvement in each of these categories—power electronic controlled motor drives for smart appliances and refrigerators, new designs of high-efficiency air conditioners, and high-efficiency compact fluorescent lamp (CFL) and light-emitting diode (LED) lighting. In addition, changing lifestyle patterns with better awareness of energy and environment, active participation in demand response schemes, and popularity of energy-efficient homes and appliances will also lead to reductions in energy demand.

Infrastructure retirements: Most power plants were originally constructed with design lives of 30–50 years, but many have continued operation well beyond their design lives. The uncertainty in when infrastructure is retired has considerable impact on planning decisions. This should be viewed in the context of the environmental hurdles imposed by societal developments where "not in my back yard" (NIMBY) public opposition may spontaneously build at any time.

VIII. EMERGING OPPORTUNITIES

A. Standardization and Interoperability

With the unprecedented level of integration found in smart grid solutions, identifying economic ways to build "system of systems" quite often reduces to the issue of standardization. On a larger scale, this problem is particularly amplified in the developed countries, such as the United States, where the legacy assets are close to a trillion dollars and expansion in the smart grids is expected to be as high in the future [30]. In order to cost effectively interface the various smart grid solutions, they need to be interoperable. The cost-effective aspect is associated with an ability to utilize different products from different vendors as the smart grid solutions get designed, upgraded, and maintained. This flexibility is essential for cost considerations since if the products are interoperable the customer has a variety of design choices for selecting the most cost-effective supplier or product. To cater to such needs the Grid Wise Architecture Council (GWAC) has developed the interoperability framework, often called GWAC stack, as shown in Fig. 4 [3]. The GWAC stack demonstrates that the interoperability issues are complex and require a disciplined design approach that looks not only at the physical interfaces but also interfaces at the data syntactic and semantic levels leading to organizational interfaces within and outside a given company. Adherence to GWAC stack principles is poised to offer multiple savings through cost avoidance associated with smart grid infrastructure deployment.

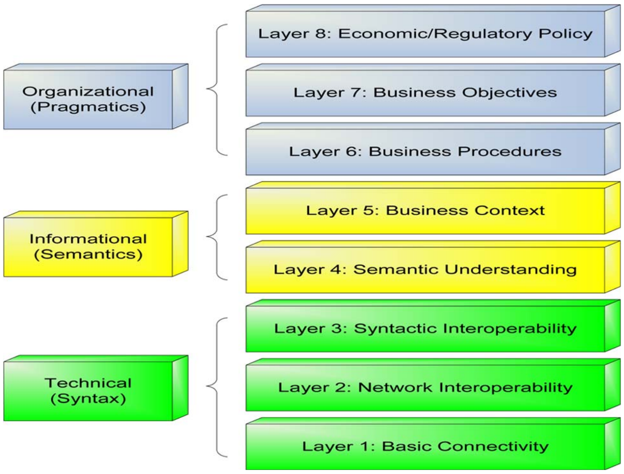

Fig. 4. *GWAC stack for interoperability.*

The latest developments in the standards coordination area to accommodate cost-effective ways of interfacing between different solutions in the smart grids were initiated by the provisions of the EISA 2007. As a result, the Smart Grid Interoperability Panel (SGIP) was formed and facilitated by NIST since 2009. This panel has attracted close to 2000 members ranging from individual professionals to major standards development (SDOs) and standards setting organizations (SSOs). In its activity, SGIP addresses many issues for cost-effective smart grid deployment such as the architecture framework, testing, and certification procedures and cybersecurity compliance. In addition, SGIP accelerated development and adoption of a number of new standards of critical importance to accelerated and cost-effective development, demonstration, and deployment of smart grids. Traditionally, power system business partners were manufacturers, utilities, and consumers with clearly delineated roles. Interoperability standards will allow other business sectors including communication and the service sector to participate, and support innovations that may enhance consumers' more active role.

B. Convergence of Electricity and Transportation

One of the key drivers for the need for the smart grid is the potential convergence between electricity and transportation. If PHEVs or purely EVs are able to capture even a modest percentage of the automobile market, the impact on the power grid could be substantial. While this scenario is unlikely to ever be realized, if all of the 250 million U.S. passenger vehicle fleet were electric, and they all were charged simultaneously, each drawing roughly 4 kW, this new load would equal the combined U.S. generation capacity of about 1000 GW. Also, from an incremental cost of operation perspective, the advantage in many locations is with the EVs. A liter of gasoline contains about 9.7 kWh of energy. Assuming a 25% efficient internal combustion engine, versus a 75% efficient battery and electric motor combination, electric energy is less expensive provided its cost is approximately less than three times that of gasoline. So at $1 per liter of gasoline, the breakeven point from a purely fuel cost viewpoint is $0.31/kWh. Of course, how quickly PHEVs and EVs are adopted depends on several factors such as battery cost, the cost of the vehicle, and on the price of petroleum.

The impact these vehicles have on the grid depends upon how their charging is controlled. A worst case scenario would be to have millions of drivers plug their cars into their garage outlets in the early evening when they return from work, drawing maximum charging current at a time when the electric load is often at its maximum, and when the distribution transformers are most stressed. A much better alternative would be to use some sort of time management approach, in which the smart grid uses information about anticipated electric grid conditions and customer preferences to determine an optimal charging schedule. One such approach would be, for example, charging the vehicle during the middle of the night, when electricity prices are often lowest. Real-time or day-ahead locational marginal prices (LMPs) could be used to transmit information about grid conditions to the car. Nighttime charging can also be particularly attractive in areas with large amounts of nighttime peaking wind generation.

While intelligent charging is a necessary first step toward the integration of PHEVs and EVs into the grid, these vehicles can be much more versatile from a grid perspective if they can also sometimes provide power back to the grid, what is known as vehicle to grid (V2G). With V2G, and an associated smart grid cyber infrastructure to communicate with the vehicles, the vehicle batteries could become an integral part of the grid, providing energy when the LMPs are high, and charging when they are low. An important advantage of V2G is since people drive their cars into urban load centers during the day, when these regions experience their maximum electric load, they tend to be in the right place at the right time. Another advantage of V2G is that the personal vehicle could be used as an emergency source of electric energy, to power at least some of the residence during a blackout. However, a potential hindrance to wide-scale V2G adoption is economics. With a usable capacity of perhaps 10 kWh for a PHEV, with one charge/discharge cycle per day with a relatively large LMP difference between charging/discharging of say $100/MWh, the total revenue would only be $1/day, with the amount paid to the owner undoubtedly less. The negative impact of the repeated charging/discharging cycles on the battery life needs to be considered as well.

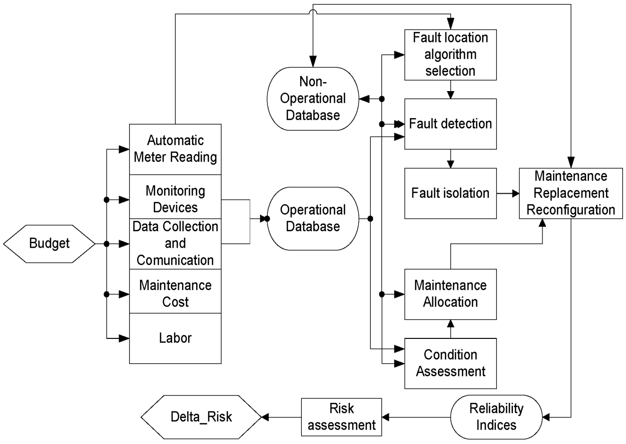

Fig. 5. ***Improving system reliability by optimizing OMS.***

C. Improvement in Reliability and Power Quality

The need for the smart grid is also driven by the need to improve customer reliability and power quality. On the one hand, utilities are unable to serve customers during power outages and the associated revenue is lost. On the other hand, consumers value the services associated with quality of the supply (filtering of "waveform pollution"), the reliability (continuity of supply), and the consistency in supply voltage (voltage quality). Customers requiring high quality of electric supply service may even be willing to pay extra money for it. Italy, Norway, and a number of other European countries have started the service quality regulation to improve the quality of service. Rewards are paid to the overperforming utilities, and penalties are paid by the underperforming utilities [31]. In such cases, utilities must improve reliability and power quality to avoid penalty and earn incentives.

As an example, the desired economic improvement can be achieved by optimizing the outage management system (OMS), which assist system operators in fault analysis, to shorten the time for fault location and service restoration, and narrow down the area for fault isolation, so that the losses (costs) associated with outages are reduced [32]. The proposed optimization includes three steps: 1) implement newly developed algorithms to improve individual OMS tasks; 2) incorporate local generation, storage, and elastic load such as PHEVs for after-fault power backup; and 3) formulate cost-assessment methods to quantify outage cost, and improve the overall performance by risk-based analysis (Fig. 5).

All the steps require new field recorded data and information from variety of intelligent electronic devices (IEDs) to be made available by smart grid deployment, in addition to traditional SCADA data.

D. Use of Energy Storage at Different Scales

A true "wild card" in assessing the future of electric power systems would be the development of low-cost storage with a time scale of at least one day. Electricity is a highly refined form of energy that is relatively easy to transport and use, but its Achilles heel has been lack of low-cost storage technologies. Of course, numerous storage technologies exist, such as batteries, pumped hydro, compressed air, and capacitors; see [33]. And each has its niche. However, none have been truly effective, practical, or economical for bulk, widely deployable electric energy storage. The result is significant variation in the spot market price of electricity, where daily variations of more than \$50/MWh are not uncommon.

The development of low-cost electric storage would transform the energy infrastructure in several important ways. The first benefit would be the already discussed electrification of the transportation sector. Second, storage would permit much greater deployment of renewable but intermittent resources such as wind and solar, both of which have significant diurnal cycles. Third, bulk storage at the transmission level could permit much greater network utilization since each storage unit would provide another fast responding system control helping to level out system flows and prices. Fourth, distributed storage in the distribution system, coupled with microgrid-type controls and local generation, would provide for much greater resiliency since these smaller grids could function at least for a time even in the event of the loss of the bulk transmission system.

However, the availability of economic storage would not necessarily make the transmission grid obsolete. Whether we ultimately get most of our electric energy from distributed local sources, such as rooftop PV, or sources connected to the bulk transmission grid such as larger nuclear, coal, natural gas, wind farms, or solar thermal, the decision will depend in part on whether these sources have economies of scale.

IX. THE FUTURE APPROACH TO PLANNING

For many years, planning engineers have used computational models to inform their decision making, and such models remain the best means of projecting the future to identify strengths and weaknesses of various planning strategies. However, the nature of the planning problem has changed. In the past, planning engineers have considered single-industry, regional, 20 year, cost-minimization planning paradigms, and this approach will continue. In addition, there is need to extend this planning paradigm in several directions, as described below.

Multiple-industry planning: Tighter coupling among different industry sectors, e.g., electric and associated fuel systems (natural gas, coal, uranium) and electrified transportation systems, requires planning processes, procedures, and tools that accommodate multiple-industry planning.

National planning: Because different energy forms vary in availability along with the potential economics of moving certain forms from one region to another, because emissions must be treated nationally, and because adaptation to climate change will include population and industrial migration throughout the country, planning models must span the nation or continent.

Forty-year horizon: Equipment lifetimes in excess of 40 years demand planning horizons of at least that long, and today there is the computational capability to do it. In addition, because the effect of emissions is cumulative over time, extending over a century or more, it is important to view emission rates dictated by investment planning for as long as possible.

Multiobjective optimization: Investment planning is inherently multiobjective, focused on optimizing costs, resilience, and sustainability, with potential for several subobjectives within each one of these. Such optimizers provide a number of "good" solutions, which can inform the sociopolitical processes necessary to choose one of them.

X. CONCLUSION

As surveyed in this paper, several future grid developments are expected:

- increased use of renewable variable generation at both the bulk and distributed level;
- profound involvement of customers in all aspects of electricity generation and uses;
- increased penetration of automation at both the distribution and transmission level;
- more comprehensive planning strategies that will deploy risk-based techniques to cope with uncertainty;
- proliferation of interoperability standards facilitating new developments, e.g., electric cars, enhanced power quality, and use of energy storage of different scales.

Several issues have been recognized but not explored in this paper due to lack of space and the need to have specialized expert focus:

- cybersecurity and physical security will play an ever increasing role in all future grid developments;
- advancements in the materials ranging from superconductive compounds to new nanoscale structures will be a continued quest in the future;
- new market paradigms that will create new business models to stimulate the growth of the electricity sector are expected in the future;
- a host of policy changes that will create incentives and reward innovation are also expected to emerge as the grid develops in the future.

The electric system will continue to rapidly evolve, requiring a vast array of human and economic resources. This will result in provision of societies energy needs in a way that is sustainable for the 21st century and beyond. ■

REFERENCES

[1] *H.R.6: Energy Independence and Security Act*, 2007.

[2] R. Galvin and K. Yeager, *Perfect Power*. New York: McGraw-Hill, 2008.

[3] *GridWise Architecture Council*. [Online]. Available: http://www.gridwiseac.org/

[4] United Nations, *Kyoto Protocol to the United Nations Framework Convention on Climate Change*, 1998.

[5] EPRI, *Intelligrid Program 161, 2012 Research Portfolio*. [Online]. Available: http://intelligrid.epri.com/

[6] PSerc, "Challenges in integrating renewable technologies into an electric power system," Power Syst. Eng. Res. Cntr. Rep. 10-27, 2010.

[7] J. McCalley, W. Jewell, T. Mount, D. Osborn, and J. Fleeman, "A wider horizon: Technologies, tools, and procedures for energy systems planning at the national level," *IEEE Power Energy Mag.*, vol. 9, no. 3, pp. 42–54, May/Jun. 2011.

[8] NETL, *Smart Grid Principal Characteristics Enables New Products, Services, and Markets*, DOE/NETL-2010/1401, Feb. 2010.

[9] *The American Recovery and Reinvestment Act*. [Online]. Available: http://www.recovery.gov/About/Pages/The_Act.aspx

[10] *National Science Foundation/Department of Energy Engineering Research Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks (CURENT)*. [Online]. Available: http://curent.utk.edu/

[11] *Consortium for Electric Reliability Technology Solutions (CERTS)*. [Online]. Available: http://certs.lbl.gov/

[12] *National Science Foundation Engineering Research Center for Future Renewable Electric Energy Delivery and Management (FREEDM)*. [Online]. Available: http://www.freedm.ncsu.edu/

[13] International Energy Agency, *World Energy Outlook*, 2007.

[14] Lawrence Livermore National Laboratory, *2008 Sankey "Energy Flow" and "Emissions Flow" Diagram*. [Online]. Available: https://flowcharts.llnl.gov/index.html

[15] Utility Wind Integration Group, *Wind Power and Electricity Markets: A Living Summary of Markets and Market Rules for Wind Energy and Capacity in North America*, Aug. 2009. [Online]. Available: www.uwig.org/windinmarkets.htm

[16] Midwest ISO Market Subcom, *Dispatchable Intermittent Resource Implementation Guide*, Mar. 1, 2011. [Online]. Available: www.midwestiso.org/Library/Repository/Meeting%20Material/Stakeholder/MSC/2011/20110301/20110301%20MSC%20Item%2012a%20DIR%20Implementation%20Update.pdf

[17] B. Kroposki, R. Lasseter, T. Ise, S. Morozumi, S. Papatlianassiou, and N. Hatziargyriou, "Making microgrids work," *IEEE Power Energy Mag.*, vol. 6, no. 3, pp. 40–53, May/Jun. 2008.

[18] KEMA. (2010, Jun.). Research evaluation of wind generation, solar generation, and storage impact on the California grid, Rep. EC-500-2010-010. [Online]. Available: http://www.energy.ca.gov/publications/displayOneReport.php?pubNum=CEC-500-2010-010

[19] Z. Zhang and C. Deshu, "An adaptive approach in digital distance protection," *IEEE Trans. Power Delivery*, vol. 6, no. 1, pp. 135–142, Jan. 1991.

[20] G. D. Rockefeller, C. L. Wagner, J. R. Linders, K. L. Hicks, and D. T. Rizy, "Adaptive transmission relaying concepts for improved performance," *IEEE Trans. Power Delivery*, vol. 3, no. 4, pp. 1446–1458, Oct. 1988.

[21] S. H. Horowitz, A. G. Phadke, and J. S. Thorpe, "Adaptive transmission system relaying," *IEEE Trans. Power Delivery*, vol. 3, no. 4, pp. 1436–1445, Oct. 1988.

[22] J. D. McDonald, "Substation automation, IED integration and availability of information," *IEEE Power Energy Mag.*, vol. 1, no. 2, pp. 22–31, Mar./Apr. 2003.

[23] M. Begovic, D. Novosel, D. Karlsson, C. Henville, and G. Michel, "Wide-area protection and emergency control," *Proc. IEEE*, vol. 93, no. 5, pp. 876–891, May 2005.

[24] NERC, *North American Electric Reliability Organization (NERC) Glossary of Terms Used in NERC Reliability Standards*, May 2011. [Online]. Available: http://www.nerc.com/files/Glossary_of_Terms_2011-May24.pdf

[25] D. Todd, M. Caufield, B. Helms, M. Starke, B. Kirby, and J. Kueck, *Providing Reliability Services Through Demand Response: A Preliminary Evaluation of the Demand Response Capabilities of Alcoa Inc.*, 2009. [Online]. Available: http://certs.lbl.gov/pdf/dr-alcoa.pdf

[26] Y. Chen, M. Keyser, M. Tackett, and X. Ma, "Incorporating short-term stored energy resource into Midwest ISO energy and ancillary service market," *IEEE Trans. Power Syst.*, vol. 26, no. 2, pp. 829–838, May 2011.

[27] P. Lako and G. Tasato, "Coal-fired power," International Energy Agency Energy, Technology Systems Analysis Programme, Technol. Brief E01, Apr. 2010. [Online]. Available: www.etsap.org/E-techDS/

[28] J. Tester, B. Anderson, A. Batchelor, D. Blackwell, R. Dipippo, E. Drake, J. Garnish, B. Livesay, M. Moore, K. Nichols, S. Petty, M. Toksoz, and R. Veatch, "The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century," Massachusetts Inst. Technol./U.S. Dept. Energy, 2006.

[29] A. Quelhas, "The patterns of flows in SO_2 allowance trading," M.S. thesis in economics, Iowa State Univ., Ames, IA, 2004.

[30] EPRI, "Estimating the costs and benefits of smart grid: A preliminary estimate of the investment requirements and the resultant benefits of a fully functioning smart grid," Tech. Rep., Mar. 2011.

[31] L. L. Schiavo and R. Malaman, "Regulation and incentives for improving continuity of supply: The experience of Italy and a comparison with other EU countries," in *Proc. CIGRE/IEEE PES Int. Symp., Quality and Security of Electric Power Systems 2003*, pp. 241–247, Oct. 9–10, 2003.

[32] Y. Dong, V. Aravinthan, M. Kezunovic, and W. Jewell, "Integration of asset and outage management tasks for distribution systems," in *Proc. Power Energy Soc. Gen. Meeting*, pp. 1–9, Jul. 26–30, 2009.

[33] B. Roberts, "Capturing grid power," *IEEE Power Energy Mag.*, vol. 7, no. 4, pp. 32–41, Jul./Aug. 2009.

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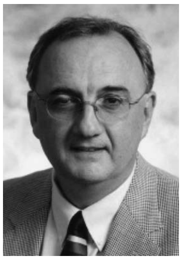

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