BACKGROUND

> **The Smart Grid**
>
> …will manage and deliver bulk electrical energy through a combined centralized and distributed system, in which many nodes are capable of producing, consuming, and storing electrical energy. Managing transactions on this network will involve extensive communications networks and distributed – hierarchical control schemes.

The need for a sustainable electrical grid or "Smart Grid." DOE's Energy Information Agency (EIA) has projected that electricity demand in the United States will increase by nearly 50% over the next 20 years [EIA 2007b]. Transmission expansion is already struggling to keep pace with this demand growth, and investment actually declined over the last two decades [EIA 2007c]. The reasons for the shortfall include the cost of transmission infrastructure, land access, and public opposition. Exacerbating these issues is deregulation, which has separated the roles of generation, transmission, and distribution in many regions, resulting in decreased coordination. The goals emerging from increasing national and statewide attention on renewable and energy policies will require renewable and alternative energy sources to supply a large proportion of the increased demand. In addition, limitations on transmission and distribution (T&D) growth coupled with increasing requirements for power quality will drive growth in the use of distributed generation technologies. Another trend calling for the grid to transform and modernize shows increasing stress and reliability failures with associated large economic costs according to the Electric Power Research Institute. The existing grid structure, combined with the centralized control philosophy, is ill suited to accommodate significant levels of flexible and distributed energy resources without dramatic changes in operations, infrastructure, and development strategy.

As illustrated in Figure 1, today's electrical demand typically undergoes large fluctuations varying with time of use. Utilities must size their grids for sufficient capacity to meet the peak demand, as shown in the evening peak hours in Figure 1. This approach, however, leaves the grid underutilized during large portions of the day, especially at night under minimum load conditions. With increasing penetration of renewable generation, finding ways to manage resources in a way that would reduce the ratio of peak to average power demand, thereby effectively increasing the total energy capacity of the grid, provides an opportunity to partially address the capacity challenge. Reducing the ratio of peak to average demand may be achievable by such actions as these:

- Placing distributed storage near loads (including the possibility of utilizing the batteries in hybrid or all-electric vehicles in a grid-controlled manner);
- Placing distributed generation near loads including on-site generation (e.g., photovoltaics, fuel cells) with net metering;
- Incorporating smart loads capable of shifting their demand in response to price or other control signals;

- Shifting existing loads to alternative, non-utility-connected sources;
- Implementing new regional market pricing strategies and incentives integrated with demand;
- Placing large storage capacity associated with wind generation, which tends to peak at minimum load conditions;
- Placing large storage capacity near solar generation, which misses the evening peak.

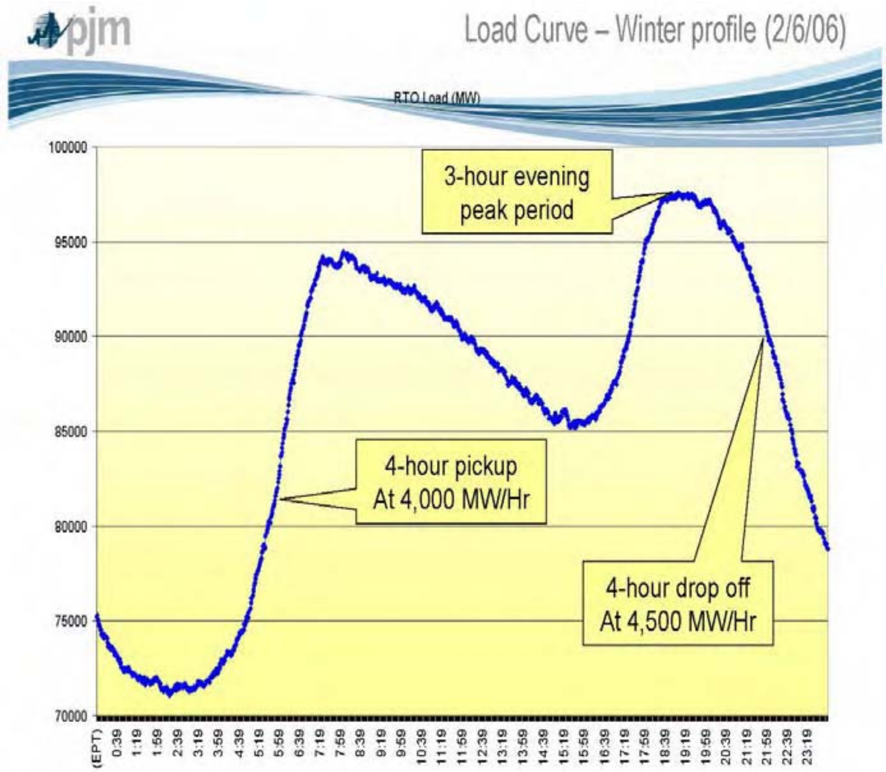

Figure 1: Diurnal Load Shape for the PJM System
(Diagram courtesy of PJM Interconnect, LLC www.pjm.com/markets/market-monitor/downloads/20070521-pjm-overview.pdf)

Incorporating significant levels of highly variable energy resources and/or widely distributed resources requires advanced, interactive control infrastructures that monitor and correct power imbalances in real time. These controls must be able to communicate with and dispatch alternative sources and utilize advanced grid management technologies, including storage, in order to smooth the effective output of low-carbon, renewable, and alternative energy sources. These alternative resources, likely placed near loads, suggest that the control infrastructure will need to include real-time distributed response and decision-making throughout the grid. The nonlinearity of the power grid, the introduction of smart loads and distributed generation sources, and the desire for and advantages of load leveling in an environment with limited predictability, make this a truly challenging problem.

Moreover, technology transformation is rapidly taking place under existing market forces, making resulting power management issues even more critical to address. For example, Toyota recently announced that it would be offering plug-in hybrid electric vehicles (PHEVs) by 2010 [Maynard 2008]. Pacific Gas and Electric (PG&E), a California based utility, became the first utility in the nation to publicly demonstrate the possibility of electric vehicles to supply homes and business with electricity at a Silicon Valley Leadership Group event in April 2007 [PG&E 2008]. A recent DOE study suggests that the current "idle" capacity in the grid (0.1-0.2 TW) could be enough to recharge approximately 158 million (73% of the light duty fleet) plug-in hybrid electric vehicles (PHEVs) using off-peak power [Kintner-Meyer 2007]. In addition, studies suggest that PHEVs are the best near-term option to reduce dependence on petroleum [Gaines 2007]. Yet the current U.S. grid is not equipped to respond to the operational needs that would follow from the widespread adoption of this technology. Appropriate infrastructure, control algorithms, and technology performance metrics are required to ensure that the electrical supply or demand created by PHEV is properly integrated into the dispatch schedule for all major stakeholders. Without such management, PHEVs may aggravate dispatch problems, especially during system extremes— peak demand or minimum load. Consider, for example, the system impacts of a concentration of PHEVs all recharging immediately after their evening commute. This extra load concentrated at a weak point on the grid would in fact further exacerbate the difficulties of satisfying the evening peak demand.

Despite the significant benefits arising from a future of net-metering, load-control technologies, grid-connected storage, and new but highly variable generation capacity, there will be significant barriers to achieving such a future if the added complexity of the new grid compromises attributes critical to consumer satisfaction—namely, safety, security, reliability, quality, and affordability. In addition, future grids will be judged by their capacity to support sustainable development. Hence, the requirements will include the ability to do the following:

- Operate and maintain assets for efficient and effective utilization of resources and capacity;
- Accommodate all types of generation and storage options, including dynamic availability of distributed generation and storage;
- Enable innovative and efficient market mechanisms to enhance resource effectiveness for consumers, producers, and service providers;
- Provide variable power quality and reliability that matches the variable demand for quality and reliability;
- Resist and recover from natural and human-induced disruptions (both cyber and physical "attacks");
- Self-correct, be information-rich, and operate interactively with users via automated controls and advanced system-wide visualization.

Maintaining an adequate portfolio of generation (conventional and renewable) capacity to meet growing electrical demand, maintaining reliability, managing reserves and costs will become ever more challenging with increasing adoption of variable (intermittent) renewables and continuing trends to cancel base load coal power plants due to environmental concerns. Even at 10-15% penetration, intermittency issues are raising resource adequacy concern among system operators especially during system extremes. This is amply evident through the recent state and utility-led integration studies which cite integration issues and potential cost with varying levels of wind penetration.

The current grid. To understand the challenges of incorporating smart loads, distributed generation, and variable sources such as solar and wind, one must have an understanding of the physical behavior of the electricity network and electrical flow.

The electricity network operates in a load-following mode; in other words, as a just-in-time delivery system (i.e., limited reserve inventory), generating, transmitting, and consuming electrical power virtually instantaneously. Operators adjust for system conditions and large shifts in loads over timescales from minutes to hours, by increasing or decreasing the generation.

Within an interconnected power system (there are three interconnects in North America), the power flows from generators to loads through transmission and distribution lines. Though the electrical grids for Alaska and Hawaii are not interconnected to the rest of the nation, they exhibit similar and more serious resource integration and control issues, as their grids are relatively more distributed because of their remote or island locations. The current system of centralized generation supports the stability of the grid. Furthermore, the frequency and phase must remain within narrow margins. (In normal operating scenarios, the frequency variation is controlled to within ±0.01%; see, for example, *Basic Research Needs for Electrical Energy Storage*, BES Workshop Report, April 2007.) Should the instantaneous generation (the supply) not match the instantaneous loads (the demand), the frequency will drift.

Grid Reliability

We must "keep the lights on," independent of natural or deliberate disturbances.

With solar and wind generators, the instantaneous electrical generation is variable on a relatively fast time scale; and therefore, it is effectively nondispatchable from the standpoint of the current grid. Furthermore, to transport power from one node to another, power will flow over *all* connected paths between them. This can and does lead to some unexpected and not easily controlled behavior, especially in unregulated markets. To avoid damage, each transmission line must operate below its rated capacity. If a transmission line becomes overloaded, it could trip out of service, overloading adjacent lines that could also subsequently trip. This might lead ultimately to a widespread outage [Albert 2004; Motter 2004]. In fact, even without the introduction of renewables, the 15-year-time-series transmission-system-blackouts data provided by the North American Electric Reliability Council suggests that blackout sizes follow a power law with significant economic impact. It is estimated that such power interruptions introduce an annual national cost of approximately $80 billion [Hamachi-LaCommare 2004].

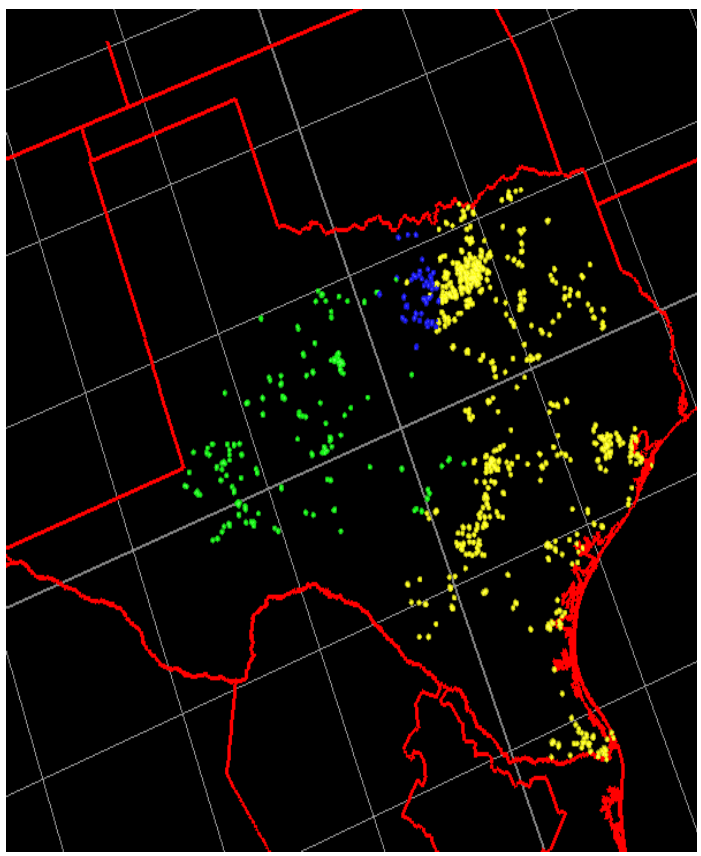

Figure 2. Simulation results show how cascading failures would break the Electric Reliability Council of Texas system into three independent islands (each shown in a different color) leading to blackouts.

Therefore, computer simulation of electrical grid failures is a key tool for understanding and preventing cascading failures leading to blackouts of electrical grid systems. In these computer simulations, the electrical grid is represented as a network of transmission lines and buses (generators and loads). During service conditions, each of the lines and buses operates below a specified rated capacity. However whenever the lines or buses are overloaded, they trip out of service, which could lead to a cascade of tripping events in the neighboring lines or buses.

Figure 2 presents a simulated scenario of such a cascading failure of the Electric Reliability Council of Texas (ERCOT) system, where each of the dots in the figure refers to a bus (or node) in the ERCOT system, which, while perhaps still operating, is isolated from nodes of other colors. Figure 2 was developed by combining National Oceanic and Atmospheric Administration National Geophysical Data Center data and geographical coordinates of ERCOT buses. This simulation clearly shows how cascading failures of transmission lines and buses break the ERCOT system into three independent islands (each shown in a different color) leading to a blackout [Phani Nukala and Srdjan Simunovic, unpublished]. Understanding the progression of cascading events allows us to develop control strategies to prevent or mitigate the effects of power blackouts. To simulate such events for larger systems such as the entire eastern interconnect or to simulate multiple, interconnected systems will require high-performance computing capability.

The U.S. electric power grid is one of the most complex systems of any type in the world. This system has evolved over the past 100 years and currently includes an array of technologies and architectures. To achieve the control needed, the system has a hierarchical structure consisting essentially of four levels:

- Physical protection for equipment (generators, lines, components)
- Local regulating feedback controls (sensors, switches, monitors)
- Automated and computer-assisted controls, including Supervisory Control and Data Acquisition (SCADA), Energy Management Systems (EMS), Automated Generation Control (AGC), and Wide-Area Monitoring and Control
- Markets and regional reliability.

In the coming years, control systems and strategies must evolve (although this will require more than evolutionary advances) in order to operate in an environment consistent with the envisioned changes that were identified earlier. New systems and strategies will also ensure that security and reliability standards are met and potential vulnerabilities are identified.

The underpinnings of power system operation are extensive analyses of system conditions to ensure compliance within standards and to indentify vulnerabilities. As generation becomes more variable (from increased penetration of renewable and alternative energy sources) and loads become more flexible (because of enhanced controllability and local storage, possibly including PHEVs), the ability of existing analysis tools to faithfully replicate actual system behavior will diminish. Future grids will require new analysis concepts and technologies to accurately assess system stability and security and formulate control actions. In terms of computational needs, the goal is to develop new high-performance computational resources and algorithms necessary to expand today's model from its current state to a potential case of 100 million distinct nodes in a multi-scale centralized and distributed system. Within this context, the panel convened to identify priority computational research directions to enable the necessary transformation and modernization of the electrical grid.

SUMMARY OF COLLECTIVE PRIORITY RESEARCH DIRECTIONS

> **Grid Evolution**
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> To accommodate diverse end-user-based energy generation, storage, and consumption, the grid must evolve from its current centralized generation and control structure to a more distributed system.

The Energy Distribution – Grid Futures and Reliability Panel convened to discuss the necessary evolution of the current grid to a future, more controllable, "greener" grid. This would be one that can effectively incorporate new forms of electricity generation, storage, and consumption in order to capitalize maximally on investments in and benefits from renewable energy generation and distributed load-management technologies. The addition of renewable and distributed energy resources to the overall energy mix poses challenges to the management of the current grid infrastructure. Specifically, the panel identified five fundamental challenges:

- Dramatic movement toward further decentralization of grid management and toward a larger, more complex, more diverse system of distributed energy resources significantly alters the operation and the structure of the grid. The challenge will be to develop and install new capabilities to monitor, assess, and control the power grid in a way that ensures its overall reliability.

- Policy instruments can and will have a strong influence on the rate and degree to which the grid decentralizes and diversifies. The challenge will be to develop capabilities to assess impacts and provide decision support for various policy instruments.

- The use of price signaling, net metering, and other market strategies has the potential to produce a very large and time-variable customer response function. The challenge will be to develop a highly adaptive transactional network in order to effectively manage these emerging market strategies in a manner that promotes reliability, efficient operation, and effective integration of new technologies.

- Grid reliability remains essential. Estimated costs based on momentary and sustained power interruptions on U.S. electricity customers (commercial, industrial and residential) range from $23 billion to over $119 billion [Hamachi-LaCommare 2004]. As the electrical grid moves toward a more distributed and diverse system, the challenge will be to strategically invest in a robust grid, to mitigate issues such as intermittency (from sources of variable generation) and to develop a capability to manage generation and load more effectively. Intermittency forecasting has shown to provide improved management potential for accommodating increasing levels of variable resources.

- For certain parts of the grid, substantial penetration of intermittent renewable sources of generation can raise system stability issues if not properly planned. The challenge is to develop new paradigms for managing flexible resources and maintaining system stability despite independent and potentially rapidly varying generation and load. Geographic diversity of wind and solar generation provides some smoothing of their variable nature, however events in both the US and Europe suggest that depending on the transmission interconnects and flexibility of other resources on the grid, challenges still remain.

The overarching goal of each of the identified priority research directions described here is to apply advanced computational resources to maintain grid robustness while managing increasing levels of renewable and alternative energy resources. In other words, future grids must continue to operate reliably through any credible (natural or deliberate) disruption. As the world makes the transition from traditional fossil fuels to more environmentally friendly energy alternatives, decision makers will need better scenario-based planning capability, control/response, and integration tools (i.e., models, sensors, new reliability metrics, high-resolution data) befitting emerging technologies. Likewise, for clean distributed energy resources (including distributed generation and demand response), further research, development, and demonstration will be needed to improve the technology, to inform industry planners, and to help decision makers transform markets and policies. Ultimately, however, all of these decisions, plans, and generating, storage, and end-use technologies must come together to motivate the critical need for methods of better managing the production, distribution, and use of electricity while ensuring the overall reliability of grid operations and enabling sustainable development.

We emphasize that effective, reliable management of the grid is critically important to achieve the benefits provided by new sources of renewable and efficient energy generation. Simply put, the impact of the large-scale introduction of nontraditional alternative and renewable resources has no historical precedence. The grid will likely be a large, complex, multi-scale network requiring dynamic feedback on a far greater scale than the one that currently exists. Thus, there is a strong need to develop new algorithms to characterize the system and to forecast future behavior (near-term and long-term) under various scenarios. There is also a strong need to develop better software and visualization packages that will move the management of the grid to a real-time automated state. Finally, there must be continued research into the properties of advanced materials and devices to drive technology innovations such as large-scale energy storage, low-loss electrical transmission, and distributed, adaptable technologies.

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EVALUATING THE EVOLUTION OF GRID INFRASTRUCTURE AND IMPACTS ON GRID RESPONSE UNDER VARIOUS MARKET AND POLICY INFLUENCES

ABSTRACT

The existing power grid is saturated, stressed, and not readily capable of accommodating large amounts of distributed sources of new electricity generation or load management. Furthermore, existing power systems, which have evolved over the past half-century, were never designed to support significant levels of renewable or bidirectional distributed resources. The regulatory and planning process to interconnect various new sources of generation (both central and distributed) will have a profound effect on the evolution of grid infrastructure as the grid strives to distribute ever-increasing amounts of power. This change requires the development of new tools and methodologies to understand and evaluate the forces transforming the system (and the consequent changing characteristics), to assess potential impacts, and to generate options (which can help inform investment and policy decisions).

The existing system is complex and composed of a multitude of components, communication devices, sensors, and control structures. The current state of modeling must simplify the system in both scale and complexity. For study purposes, the representation of high-voltage transmission systems within the Western Interconnect used 14,000 nodes [Albert 2004]. In reality, the total number of nodes in this interconnect is several orders of magnitude higher. Practical analysis has had to omit the details within the distribution system. Clearly, there is a need for new and higher fidelity methodologies and efficient computational algorithms in order to capture the essential details of existing grid conditions, let alone model their behavior under new market and policy influences, and as the grid evolves to an even more complex structure.

EXECUTIVE SUMMARY

Building a sustainable and resilient electricity infrastructure to incorporate new alternative and renewable resources and technologies and meet ever-growing demand remains a challenging task. If not properly considered, this challenge will result in detrimental consequences not only to our economy but also to our national security. With the growing worldwide need for electric power, diminishing fossil resources, and increasing concern over security and the environment, there is a clear case for adopting alternative and indigenous energy-generating resources and optimize their integration onto the power grid. ("Indigenous resources" are those available locally or regionally and not globally, such as wind, biomass [including municipal solid waste and wood], geothermal, solar, or related industry by-products of heat.) One particular need is a framework or system of computational models with which to simulate the temporal evolution of the future grid with enough fidelity to inform critical decisions. This represents a crucial element to avoid unintended, damaging, and unforeseen interactions. This framework must be capable of reliably modeling various possible future grid scenarios in a dynamically scalable manner. It also needs to identify strategies to implement alternative and renewable resources and technologies that support various policy goals.

SUMMARY OF RESEARCH DIRECTIONS

With the widespread incorporation of alternative and renewable energy sources, including those on the scale of individual households, the grid would be composed of more than 1×10^8 individual nodes. Each individual node might be able to buy or sell electricity at any given time and respond to different efficiency and optimization objectives; thus, the new grid must be able to accommodate a variety of simultaneous load-response strategies. Moreover, there is a need to construct accurate models of the grid in order to evaluate many different "what if" scenarios. For example, policy makers and industry might want to know the effect of supplying wind-generated electricity at a 10%, 20%, or 30% share of total generation [California Energy Commission 2007] and know if any effects depend on other critical factors, in addition to the percentage. Other drivers of "what if" scenarios are various policies for energy distribution and production, particularly as they relate to market or policy incentives for the customer and the service provider. A simple example is a plug-in hybrid electric vehicle or PHEV [Pacific Gas and Electric Company2007; Letendre 2002]. In principle, a PHEV gives the consumer devices that can act as local electrical storage in addition to providing energy for mobility. Acknowledging that policy will encourage the technologies driving energy efficiency, what would be the effect of a given policy on the overall energy system and what are the interdependencies with other policy or market actions? One example would be to evaluate the effects of large numbers of PHEVs in several scenarios. Due diligence in encouraging the widespread adoption of this technology, via policy incentives, will be necessary to avoid overstressing existing grid infrastructure. These distributed technologies represent a dramatically different way of operating the grid. They have the potential to provide tremendous benefits in the overall performance of the grid, yet they come with an equally important obligation to ensure appropriate integration strategies to avoid detrimental effects. In addition, models will have to be able to capture critical dependencies on existing infrastructure, human actors, and outside market responses, as they attempt to simulate the grid-evolution under forcing functions arising from various technology and policy scenarios [Parsons 2006].

Power system operation is becoming increasingly dependent upon modern information technologies to solve management and control problems in the distributed electric power grid. The transient dynamics and information processing mechanisms embedded within the complex interconnected electric grid could already benefit from more fundamental understanding, but current state-of-the-art models for cascading failures and distributed behaviors consider only smaller systems that are simplified steady-state network models. The resulting change in scale from the current state-of-the-art (order 1×10^5 nodes) and the introduction of complexity resulting from realistic modeling of disruptive technologies, policies, market mechanisms, and human/market forces requires the development of simulations capable of taking advantage of leadership class computers. More specifically, we can define the main computational challenges by the following elemental needs:

- To create a capability to model human and market responses in order to understand the likely effectiveness and impact of different choices among technology development, investment strategies, and policy instruments;
- To create a capability to model the integrated dynamics of social, technology, economic/market, and environmental impacts with a large number of diverse and interdependent elements;

- To create discovery-based tools to explore “known unknowns,” as well as to reveal unknowns that cannot yet be contemplated (“unknown unknowns”);
- To develop a fundamental knowledge base to underpin the development of control strategies to maintain stability, security, reliability, affordability, and sustainability.

The priority research directions described below capture different aspects important to enabling a smooth transformation and modernization of the electrical grid.

- Planning, informing key stakeholders, and guiding the evolution of the grid;
- Considerations for operating and managing complexities in the future grid;
- Considerations for implementation to ensure interoperability between diverse elements of the grid and between existing and future elements;
- Exploratory and discovery-based tools to understand the fundamentals determining performance attributes, to elucidate potential unexpected or perhaps emergent behavior, and to uncover vulnerabilities within possible future grid states and topologies;
- Advancing technology innovations to enable the future grid.

Trends and needs are driving the electrical grid to a networked system with no previously explored analog. The combined flow of electrons, information, and instructions makes this network-based system far more complex than the Internet. The electrons must be consumed as they are created; the information is rapidly varying, heterogeneous, and distributed; and the instructions are of numerous types and depend on past and existing states. The system is not only complex, but is also complex-adaptive and a system of systems; the sciences of complex adaptive systems and of systems of systems are both in their infancy.

COMPUTATIONAL NEEDS

A power system model that integrates generators, loads, transmission lines, control processes, and packet-switching data networks is an example of a hybrid system (some continuous flows and some discrete events.) The behavior of physical systems is describable with differential-algebraic equations, with some discrete dynamics that result from circuit breakers, relays, and other types of local response mechanisms. In contrast, packet switching networks are best describable as discrete event systems with a dynamic behavior represented by chains of significant events. What is required are modeling and simulation capabilities that support such hybrid systems at large scale and high fidelity as a core set of capabilities [Hiskens 2000]. The computational challenges in this area include not only a sophisticated model construction that can combine complex, continuous, and discrete representations but also credible validation methodologies to build confidence in the results.

Given the high degree of uncertainty in modeling all the key phenomena, uncertainty analysis, and the ability to detect high consequences (even if low probability states) will be essential [Hiskens 2006]. This requires a forward model that is able to predict with reasonable confidence the system response to specific stimuli; however, the real goal is to identify both short- and long-term responses on multiple temporal and spatial scales. Pursuing this goal requires studying inverse models [Hiskens 2004] and, possibly, radically new approaches in representing the forward problem underlining the importance of studying nonlinear systems with discrete and continuous interfaces.

POTENTIAL IMPACT ON ALTERNATIVE AND RENEWABLE RESOURCES AND TECHNOLOGIES

With all the benefits of renewable resources, the realities of large-scale integration of such resources present technical as well as economic challenges for our electrical system as it stands today. For example, in many parts of Europe and the United States, wind generation is becoming a dominant renewable resource, leading to, because of the variability, a compounding of pre-existing grid quality issues [IEA 2007]. Variable and remotely distributed resources are posing significant grid integration and operational challenges for the current electricity infrastructure. Predominately because of the variability of the wind resources and the lack of operational confidence at high renewable penetration levels, there is a sense of "uneasiness" in pushing for more renewables. The lack of advance forecasting and planning tools that can utilize reliable data (both temporal and spatial) and new sources of data befitting the new technologies contribute to the discomfort and uncertainty experienced throughout our nation's utility industry. Other alternative and renewable resources and technologies such as biomass, biobased fuels, and solar (PV, CPV, and CSP) face similar source-to-sink issues as a result of the lack of transmission capacity and operational experience. Thus, it is essential to develop grid planning tools or modes of simulation that can more easily accommodate with confidence these new but variable sources of electricity generation without unintended consequences.

Finally, this priority research direction enables the exploration of technologies under different policy and market influences, providing the ability to evaluate strategies without compromising the the security, economics, or reliability of the grid while ensuring the realization of the intent of the strategy. It will provide the tools to reduce risk and enable informed decision making regarding our future infrastructure.

TIME FRAME

The grid is transforming under natural forces and policies are being implemented without any reliable tools to assess whether the results will be consistent with the goals. Hence, the need exists now and will continue for at least a decade or longer.

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EVALUATING AND INTEGRATING AUTOMATION AND SCALABLE OPERATING STRATEGIES INTO THE FUTURE GRID

ABSTRACT

As the grid becomes more complex as a result of increased demand, limited capacity, new market mechanisms, and new technologies, the management of this complexity in near-real-time becomes an increasingly arduous task.

There is a need to develop a set of tools that will enable real-time operational management of the future grid — including decision making, associated with generation and load management, ancillary services, distributed generation, select markets, and grid reliability. Real-time operation and distributed decision-making capabilities will be critical enablers in any future grid that is able to better accommodate distributed technologies and variable generation capacity; this requires the use of new tools.

EXECUTIVE SUMMARY

There is a growing concern that the aging grid infrastructure is at risk of becoming more vulnerable to system-wide failures by naive integration of alternative and renewable resources and technologies. More important, grid sustainability and reliability require ancillary services such as frequency regulation, transmission voltage support, and spinning reserves. As new load and generation technologies are integrated, it will be necessary to address these ancillary services separately. It is no longer appropriate to assume they are automatically available as part of these new technologies as they were with legacy generation.

Experienced utility dispatchers and system engineers currently manage these issues; however, the characteristics of renewable sources and distributed load management differ enough from conventional operating paradigms, thereby creating a need for new operating paradigms to prevent local failures from cascading into system-wide blackouts. The anticipated complexity will require movement toward intelligent/automated management of the grid.

SUMMARY OF RESEARCH DIRECTIONS

The essence of this priority research direction is to identify new models and algorithms to enable real-time management and distributed decision-making in the absence of precise knowledge of the structure of the future grid. In fact, developments here could materially affect the outcome of the grid's evolution.

Existing standards might need modifications, and new standards might need to be developed, in response to the findings from various simulations studying system transformations. A crucial aspect of meeting this challenge lies in the ability to perform rapid state assessments of the operating grid and the ability to represent that state in a form that is an easily accessible and understandable visual interface [Power World Corporation; Overbye 2001].

Operational training on simulator modeling would provide an extremely useful mechanism for both the operator and the engineer to understand the behavioral characteristics of the grid and to have the ability to determine, effectively and efficiently, appropriate methods of interaction. Development of a visually enhanced, grid simulation capability with diverse and distributed data sources will undoubtedly require significant algorithmic development to quickly assess normal versus abnormal operation anywhere in the grid, make the appropriate decision, and signal the appropriate corrective action, as needed, all in real-time, despite the complexity of the system. Development and validation of such capabilities will be practical only by using high-performance computing platforms.

Industry standards exist to protect equipment integrated into the grid and to ensure an adequate level of reliability for consumers and industries. U.S. electric power grid reliability requirements are implemented and enforced by the North American Electric Reliability Company (www.nerc.com), and they are overseen by the Federal Energy Regulatory Commission. Standards include those developed by the Institute of Electrical and Electronics Engineers. Utility managers maintain a balance between electricity supply and demand using the availability of generation resources and demand technology in order to "keep the lights on." With the likely increase in the number of distributed elements, which react to load and generation imbalances within the overall network, grid management must become more automated, resulting in systems within systems. The operator function thus would move closer toward managing control systems rather than managing individual grid components. This trend is becoming more evident in today's grid, where grid operators' responsibilities now include the management of wide-area control systems, referred to as Remedial Action Schemes (RAS) or Special Protection Schemes (SPS).

The blackout of August 2003 in North America demonstrated that a fault in one part of the power system can ripple and cascade to ultimately disrupt neighboring transmissions [Wald 2005]. The post-disturbance analysis and report highlighted the clear need for wide-area situational awareness. Human operators in the loop are currently unavoidable for the reliable management of the power grid, since the robustness of automation is not at a level where the system can allow autonomous operation. A utility's supervisory control and data acquisition (SCADA) network monitors the balancing authority's status. Increasingly, however, operators require visibility into the grid beyond their own area. Thus, the wide-area system now requires an overarching layer that can collect information and provide operators with a broader context of the state of the grid.

Existing power system operating strategies exploit the predictability and periodicity of daily load variations. Increased utilization of renewable generation will result in generation and load patterns that are much more sensitive to weather conditions and hence exhibit greater variability. Other technological changes, such as distributed generation, price-responsive loads, direct load control, and vehicle-to-grid concepts will tend to further reduce the predictability of operating strategies. Operating strategies will always require some predictive capability, though, to account for time delays and rate limits that are inherent in rescheduling large generators. Research is required to establish operational requirements that are suited to this new, more dynamic environment. Compensating for less intrinsic predictability is achievable through increased awareness of the current state of the system and improved predictive modeling of components. This implies a need for both capabilities for vastly more extensive state estimation and algorithms for significantly faster and more reliable calculations.

Power system emergency operation, following a large disturbance, is largely operator-initiated and responsive. Some special protection schemes (also known as remedial action schemes) have been established to assist operators. But even they offer limited flexibility, responding to preset triggering conditions in a predetermined way. As power systems become more heavily loaded and approach stability and security limits, the effectiveness of such responsive control efforts will diminish. The future grid will require control schemes that incorporate short-term predictive capabilities. The underpinnings for such schemes will be fast, reliable, and accurate capabilities to create situational awareness. Disturbances will be quickly detected, along with the estimated system state used for predicting a range of possible transient responses. The event-detection process will need to be capable of assessing, in real-time, the proximity of the system to the boundary of the stable, secure operating region. The control algorithm will use this predictive capability to determine actions that minimize the maximum disruption. This min-max objective implies a need for algorithms that solve large-scale games.

Such predictive control is dependent upon system models that are sufficiently accurate—the required level of accuracy is itself an open question. Maintaining the appropriate level of accuracy will require an online model validation process that is continuously monitoring system behavior and updating model descriptions.

Although we cannot completely know, at this time, all the operational components of any future grid, it will nevertheless likely include the following:

- A hierarchical control structure consisting of centralized coordinating controls and distributed decision making, with two-way information flow between the levels;
- Integration of real-time communication infrastructure to accommodate wide-area monitoring and real-time control of the grid;
- Real-time situational awareness of the system state, consisting of order 1×10^8 independent and sometimes autonomous generators, storage, and loads. This awareness would likely be produced using visualization technologies that incorporate tools to filter out irrelevant background data. Decision management tools, helping the operator to determine the optimal robust path forward, depending on the situational awareness;
- Closed loop, wide-area, adaptive control algorithms;
- Real-time load-leveling and distributed load-management, including the ability to turn loads both on and off varying dispatch orders, as needed, to smooth intermittent resources such as wind or solar generation;
- New methodologies for self-diagnostics, design, and assessment of operational health.

COMPUTATIONAL NEEDS

The sheer quantity of transactions required for supporting real-time monitoring and control makes the priority research direction a major computational challenge, in terms of both the computational capacity needed and the subsequent information network required to support decision making. There is a need for large-scale, real-time, spatio-temporal situational awareness tools for monitoring and state estimation of the grid.

Deregulation of electricity markets, compounded with the introduction into the grid of alternative and renewable resources and technologies, further enhances the transactional and pricing complexity of electricity markets [Joint Western Public Utility Commission 2007; Geerli 2003]. Development of models and algorithms for efficient transactional management of electricity, especially in the presence of alternative and renewable resources, becomes necessary for the seamless integration of alternative and renewable sources into conventional electricity markets. Internet and/or banking traffic models may be reasonable surrogates to address this issue [University of Oregon Route Views Project 2005]. In addition, game-theory based models may play a role in addressing the large numbers of transactions arising as a result of the increasing number of market-participants associated with distributed energy resources.

State estimation, dispatch optimization, real-time predictive modeling (which continually predicts the future state of the grid), and contingency analysis are complex tasks, especially in a large, heterogeneous network with renewable generation. Combining these complex tasks and including market optimization will require impressive breakthroughs in algorithmic development and solution methods.

POTENTIAL IMPACT ON ALTERNATIVE AND RENEWABLE RESOURCES AND TECHNOLOGIES

Identifying needs for tools that will enable real-time management techniques is a critical first step toward a robust and efficient future grid that is able to manage the complexity resulting from the large penetration of alternative and renewable resources.

To date, a number of utilities have distributed generation and distributed energy resource programs and have gained considerable “behind the meter” experience, but the penetration and the technology are limited. Although transmission and distribution infrastructure planning for the future grid is happening now, it lacks good scenario-based system evaluation tools. Such tools will be very useful in guiding and informing major infrastructure transformation investment and policy decisions, and they could even accelerate the decision-making process.

TIME FRAME

This is not something solvable in one pass. In the face of these new complexities, it will be important that new control paradigms be explored, options developed, and the best concepts allowed to mature to commercialization. This is likely a decade-long endeavor, and efforts must start as soon as possible.

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MAINTAINING CONTINUITY AND INTEROPERABILITY AS THE GRID TRANSFORMS

ABSTRACT

It cannot be emphasized too strongly how critical and difficult it will be to ensure continuous, reliable, and secure operation of the power grid during periods of changing technology and infrastructure to a qualitatively different, more sustainable grid, and to do so in a timely manner. The ability to evolve the grid requires continued or enhanced interoperability among all of its constituent parts and players.

EXECUTIVE SUMMARY

Renewables and the integration of new technologies into the existing electrical infrastructure are causing a number of operational and reliability concerns for the grid. This is in part because the characteristics of most renewable and demand management technologies are different enough from their legacy counterparts, but more fundamentally, the existing infrastructure was never designed to accommodate such diverse and distributed technologies or rapid controls envisioned for the future [Tomsovic 2005]. The electricity grid is undergoing a rapid transformation, but there are important lessons from our current and past experiences. It will also be important to ensure a smooth transformation that does not compromise system performance yet will promote competitive engagement by industry.

SUMMARY OF RESEARCH DIRECTIONS

The priority research direction in this section focuses on utilizing current knowledge of the system and extracting that knowledge to maintain a high degree of grid reliability as grid technologies undergo change.

Because of the evolutionary development process, our current grid and grid management and business processes have inherent strengths and weaknesses at various levels. These processes are specific to certain infrastructures and locations—design, communication, operation, controls, and technology. As change continues, our understanding of the existing infrastructure becomes more disparate and incomplete as personnel change, resources diversify, and incremental changes occur in the grid. At the most basic level, this priority research direction captures the need to ensure that standardized communication taxonomies be maintained for cross-platform interoperability. Similar to managing computer infrastructure changes from mainframe-based computing to client-server based platforms, control algorithms and standard communication protocols are needed to convert from a legacy structure to more flexible data exchange methods. There is a need to adapt smart technologies and control algorithms to legacy platforms while the grid makes its transition from its current state to a smart grid. From the system design point of view, this requires the development and implementation of standardized communication taxonomies. One such industry entity that exists solely to address this grand challenge is the GridWise Architecture Council [2007a]. Their mission, as they defined by their vision statement, is to do the following:

> Weave together the most productive elements of our traditional infrastructure with new, seamless plug-and-play technologies. Using advanced telecommunications, information, and control methods, we can create a "society" of devices that functions as an integrated, transactive system. [GridWise Architecture Council 2007b]

At a more functional level, transformation to new grid technologies requires that we maintain "institutional" memory and the links that are unique to other interdependencies, including location constraints, unique architectural designs, generation portfolio management, co-located resources, and other community considerations. The expert knowledge currently held by system operators and planners needs to be captured, assessed, and utilized to simulate functional designs for grids of the future [Kontogiannis and Safacas 2004]. The ability to transcend quickly from micro to macrosystem perspectives is the essence of the research challenge. Approaches to capturing this information, and the sheer volume of information to organize for further assessment, makes this a priority research direction.

COMPUTATIONAL NEEDS

The objective of this priority research direction is to develop, test, and implement knowledge and data capture, data control, and exchange principles that serve to maintain the continuity of the current grid as its components evolve to form the future grid. Methods to capture expert knowledge and maintain interoperability among old and new components will be necessary to ensure smooth grid operations [Zheng et al. 2006]. This includes trending and assessment of existing system operations and effectiveness of control [Tullis and Albert 2008] (especially during system excursion times or out of limit operations). Simulation training for utility operators can be expanded not only to include historical events but also to research methods of operation using new tools, effective tools, and technologies to see how they respond to out-of-normal operations when significant penetrations of alternative and renewable technologies have been integrated with the grid.

The computational challenges involved include the following:

- Ensuring interoperability between legacy controls and generation technologies and new platforms; this requires large-scale, high-resolution modeling of power system components to develop valid choices of standards and their potential impact on market adoption of innovative new technologies and strategies;
- Developing system simulation models to capture details down to the power distribution level and integrate cross-dependencies (renewable technology, market, and policy influences) to ensure the ability to uncover potential but unexpected incompatibilities after incorporation;
- Maintaining user confidence in real-time management and situational awareness tools;
- Addressing data standards, protocols, annotation, archival storage, and access control issues for legacy data, future data, and derived data captured;
- Integrating advanced visualization, knowledge discovery, and data analysis to identify new extremes for operations during the transformation period in the operating grid.

POTENTIAL IMPACT ON ALTERNATIVE AND RENEWABLE RESOURCES AND TECHNOLOGIES

As more renewable and alternative energy resources penetrate the grid, implementation strategies need due diligence to ensure interoperability with other infrastructural elements. Whether modifications to existing practices will be incremental or will require fundamental shifts in operating paradigms is a current debate among many; however, considerations of interoperability and the effect on operations need to be addressed today in order to ensure maximal benefit from these technologies. Implementation strategies also need to be sound to ensure reliable delivery of power. Computational capability exists from the research community for visualization and knowledge discovery. These tools can be leveraged, and further adapted, and then applied in support of the transforming grid. They can also establish confidence in the adoption of new innovative technologies and strategies.

TIME FRAME

As the grid is already undergoing rapid change, and as policies to promote change are increasing in popularity—for example, a number of states have already adopted renewable portfolio standards—addressing issues of interoperability and implementation to avoid catastrophic disruptions of electric service is pressing. Hence, the time is now and will continue at least for a decade.

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EXPLORING COMPLEX BEHAVIORS IN GRID SCENARIOS

ABSTRACT

Complex and emergent behavior is the surfacing of a systemic pattern not characteristic of the components that comprise the system. This presents a unique challenge within the evolving power grid. Designing benign control systems such as automated demand response controls into a residential house may not be benign at all when vast numbers of homes exhibit the same behavior. Understanding what will happen when a large population starts to use a new technology is critical before deploying the technology in large numbers. If emergent behavior would result from large-scale implementation of a particular technology, and not identified before integration into the grid, then cascading effects could occur. Identification beforehand presents an opportunity to develop mitigation strategies to retain the principally desirable benefits while eliminating any propensity to cause detrimental emergent behavior and hence, safe incorporation into an electric power grid. Similarly, emergent behavior could result from crossing a threshold in a changing topology as added resources incorporate at nodes or edges of the grid network. Identification beforehand again presents an opportunity to develop mitigation strategies to guide growth to eliminate any propensity to cause detrimental emergent behavior through naïve growth.

EXECUTIVE SUMMARY

In the future grid, we can reasonably expect a variety of different behaviors to emerge from the interaction between demand response, distributed resource technologies, and the topology of the electric system as a whole. These unanticipated emergent behaviors can arise from interactions between infrastructural elements within the energy system.

Discovering emergent behavior (whether beneficial, benign, or harmful) requires highly credible models of the grid in order to detect anomalies that might represent any unusual behavior and be confident that it is not an artifact of the model. These models must be detailed enough to capture subtle interactions, large-scale feedbacks, and low-level but amplifying changes in component, system behavior, and traffic (power and information flow).

SUMMARY OF RESEARCH DIRECTIONS

There are vast numbers of potential drivers for emergent behavior (e.g., sunrise on a PV farm, wind picking up on a wind farm, consumers postponing usage until prices drop) that can alter the flow of power to different regions of the country. These small-scale perturbations and the interaction among the nodes of the grid that amplify these perturbations need to be clearly understood under a variety of "what if" scenarios in order to identify potential forms of overall grid-emergent behavior. Furthermore, the ability to model emergent behavior allows for identification and possible mitigation of behavior or growth patterns that are detrimental to the grid's performance. Thus, early indicators of emergent behavior need to be formulated, methods for identifying the most important components influencing the behavior need to be developed, and strategies for limiting the impact of the behavior need to be tested. This requires identifying and assembling the relevant data that might serve as critical indicators of any impending problem and having the capacity to rapidly communicate this information to planners and grid operators. The need for visual or graphical representation of the grid as it approaches the critical behavior may require new computational and information architectures suitable for efficient portraying of models that are capable of representing these emergent behaviors [Foster].

In order to understand emergent behavior, power system models will need added sophistication to include components on many scales and as fine as down to the consumer level. The resulting model dimension will increase by several orders of magnitude, making traditional solution approaches infeasible. When market effects, weather effects, and policy effects are included, the model will become even more complex.

A few models exist that characterize the overall emergent behavior of a complex system. However, these models are still in their infancy and are limited to small, idealized networks with simple interactions among the agents that make up the network. Algorithms that can extend to real networks with hybrid (continuous and discrete) interactions are needed to explore emergent behavior in grid systems. Furthermore, significant challenges exist in the proper mathematical description of the model, designing new algorithms for simulating the model, and designing tools to extract useful information and knowledge from the simulations.

COMPUTATIONAL NEEDS

The computational challenges associated with this priority research direction include the following:

- Identify methodologies to characterize the grid system (electron flow, information, and transactions) on various temporal and spatial scales;
- Apply appropriate model construction to represent a wide range of possible grid structures and topologies;
- Develop new algorithms to simulate various possible grid structures and topologies with a goal of exploratory and discovery-based investigations of the relationship between structure and performance attributes; find and elucidate patterns and unusual behaviors to promote or to avoid;
- Develop new algorithms to treat the possible grid structures and topologies as complex adaptive systems or a system of systems and uncover key characteristics that lead to robustness, resiliency, and sustainability;
- Acquire and use current system data to validate, improve, and refine simulation models;
- Design data analysis tools to extract information and knowledge from current and simulation-based systems.

POTENTIAL IMPACT ON ALTERNATIVE AND RENEWABLE RESOURCES AND TECHNOLOGIES

Energy security and environmental concerns are placing significant investment in alternative and renewable resources; however, it will be important to have reliable capabilities to assess the performance characteristics of resulting new grid topologies, depending on various incorporation strategies, as some naïve strategies can increase renewables on the grid yet decrease reliability or even increase greenhouse gas emissions. The efforts identified will enhance our ability to identify hidden incompatibilities or hidden interdependencies that these different technologies might induce in the grid to characterize their behavior in the future grid and to provide requirements for new controls and information strategies in the grid.

TIME FRAME

As demand increases and the market responds and as policies promote the incorporation of new resources the nation is at significant risk of unanticipated consequences from the creation of an ever-increasing complex grid and limited understanding of its fundamental characteristics. Hence, it will be important to see efforts in the next one to two years and grow those efforts over *the* next decade or more.

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DEVELOPING AND INTEGRATING INNOVATIVE COMPONENTS AND PROCESSES FOR THE NEW GRID

ABSTRACT

Advanced computational materials research and validation remain crucial to component research for the future grid. New materials will allow increased grid capacity through, for example, high-temperature superconducting or nanotechnology transmission lines, demand-leveling of the grid through electrical storage, and the use of distributed generation technologies such as advanced fuel cells.

EXECUTIVE SUMMARY

The development, design, deployment, use, and characterization of advanced materials and technology components can benefit enormously from computationally based research in order to enhance the adoption of renewable and alternative resources by accelerating development, reducing technology risks, and generally building confidence. Specifically, the deployment of potentially large amounts of electrical storage, enabled by the development of new materials, will require impact analysis, integrated testing facilities, and new controls to facilitate robust integration into the future grid. Thus, adopting new materials for transmission lines, such as high-temperature superconducting lines and nanotechnology (e.g., carbon nanotubes for transmission lines) may, without proper planning and integration, create new challenges for managing the grid. As an example, one objective of the current grid design is to sustain an outage of at least a single element without propagating a failure; however, superconducting transmission lines will carry a disproportionate amount of electricity, and if a contingency were to occur on one, it might increase the probability of a cascading outage. The design of appropriate scalable markets needs consideration, because devices need to be engineered to perform robustly in response to market signals (e.g., price), enabling a complex market where devices may be polled periodically and each may have the option to buy or sell electricity or do nothing for some period of time. Such transactions must be accurately recorded; modeling or running such a system is a distributed petascale data management and processing challenge.

SUMMARY OF RESEARCH DIRECTIONS

New industry facets will likely emerge, centered on the computational requirements to design, manage, and process grid information envisioned for the future. Advances in material and computational research offer the possibility of using superconducting materials for transmission and storage and the utilization of advanced computational resources to properly characterize and design respective technologies as well as aid in their testing; however, building off other scenario-based priority research directions, the focus of this research area is to derive new knowledge of system functionality and need. With that knowledge base, researchers can then use extracted information to guide the design of new grid components and properly parameterize the system conditions to aid the design of technology solutions (e.g., advanced electrical storage, transmission, generation capacity, conversion, or system management and control to integrate PHEVs, market signals, other distributed technologies, and so on).

There is also a critical need for significant advances in materials research to create effective, low-cost solutions to the electrical storage problem such as batteries, supercapacitors, superconducting magnetic energy storage, and high-speed flywheels. Thus, significant research into electrical storage and properties of new materials, which operate safely, is crucial to an efficiently operating energy infrastructure.

In addition, each unique technology brings with it a need to control it as an integral element of the grid. For example, if all devices on the network were polled every second, approximately equivalent to using the SMS protocol, the data rate could be as large as two terabits per second continuously. Managing the grid using this data set would require new algorithms and high-performance computing.

These new operational paradigms—such as managing versus preventing interruptions with distributed electrical storage and generation, demand response, and high capacity transmission—will require new methods and algorithms for robust control.

COMPUTATIONAL NEEDS

Computational needs include these:

- Improving the accuracy of numerical physics-based models that deal with chemical, material, fluid, and thermodynamic processes—basic science, engineering and design tools
- Utilizing system knowledge extracted to inform the design and characteristics of components intended for specific grid enhancements (speed, efficiency, decarbonization, real-time processing, alternative operations during extreme conditions by applying game theory,, chaos theory or other types of behavior-based processes)
- Exploring market infrastructures and other infrastructure models (banking internet) and seeing if there are complementary platforms (i.e., communication, controls) to maximize grid operations (not only electricity but coupled with natural gas and water management).

POTENTIAL IMPACT ON ALTERNATIVE AND RENEWABLE RESOURCES AND TECHNOLOGIES

The exact layout of the future electric grid is unknown at this time. The grid will continue to evolve with technology, policy, and market forcing functions; however, our ability to shape future designs and future grid requirements is dependent on what we can envision today based on anticipated needs to improve reliability and security, reduce costs, and to incorporate renewables and environmentally friendly alternatives. To make those visions a reality, findings of simulation-based scenario analyses are essential in shaping the design and characteristics of technologies that complement needs.

One of the biggest promises of alternative and renewable resources and technologies lies in their potential ability to become a controlled source of electricity to the grid. A typical house could have many forms of energy generation—some in the form of more traditional generation such as rooftop PV or hydrogen fuel cells. Another type of energy generation is simply the controlled ability to curtail load. Finally, electric storage, including PHEVs, might serve the grid. Enabling these energy technologies, and controlling them in a manner to aid both the electric power grid as a whole and the local communities they serve is a key component to meet this realization.

TIME FRAME

To maximally impact the modernization of the grid, the next three to five years and then ongoing ones will be important, noting that the technology will continue to evolve.

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APPENDICES

APPENDIX 1: WORKSHOP PARTICIPANTS

Computational Research Needs in Alternative and Renewable Energy

Hilton Rockville
Rockville, Maryland
September 19-20, 2007

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Jeffrey Neaton	Lawrence Berkeley National Laboratory
Mark Nimlos	National Renewable Energy Laboratory
Phani Nukala	Oak Ridge National Laboratory
James Nutaro	Oak Ridge National Laboratory
Ruth Pachter	Air Force Research Laboratory
Ellen Panisko	Pacific Northwest National Laboratory
Sreekanth Pannala	Oak Ridge National Laboratory
Eleftherios Papoutsakis	University of Delaware
Edward (Ned) Patton	National Center for Atmospheric Research
Roger Pawlowski	Sandia National Laboratories
Mark Pederson	Naval Research Laboratory
Joerg Petrasch	ETH Zurich (Swiss Federal Institute of Technology)
Stephen Picataggio	Synthetic Genomics
Alex Pothen	Old Dominion University
Tijana Rajh	Argonne National Laboratory
Jennifer Reed	University of Wisconsin-Madison
Angus Rockett	University of Illinois
Michael Sale	Oak Ridge National Laboratory
Andy Salinger	Sandia National Laboratories
Russell Schmehl	Tulane University
Scott Schreck	National Renewable Energy Laboratory
Thomas Schulthess	Oak Ridge National Laboratory
Eric Schwegler	Lawrence Livermore National Laboratory
Mark Sears	U.S. Department of Energy
Radu Serban	Lawrence Livermore National Laboratory
Rekha Seshadri	The J. Craig Venter Institute
Andrew Shabaev	George Mason University
John Shadid	Sandia National Laboratories
Mallikarjun Shankar	Oak Ridge National Laboratory
Mark Shephard	Rensselaer Polytechnic Institute
Abhijit Shevade	Jet Propulsion Laboratory
Blake Simmons	Sandia National Laboratories
David Singh	Oak Ridge National Laboratory
Jeremy Smith	Oak Ridge National Laboratory
Philippe Soucaille	Metabolic Explorer
Ranjan Srivastava	University of Connecticut
Ellen Stechel	Sandia National Laboratories
G. Malcolm Stocks	Oak Ridge National Laboratory

Galen Stucky	University of California
Tatiana Tatusova	National Institute of Health
Jeremy Templeton	Sandia National Laboratories
Robert Thomas	Cornell University
Donald Thompson	University of Missouri – Columbia
Jean-Francois	Tomb DuPont
David Trebotich	Lawrence Livermore National Laboratory
Dallas Trinkle	University of Illinois
John Turner	National Renewable Energy Laboratory
Jeffrey Varner	Cornell University
Ross Walker	San Diego Supercomputing Center
Cai-Zhuang Wang	Ames Laboratory
Lin-Wang Wang	Lawrence Berkeley National Laboratory
Theresa Windus	Ames Laboratory and Iowa State University
Boris Yakobson	Rice University
Dora Yen-Nakafuji	Lawrence Livermore National Laboratory
(Alan) Qi Yuan	Purdue University
Shengbai Zhang	National Renewable Energy Laboratory
Yong Zhang	National Renewable Energy Laboratory
Zhenyu Zhang	Oak Ridge National Laboratory
Yufeng Zhao	National Renewable Energy Laboratory

APPENDIX 2: WORKSHOP PROGRAM

Tuesday, September 18, 2007		
6:00pm	Working Dinner for Organizing Committee, Breakout Leaders, and DOE Program Managers Location: Madison Room on the first floor of the Hilton. Cash bar available outside Madison Room 5:30-7:30pm	
Wednesday, September 19, 2007		
7:00-8:00am	Working Breakfast and Introduction	Gary Johnson
8:00-8:15	ASCR Workshop Goals and Welcome	Michael Strayer
8:15-8:30	EE Workshop Goals	Sam Baldwin
8:30-9:15	Renewable Energy Opportunities and Challenges	Dan Arvizu
9:15-9:45	Break	
9:45-11:45	Parallel Working Sessions Led by Breakout Leaders • Renewable Fuels - Hydrogen • Renewable Fuels - Bioenergy Conversion • Renewable Electricity - Wind Energy • Renewable Electricity - Solar Energy Conversion • Energy Distribution - Grid Futures and Reliability	
11:45-12:45pm	Working Lunch	
12:45-1:30	Can Energy Production Scale? Choices and Challenges from the Current Century	Greg Bothun
1:30-3:20	Parallel Working Sessions (Continued)	
3:20-3:50	Break	
Reports on Panel Working Sessions		
3:50-4:10	Renewable Fuels - Hydrogen	Breakout Leads
4:10-4:30	Renewable Fuels - Bioenergy Conversion	Breakout Leads
4:30-4:50	Renewable Electricity - Wind Energy	Breakout Leads
4:50-5:10	Renewable Electricity - Solar Energy Conversion	Breakout Leads
5:10-5:30	Energy Distribution - Grid Futures and Reliability	Breakout Leads
5:30-5:40	Closing Remarks	Michael Strayer
7:00-9:00	Writing Time for Breakout Leads	

Thursday, September 20, 2007		
7:00-8:15am	Working Breakfast	
8:15-9:00	Computational Advances in Predicting Molecular Properties for Alternative Energy Solutions Dave Dixon	Dave Dixon
9:00-9:30	Break	
9:30-12:00	Parallel Working Sessions Led by Breakout Leaders • Renewable Fuels - Hydrogen • Renewable Fuels - Bioenergy Conversion • Renewable Electricity - Wind Energy • Renewable Electricity - Solar Energy Conversion • Energy Distribution - Grid Futures and Reliability	
12:00-1:00pm	Working Lunch	
1:00-3:20	Parallel Working Sessions (Continued)	
3:20-3:50	Break	
Reports on Panel Working Sessions		
3:50-4:10	Renewable Fuels – Hydrogen	Breakout Leads
4:10-4:30	Renewable Fuels - Bioenergy Conversion	Breakout Leads
4:30-4:50	Renewable Electricity - Wind Energy	Breakout Leads
4:50-5:10	Renewable Electricity - Solar Energy Conversion	Breakout Leads
5:10-5:30	Energy Distribution - Grid Futures and Reliability	Breakout Leads
5:30-5:40	Closing Remarks	Michael Strayer
7:00-9:00	Writing Time for Breakout Leads	
Friday, September 21, 2007		
7:00-8:00am	Working Breakfast	
8:00-12:00	Writing time for Breakout Leads	
12:00pm	Adjourn	