A Grand Challenge for the Future Grid

A PSERC White Paper

Power Systems Engineering Research Center

Empowering Minds to Engineer
the Future Electric Energy System

A Grand Challenge for the Future Grid

A White Paper from the Power Systems
Engineering Research Center

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PSERC Document 14-4

October 2014

About this White Paper

This white paper was written at the request of the Executive Committee of the Power Systems Engineering Research Center to communicate a grand challenge about the future grid that could be used to inform thinking about the future electric power grid over a wide spectrum of decision-making. The decision-making could range from research and education to actual planning and policy decisions resulting in the specification and design of the future grid. To produce the white paper, the lead authors consulted with industry and university PSERC members. Feedback on an early draft of the white paper was particularly useful. The views expressed in the white paper are those of the authors, and not necessarily those of PSERC industry or university members.

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Power Systems Engineering Research Center

The Power Systems Engineering Research Center (PSERC) is a multi-university Center conducting research on challenges facing the electric power industry and educating the next generation of power engineers. More information about PSERC can be found at the Center's website, http://www.pserc.org, or by contacting PSERC at its lead university:

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A Grand Challenge for the Future Grid

The Challenge: **Design an electric power system that takes full advantage of the convergence of energy, communications, sensing, and computing technologies in a cyber-physical system that enables society to reach its diverse energy objectives, such as 50% renewables or 80% carbon reduction by 2050. Part of the challenge is to make the transition to high levels of renewable resources transparent to users of electric energy where this transparency relates to both reliability of the electric supply as well as its economy.**

Power and energy engineering in its first century of existence has largely been concerned with alleviating mankind of its burdens. In the latter portion of the previous century, information collection, transfer, and processing have augmented the role of energy and power utilization. Not only is technology changing, but societal expectations of the electric power system are changing, particularly as environmental and economic concerns grow. As a result, the energy objectives are becoming even more diverse: to transition to an electric power supply, demand, and delivery system that is environmentally benign; that protects our national energy security interests; that is highly reliable, economically competitive and stable; that facilitates economic vitality while keeping energy affordable; and that is flexible enough to welcome future technical and economic innovation. Diversity not only characterizes the energy objectives, but also the energy technologies, particularly as renewables, demand, and storage technologies become even more widely used. The diversity in objectives and technologies introduces unprecedented levels of uncertainty in operation, planning, and investment. We need to re-examine the needs of the electric grid for the next century, some of which are addressed in references [1] and [2].

In this white paper we discuss the Grand Challenge, and how to design and implement tools to achieve its goals. The Grand Challenge does not contain a firm target date for implementation of a newly designed Future Grid. The grid must be able to support secure and reliable power system operation continuously no matter how soon new technologies are introduced. Being able to have an evolving Future Grid that meets that objective is a critical element of the challenge.

1. Unpacking the Grand Challenge

Traditionally, electric power engineering has been divided into three overlapping areas: power generation, transmission, and distribution. These areas logically form a basis of all of power engineering. One depiction of the Future Grid is shown in Fig. 1. This view is premised on the traditional approach of power flowing one way - from central station generation through the transmission system to the distribution system, and ultimately to the load (i.e., end-use customers). Strong evidence in technological trends today suggest that this premise of one-way power delivery, and clear separation between generation, transmission, and distribution, will prove to be less and less valid in the future. The stated grand challenge is to transition to an electric power supply, demand, and delivery system that is environmentally benign, that protects our national energy security interests, is highly reliable, economically competitive and stable, and that is flexible enough to be welcoming to future technical and economic innovation.

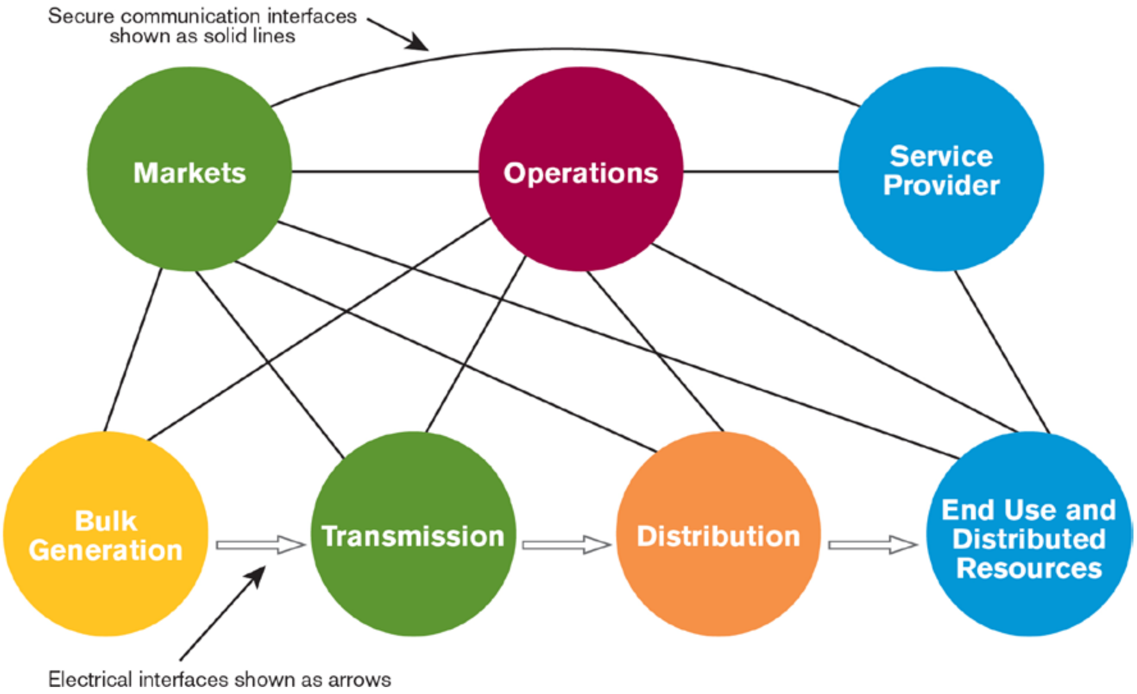

Fig. 1 Depiction of the Future Grid inspired by [3]

Already the proliferation of distributed generation in some areas, particularly rooftop solar, has caused many changes in the grid: load shapes are changing, power is flowing back onto the grid, and there are increasing communication needs in the system. The Future Grid is anticipated to have many more sources of energy and power, in addition to more renewables and cleaner sources of central station generation, including nuclear, natural gas and clean fossil fuel plants. The largest sector renewable resource is presently hydro, but wind energy is the fastest growing sector and wind is likely to overtake hydro as a percent resource in ten years. If one coalesces power marketing, transmission distribution, generation resources, and energy utilization, one obtains the overlapping domains depicted in Fig. 2.

Fig. 2 A pictorial of power engineering coverage for the Future Grid

Some of the factors that will influence how the Future Grid must evolve include:

- Continuing growth in electricity use by an estimated 0.9 percent annually to 2040 supplied in part by growth in natural gas and generation from renewables that exceed growth in coal and nuclear generation [4]
- Significant uncertainty in generation investment, but possibly some 351 gigawatts of new capacity to meet demand growth and to offset retirements of existing capacity, with natural gas plant additions dominating followed by major renewables generation additions [4]
- An increasing reliance on wind and solar renewable resources, and their concomitant necessary transmission capability
- An increasing reliance on underground transmission and distribution technologies
- An increased dependency on natural gas – at least as a stopgap measure for fuel supply in the next ten years
- Implementation of bulk energy storage
- Expanded computational intelligence in energy end-use devices allowing them to respond to grid conditions
- The connectivity of the grid and adjacent infrastructures (e.g., the 'Internet of Things'), edge-computing (embedded intelligence at the edge of the grid and device level)
- Increased reliance on market mechanisms, incentives and decentralized decision making in planning, investment, procurement and allocation of resources in the Future Grid
- Implementation of a *diversity of strategies* that can accommodate a wide range of developments in the power and energy sector
- Increased interest in microgrids, and the identification of the proper role of the decentralization of the electric energy infrastructure
- Managing reliability in the face of regulatory rules impacting the mix of generation
- Resilience to disturbances of a wide range of characteristics – including weather, earthquake, civil unrest
- The evolution of energy efficiency as a national objective
- Designing grid expansion and operation strategies recognizing the sheer size of the energy sector and infrastructure, and recognizing the need for compatible technologies that allow incorporation without disruption
- A policy of addressing a broad spectrum of environmental issues, including – but not just CO2.

Some of the characteristics needed in the Future Grid include:

- Enhanced flexibility in the system
- Enhanced resiliency and faster restoration times
- Communication improvements and security
- Increased visualization of the system in real time
- Ability to maintain reliability while incorporating numerous diverse and intermittent sources of power

- Electrification of transportation
- Increased competition for water resources
- Ability to match load to generation and not just generation to load.

The transition to the Future Grid is underway and progressing at different rates in different parts of the U.S. This transition will require advanced two-way communications on the system, as well as ultimate development of bulk energy storage. Fig. 3 shows an expected time scale for power engineering developments in the United States. Note that the elements depicted in Fig. 3 show the expected evolution of various eventualities of power engineering – but the 15 year horizon is not the expected horizon of the evolution of the future grid: instead the year 2050 is estimated as the eventual evolution of the future grid.

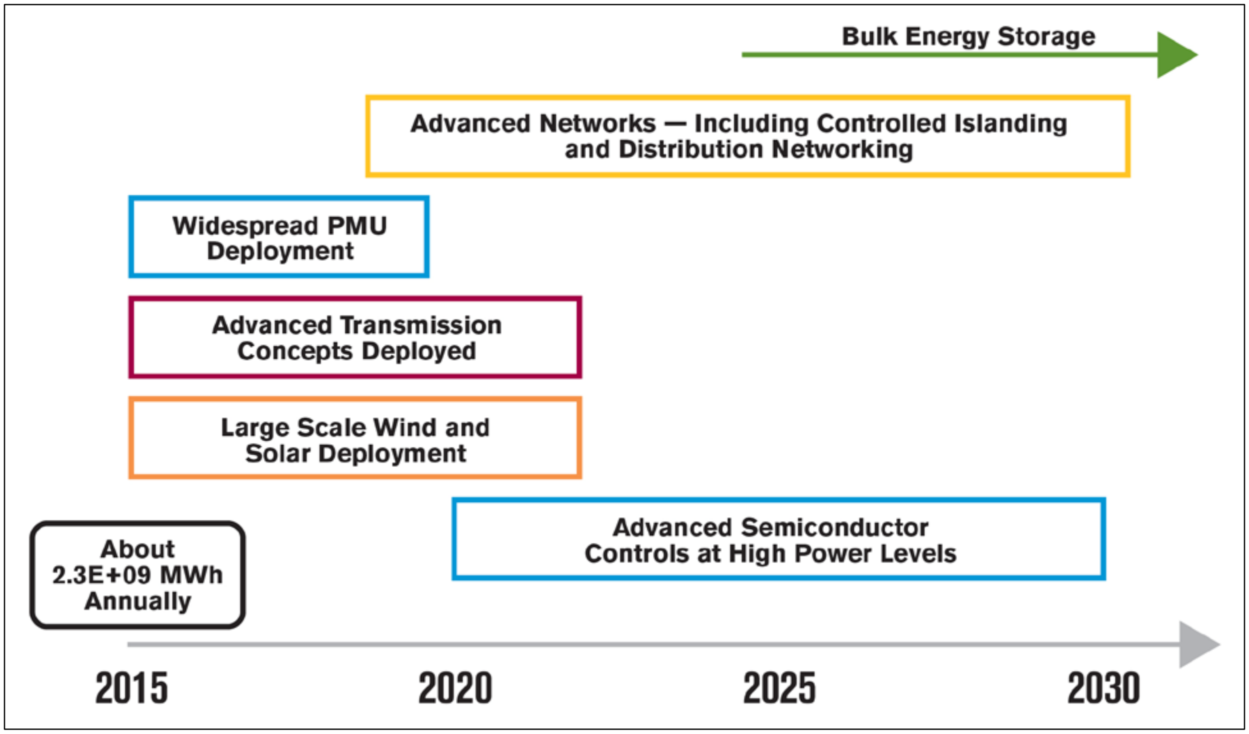

Fig. 3 An expected time scale for power engineering developments in the United States

2. Tools and needs to address the Grand Challenge

The three broadly organized tools which are expected to implement the Future Grid are depicted in Fig. 4. The identified tools are succinctly described and discussed below.

Tool #1: The design of public and private institutions, and a regulatory framework along with market mechanism and business models that will align incentives for efficient implementation of the Future Grid vision.

There have been two major policy drivers that have triggered and will continue to dominate the Future Grid development.

First, environmental policies seeking to curb climate change by limiting greenhouse gas emissions has motivated a worldwide shift toward sustainability and massive integration of renewable resources into our energy supply infrastructure.

Second, there has been a growing trend toward decentralization of the supply infrastructure and empowerment of customers to make choices concerning choice of resources, economics, and reliability of their energy supply. This trend will manifest itself in several ways.

1) Massive growth in the participation of decentralized resources in the electricity infrastructure, blurring of the boundaries between suppliers and consumers with new emerging entities such as “prosumers” or “prostormers” (e.g., a consumer with solar panels and local storage).

	Goal	Main elements of the needed tools
Policy and infrastructure	To design the governmental, private, and financial sector infrastructure to accommodate the Future Grid and facilitate its underlying objectives.	The development of **practical business models** for renewable and distributed resources and for utilities as they transition to a more distributed future.
		Market mechanisms to allow **load flexibility, implicit energy storage** capabilities, and enhancement of efficiency at points of end use
		Development of **institutions and regulatory frameworks** that will accommodate needed utility industry changes driven by customer choice and public policy
		Part of the stated Grand Challenge is **addressing environmental impact, not only the reduction of CO_2.** The policy and infrastructure development, as well as the system theory evolution, should consider a goal of 80% CO_2 reduction by 2050.
		Unbundling and appropriate pricing of the components of electricity and its ancillary services (e.g., power, reactive power, regulation, frequency) to allow participation in the market by new technologies.
System theory	To use advanced system theory, mainly fashioned with cyber technologies, to extract the most from the present and future electrical grid and to develop and use appropriate short-term and long term planning tools. This includes: computation, optimization, and data analytics tools	**IT overlay** – to invent tools based on advanced mathematics and system theory, including cyber security, to effectuate direct digital control of the large scale power system. The development must include operability of the system.
		To maximize the value of **networking** at all levels (e.g., transmission and distribution levels and control and information levels) to maximize reliability and the value of investments in those networks (both existing and future). This effort includes a national flexible transmission overlay. The concept of autonomous self-healing shall be implemented at all levels.
		Match load to generation rather than vice versa - reserve requirements and the development and implementation of large scale energy storage. Dynamic co-optimization of resource deployment and reconfiguration of grid topology with explicit accounting for uncertainty.
		Joint planning of electricity, fuel, and transportation infrastructures incorporating an appropriate accounting of the benefits of the transmission grid and incorporating new levels of uncertainty.
Advanced components	To utilize advanced components and materials immediately as they become available to implement the Future Grid.	Implement **semiconductor devices** for power and energy control
		The use of **advanced materials** to implements power grid operability
		To **deploy sensors massively** including PMUs and next generation sensors. This includes extraction of models using PMU data and a leverage of investments for PMUs

Fig. 4 Tools to address the Grand Challenge

2) A paradigm shift from a system where generation capacity exclusively follows the load to a system where demand increasingly adapts to available supply.

3) System reliability shifting from being a treated exclusively as a public good to allow its treatment as a private good so that consumers make their own decisions regarding trade-off between service reliability and cost.

While the above changes are enabled by technological innovation in metering, control, information and computation technologies, they will also require a major overhaul in the way the grid is planned and paid for (using all the benefits to make investment decisions). Current recovery of grid costs through mostly volumetric charges by utilities will shift the burden of paying for the grid from those who can afford distributed generation to those who cannot. Changes in market design and incentive mechanisms are needed to send the correct price signals; for example, the kWh needs to be unbundled into its component parts, including frequency, regulation, and appropriate prices set for the capacity, energy and ancillary services used by the system. Diversification of the resource base and democratization and decentralization of the power system infrastructure adds diversity and redundancy. If properly handled, this can lead to improved reliability as in the case of the Internet. But a potential alternative result is gridlock and chaos: the challenge is to avoid the latter. A particular structure that has garnered attention is the microgrid. According to CIGRÉ [5],

> *Microgrids comprise low voltage distribution systems with distributed energy sources, storage devices, and controllable loads, operated connected to the main power network or islanded, in a controlled coordinated way.*

The developed tools will put the microgrid concept in its proper perspective in the mosaic of diverse electric energy infrastructures with their attendant multiobjectives from all societal sectors. The developed tools and algorithms should incorporate into the electric energy infrastructure eventualities, such as electrification of transportation, realization of microgrids, and widespread utilization of 'smart buildings'. The business models and regulatory frameworks needed should enable utilities to continue to provide service and to have appropriate levels of certainty in cost recovery. Relating to regulatory, investment and market tools, it is important to create a more certain investment climate, reconcile 'duty to serve' with new entrant 'cherry picking' and 'free ridership', with a focus on the long-term, commensurate with asset lead-times and life cycles.

Tool #2: The utilization of advanced system theory, including the modeling of uncertainty, tailored to opportunities created by radical changes in the nature of both grid hardware and grid cyber-technologies. The tools developed should extract the highest possible performance from the future electric power system while maintaining their robustness in the face of disturbances.

Applications of system analysis for control and optimization of grid operations have long been constrained by capabilities of three classes of hardware: (i) the equipment that directly exercises grid control (e.g., generators, transformers, switchgear, and capacitor banks); (ii) the sensors that measure the state of system; and (iii) the communication and computational hardware that intelligently coordinates other classes of equipment. All three of these classes are undergoing radical changes which, in turn, dictate a fundamental re-examination and expanded application of advanced control, estimation, and optimization algorithms to grid operations.

Among the hardware that directly exercises control, that in systems terminology are the bulk power grid's "actuators," traditional synchronous generators have long dominated as the most significant elements. However, this characteristic is changing as an indirect consequence of rapidly growing penetration of renewable energy sources. In particular, generation sources such as wind and photovoltaic arrays are typically non-synchronous, and they couple to the grid through power electronic interfaces that present very different electrical terminal characteristics to the grid, but that also offer much greater flexibility than a synchronous machine.

To date, effort in the research literature and in vendors' products have sought to use the flexibility of the power electronic coupling only to make the new, non-synchronous renewable sources behave as much like traditional synchronous generators as possible. While this approach allows the new sources to "fit" into existing grid control architectures, it is far from optimal. Among the challenges for the Future Grid is the utilization of optimal control design to realize the full actuation capability of power electronically coupled, renewable energy generation sources.

Accompanying the dramatic improvements in the hardware exercising control, and the vast deployment of sensors to measure grid response, is the commensurate expansion in computational power that can be embedded in distributed devices and assembled at central control facilities. While analogies between power networks and computer networks must be used with care, due to very different underlying physics, there are important lessons the Future Grid can learn from the evolution of computer network architectures. If the 80s and 90s were dominated by a trend toward decentralization and distribution of resources in computing (i.e., the personal computer revolution), the evolution of web and cloud computing service in the 21st century is demonstrating the power of a mixed architecture. In particular, there is strong evidence that the greatest performance lies not in purely centralized nor purely distributed architectures, but rather from structures that mix significant local capabilities at distributed elements with tremendous processing and data handling power at a number of centralized network locations. The Future Grid may benefit from a similar organizational structure in which distributed resources, such as distributed generation, responsive loads, and microgrids, play a significant role, but have their local capabilities dramatically enhanced by centralized grid services.

Contemporary system theory has made considerable progress in modeling and accounting for uncertainty in both feedback control design and optimization. Uncertainty in this context ranges from the relatively short term and low impact issues, such as uncertainty in wind generation and short term load forecast error, to the longer term and potentially impactful issues such as the price of fuels, the status of the American financial institutions, and the role of electric vehicles on system loads. Some elements of uncertainty should be treated as robust design procedures – for example, the design of power transmission and distribution systems to withstand natural disasters. Effective treatment of uncertainty in design and decision-making, and the management of uncertainty versus robustness, are among the challenges.

Tool #3: The development and use of advanced components and materials for power and energy control

Semiconductor devices have almost universally replaced vacuum and mercury valve technologies at the lower power levels in a wide range of engineering applications. The tremendous unfulfilled promise in use of these devices at bulk power levels has been apparent for more than twenty years, as evidenced by the long-standing interest (but very low adoption rates) associated with “Flexible AC Transmission Systems” (FACTS). The tools that are needed in this area should include the rapid utilization of advanced materials including insulators, optical devices, new magnetic materials, and structural materials. The stumbling blocks for wide-spread, cost effective implementation of semiconductors for high-level power and energy control have been focused on four stubborn problems:

1) The reduction and management of active power losses due to high currents passing through bulk semiconductor
2) The reduction and management of losses due to current passing across a semiconductor junction when there is a voltage difference across that junction
3) The exploitation of the high (electronic) speed capabilities of semiconductor switches.

The subject of advanced components should incorporate advanced materials and their incorporation into designs as rapidly as possible. Advanced components would hopefully include bulk storage (a particularly stubborn economic design problem) and their controls, conductor materials and designs, and the integration of innovative conduction processes such as high phase order transmission technologies.

3. Collaborative efforts

A particular challenge of the future grid is the human challenge: to design and integrate technical advancements in a strategy that is compatible with existing assets and needs, and professionally staff the future energy infrastructure. The optimal approach is to coordinate all sectors (industry, government, academics) to cooperate in solving the challenges. While there have been improvements in cooperative efforts in the last 40 years among these sectors, there is room for enhancement. The role of professional organizations should be strengthened. Academics need to advance technical skills through research yet retain a strong role in education and training. And all of these efforts must align with a goal of implementing the future grid in a way that does not impair contemporary industry and society.

It seems that the longest time constant in the dynamic energy future is the *human time constant*. The time horizon for updating and accommodating new developments and technologies in educational programs should be shortened. But this effort needs to be accomplished without sacrificing the mainstays of energy and power engineering. Examples of collaborative efforts among educational sectors and others include:

- Industry / university collaboratories
- Engineering research centers
- Governmental efforts to bring industry leaders together
- International programs to integrate the best technologies worldwide.

An example of a multi-university / industry collaborative effort appears in [6].

4. Conclusions

The important but differing social objectives for the future electric system, coupled with significant economic, technological, and public policy uncertainties, complicate decision-making about its design. Embracing diversity in design and technology choices could provide a risk-mitigating path for the electric system's evolution. The challenge is to fully take advantage of the convergence of energy, communications, sensing, and computing technologies to enable the electric system to be increasingly diverse in economical, reliable, affordable, and environmentally beneficial ways. Collaboration among the sectors that have a stake in the future grid is important for an expedient solution to the grand challenges in a way that is compatible with serving the energy needs of society without interruption.

General References

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[5] CIGRÉ, *Microgrids Evolution Roadmap*, Working Group C 6.22, Paris, 2010.

[6] Raja Ayyanar, "PSerc Academy," a presentation at the IEEE General Meeting, panel on "Educational Tools for the Workforce Development for the Future Grid to Enable Sustainable Energy Systems," PESGM2014-001975, National Harbor, MD, July 2014.

PSERC Future Grid Initiative References

With funding from the Department of Energy, PSERC initiated the Future Grid Initiative under the title "The Future Grid to Enable Sustainable Energy Systems." The objective was to conduct research on how to integrate higher penetrations of renewable generation and other future technologies into the grid while enhancing grid stability, reliability, and efficiency. Research was done in the following areas:

- Electric Energy Challenges of the Future
- Control and Protection Paradigms of the Future
- Renewable Energy Integration – Technological and Market Design Challenges
- Computational Challenges and Analysis Under Increasingly Dynamic and Uncertain Electric Power System Conditions
- Engineering Resilient Cyber-Physical Systems
- Workforce Development.

There were also white papers written in the following topic areas:

- The Information Hierarchy for the Future Grid
- Grid Enablers of Sustainable Energy Systems.

Documents, presentations and webinars related to the Initiative can be found on the PSERC website at http://pserc.wisc.edu/research/FutureGrid.aspx.

PSERC has also conducted executive forums and prepared white papers on critical grid investment issues. They can be found at http://www.pserc.wisc.edu/research/white_papers.aspx.