Control for Renewable Energy and Smart Grids

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Introduction

The use of renewable energy increased greatly just after the first big oil crisis in the late seventies. At that time, economic issues were the most important factors, hence interest in such processes decreased when oil prices fell. The current resurgence of interest in the use of renewable energy is driven by the need to reduce the high environmental impact of fossil-based energy systems. Harvesting energy on a large scale is undoubtedly one of the main challenges of our time. Future energy sustainability depends heavily on how the renewable energy problem is addressed in the next few decades.

Although in most power-generating systems, the main source of energy (the fuel) can be manipulated, this is not true for solar and wind energies. The main problems with these energy sources are cost and availability: wind and solar power are not always available where and when needed. Unlike conventional sources of electric power, these renewable sources are not "dispatchable"—the power output cannot be controlled. Daily and seasonal effects and limited predictability result in intermittent generation. Smart grids promise to facilitate the integration of renewable energy and will provide other benefits as well.

Industry must overcome a number of technical issues to deliver renewable energy in significant quantities. Control is one of the key enabling technologies for the deployment of renewable energy systems. Solar and wind power require effective use of advanced control techniques. In addition, smart grids cannot be achieved without extensive use of control technologies at all levels.

> Control is a key enabling technology for the deployment of renewable energy systems. Solar and wind power require advanced control techniques for high-performance and reliable operation.

This section of the report will concentrate on two forms of renewable energy—wind and solar—and on the role of smart grids in addressing the problems associated with the efficient and reliable delivery and use of electricity and with the integration of renewable sources. Solar and wind power plants exhibit changing dynamics, nonlinearities, and uncertainties—challenges that require advanced control strategies to solve effectively. The use of more efficient control strategies would not only increase the performance of these systems, but would increase the number of operational hours of solar and wind plants and thus reduce the cost per kilowatt-hour (KWh) produced.

Both wind and solar have tremendous potential for fulfilling the world's energy needs. In the case of wind, if conventional onshore wind turbines with 80-m towers were installed on 13% of the earth's surface, the estimated wind power that could be commercially viable is 72 terawatt (TW). That amounts to almost five times the global power consumption in all forms, which currently averages about 15 TW. With capacity that has tripled in the last five years, wind energy is the fastest growing energy source in the world. Using larger wind turbines to convert kinetic energy into electricity has significantly increased the average power output of a wind turbine unit; most major manufacturers have developed large turbines that produce 1.5 to 3.5 megawatts (MW) of electric power, even reaching 5 to 6 MW per turbine in some cases. At the end of 2009, with 159.2 gigawatt (GW) of wind-powered generators worldwide, primarily grouped together to create small wind farms, the global collective capacity was 340 terawatt-hour (TWh) of energy annually, or 2% of global electric energy consumption. Several countries have achieved relatively high levels of wind power penetration: about 19% in Denmark, 14% in Spain and Portugal, and 7% in Germany and Ireland. Government subsidies have been a key factor in increasing wind power generation. These subsidies, in turn, have often been justified by the renewable portfolio standards (RPSs) that several countries have adopted and that require increasing the production of energy from renewable sources. In particular, RPSs generally obligate utilities to produce a specified fraction of their electricity from renewable energy. The European Union has a regionwide RPS of 20% by 2020; the United States of 20% by 2030, with different targets and years depending on the state (for example, 15% by 2025 in Arizona and 20% by 2020 in Colorado).

Although wind energy is a clean and renewable source of electric power, many challenges must be addressed. Wind turbines are complex machines, with large flexible structures working under turbulent and unpredictable environmental conditions, and are connected to a constantly varying electrical grid with changing voltages, frequency, power flow, and the like. Wind turbines have to adapt to those variations, so their efficiency and reliability depend heavily on the control strategy applied. As wind energy penetration in the grid increases, additional challenges are being revealed: response to grid disturbances, active power control and frequency regulation, reactive power control and voltage regulation, restoration of grid services after power outages, and wind prediction, for example.

Another abundant, sustainable source of energy is the sun. One of the greatest scientific and technological opportunities we face is developing efficient ways to collect, convert, store, and utilize solar energy at an affordable cost. The solar power reaching the earth's surface is about 86,000 TW. Covering 0.22% of our planet with solar collectors with an efficiency of 8% would be enough to satisfy the current global power consumption. Estimates are that an energy project utilizing concentrating solar power (CSP) technology deployed over an area of approximately 160 x 160 km in the Southwest U.S. could produce enough power for the entire U.S. consumption.

Solar-sourced electricity can be generated either directly using photovoltaic (PV) cells or indirectly by collecting and concentrating the solar power to produce steam, which is then used to drive a turbine to provide the electric power (CSP). We focus on CSP in this section, as control has greater relevance to it.

Concentrating solar thermal systems use optical devices (usually mirrors) and sun-tracking systems to concentrate a large area of sunlight onto a smaller receiving area. The concentrated solar energy is then used as a heat source for a conventional power plant. A wide range of concentrating technologies exists, the main ones being parabolic troughs, solar dishes, linear Fresnel reflectors, and solar power towers. The primary purpose of concentrating solar energy is to produce high temperatures and therefore high thermodynamic efficiencies.

Parabolic trough systems are the most commonly used CSP technology. A parabolic trough consists of a linear parabolic mirror that reflects and concentrates the received solar energy onto a tube (receiver) positioned along the focal line. The heat transfer fluid is pumped through the receiver tube and picks up the heat transferred through the receiver tube walls. The parabolic mirror follows the sun by tracking along a single axis. Linear Fresnel reflectors use various thin mirror strips to concentrate sunlight onto tubes containing heat transfer fluid. Higher concentration can be obtained, and the mirrors are cheaper than parabolic mirrors, but a more complex tracking mechanism is needed.

The main control problems with solar plants are related to sun tracking and control of the thermal variables. Although control of the sun-tracking mechanisms is typically done in an open-loop mode, control of the thermal variables is mainly done in closed loop. Solar plants exhibit changing dynamics, nonlinearities, and uncertainties, characteristics that result in detuned performance with classical PID control. Advanced control strategies that can cope with these issues are needed for better performance and for decreasing the cost per kilowatt-hour generated.

The uncertainty and intermittency of wind and solar generation are major complications that must be addressed before the full potential of these renewables can be reached. The *smart grid*—an evolution of electricity networks toward greater reliance on communications, computation, and control—promises a solution. The term gained prominence through the U.S. Energy Independence and Security Act (EISA) of 2007, the European Technology Platform for the Electricity Networks of the Future, and similar initiatives across numerous other countries. The U.S. Department of Energy has provided a concise description of the smart grid [1]:

> The application of advanced digital technologies (i.e., microprocessor-based measurement and control, communications, computing, and information systems) are expected to greatly improve the reliability, security, interoperability, and efficiency of the electrical grid, while reducing environmental impacts and promoting economic growth. Achieving enhanced connectivity and interoperability will require innovation, ingenuity, and different applications, systems, and devices to operate seamlessly with one another, involving the combined use of open system architecture, as an integration platform, and commonly shared technical standards and protocols for communications and information systems. To realize Smart Grid capabilities, deployments must integrate a vast number of smart devices and systems.

The EU's SmartGrids technology platform summarizes the benefits of smart grids as follows. They:

- Better facilitate the connection and operation of generators of all sizes and technologies;
- Allow consumers to play a part in optimizing the operation of the system;
- Provide consumers with greater information and options for choice of supply;
- Significantly reduce the environmental impact of the whole electricity supply system;
- Maintain or even improve the existing high levels of system reliability, quality and security of supply;
- Maintain and improve the existing services efficiently;
- Foster market integration.

The broad spectrum of entities and stakeholders covered by the smart grid is evident from the conceptual model of Fig. 1. The smart grid further broadens the already highly distributed nature of power systems by extending control to the consumer level. The smart grid can be conceptualized as an extensive cyber-physical system that supports and significantly enhances controllability and responsiveness of highly distributed resources and assets within electric power systems.

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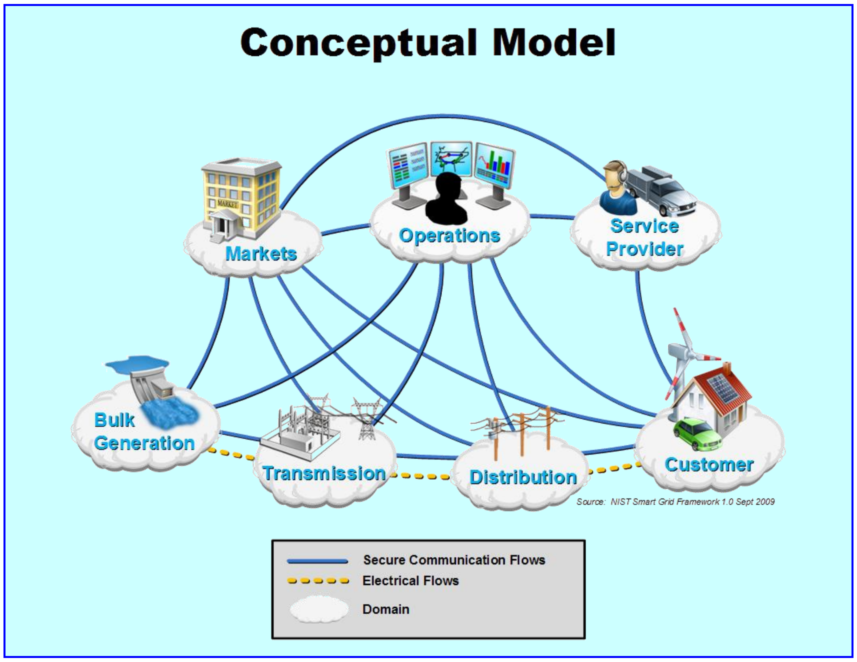

Source: NIST Smart Grid Framework 1.0, Sept. 2009

Figure 1. Depiction of the NIST smart grid conceptual model [2].

The term *smart grid* implies that the existing grid is dumb, which is far from true. The current grid structure reflects carefully considered trade-offs between cost and reliability. The responsiveness achievable through smart grid concepts will, however, play a vital role in achieving large-scale integration of new forms of generation and demand. Renewable generation will make an increasingly important contribution to electric energy production into the future. Integration of these highly variable, widely distributed resources will call for new approaches to power system operation and control. Likewise, new types of loads, such as plug-in electric vehicles and their associated vehicle-to-grid potential, will offer challenges and opportunities. Establishing a cyberinfrastructure that provides ubiquitous sensing and actuation capabilities will be vital to achieving the responsiveness needed for future grid operations. Sensing and actuation will be pointless, though, without appropriate controls.

Successful Applications of Control

Wind Energy

Charles F. Brush is widely credited with designing and erecting the world's first automatically operating wind turbine for electricity generation. The turbine, which was installed in Cleveland, Ohio, in 1887, operated for 20 years with a peak power production of 12 kW (Fig. 2). An automatic control system ensured that the turbine achieved effective action at 6.6 rpm (330 rpm at the dynamo) and that the dc voltage was kept between 70 and 90 volts. Another remarkable project in early wind energy research was the 1.25-MW wind turbine developed by Palmer Putnam [3] in the U.S. The giant wind turbine, which was 53 m (175 feet) in diameter, was installed in Vermont, Pennsylvania, around 1940 and featured two blades with a hydraulic pitch control system.

Modern wind-driven electricity generators began appearing during the late 1970s. At that time, the average power output of a wind turbine unit was about 50 kW with a blade length of 8 m. Since then,

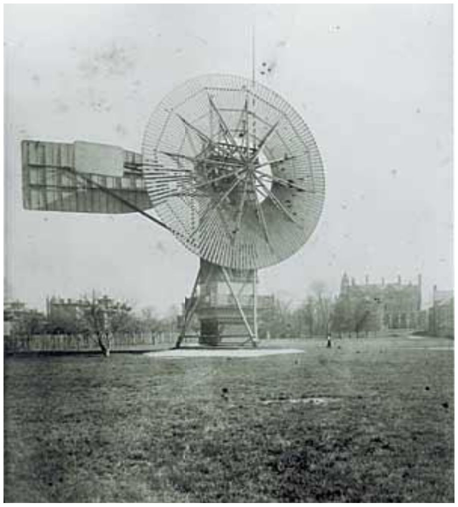

Figure 2. Charles F. Brush's wind turbine (1887, Cleveland, Ohio), the world's first *automatically operating* wind turbine for electricity generation.

the size of the machines has increased dramatically. Nowadays, the typical values for power output of the modern turbines deployed around the world are about 1.5 to 3.5 MW with blade lengths of more than 40 m for onshore and 60 m for offshore applications. Simultaneously, the cost per kilowatt has decreased significantly, and the efficiency, reliability, and availability of the machines have definitely improved.

New multidisciplinary computer design tools [4],[5], able to simulate, analyze, and redesign in a concurrent engineering way the aerodynamics, mechanics, and electrical and control systems under several conditions and external scenarios [6],[7],[8], have extended the capability to develop more complex and efficient wind turbines. In this new approach (Fig. 3), the control system designs, and the designers' understanding of the system's dynamics from the control standpoint, are playing a central role in new engineering achievements.

Far better than in the old days, when the design of any machine was carried out under a rigid and sequential strategy, starting from the pure aerodynamics and following with the mechanical, the electrical, and finally the control system design, the new tools have opened the door to a more central role for control engineers. The new philosophy brings a concurrent engineering approach, where all the engineering teams work simultaneously to achieve the optimum wind turbine design. This strategy allows the control engineers to interact with designers from the other fields from the very beginning, discussing and changing the aerodynamics, mechanics, and electrical systems to improve the dynamic behavior, efficiency, reliability, availability, and cost, and finally to design the most appropriate controllers for the machine.

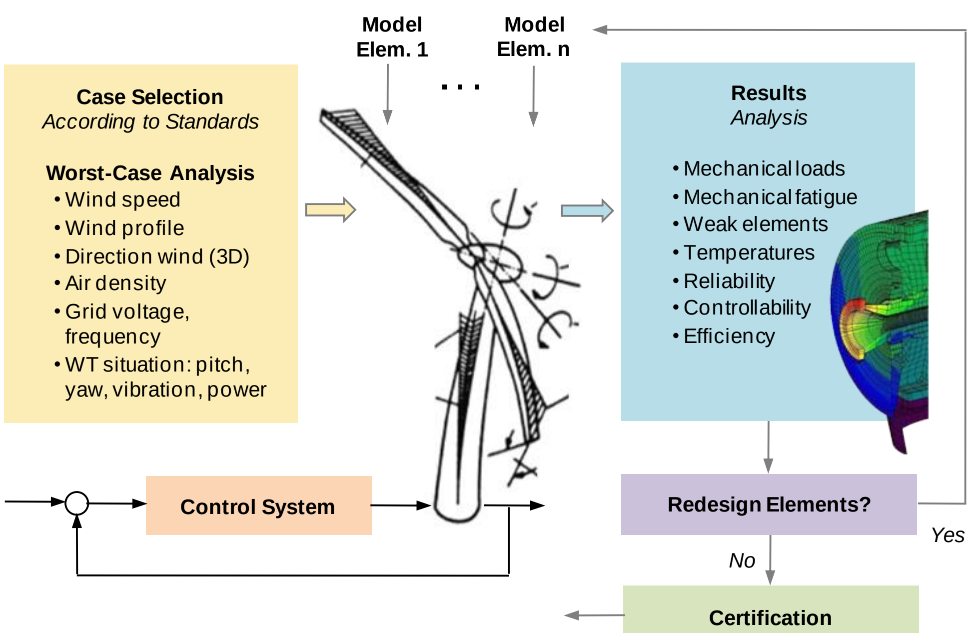

Figure 3. Multidisciplinary computer design tools for wind turbine design.

Nowadays, there are essentially two types of wind turbines: constant-speed and variable-speed machines. Until the late nineties, the constant-speed concept dominated the market. Today, it still represents a significant share of the operating wind turbines, but newer requirements have led to the emergence of variable-speed designs [5],[9],[10],[11].

Three main alternative strategies are used for regulating the amount of power captured by the rotor: passive stall control or fixed pitch, variable pitch control, and active stall control. So far, over the entire range of wind turbine sizes, no one of these strategies has taken the lead over the others. However, as machines get larger and power production increases, the trend is toward pitch control and active stall control [5],[9],[10],[11].

The configuration of a fixed-speed wind turbine is based on a gearbox and an asynchronous generator, which is usually a squirrel-cage induction generator to reduce costs. The gearbox links the wind turbine shaft with the rotor of a fixed-speed generator, providing the high rotational speed required by the generator. The generator produces electricity through a direct grid connection, and a set of capacitors is used to compensate reactive power. Due to lack of a frequency converter, the generator speed is dictated by the grid frequency. One disadvantage of fixed-speed operation is poor aerodynamic efficiency, particularly at partial-load operation. From the electrical system's standpoint, another disadvantage is that this type of operation has a detrimental effect on voltage because asynchronous generators demand reactive power from the grid.

Another alternative to the popular squirrel-cage asynchronous generator is the so-called slip control method, which adjusts the slip continuously. In this case, a wound rotor is connected to some variable resistors through slip rings. By changing the electrical resistance of the rotor, small changes in the rotational speed variation of about 10% above the synchronous speed can be compensated for without varying the generator output frequency.

Many options have been developed to achieve some degree of speed variation: (1) dual-speed generators with pole switching (the use of a lower speed in low wind conditions improves performance and reduces noise emissions); (2) variable-resistance asynchronous generators for a low range of variable speed; (3) doubly fed induction generators (DFIGs) for a moderate range of variable speed; and finally, (4) direct-drive multipole synchronous generator systems and (5) hybrid systems (combination of multipole generators with small gearboxes), both for a wide range of variable speed.

Especially dominant in new markets is the DFIG, also called the wound rotor induction generator. In this machine, the stator windings are directly connected to the grid, while a frequency converter interfaces between the standard wound rotor and the grid. The stator winding connection carries most of the power production, although the frequency converter may carry up to a third of the total power, depending on the operating mode. This configuration allows the machine to control the slip in the generator, and thus the rotor speed can vary moderately, achieving better aerodynamic efficiency. Furthermore, as the converter controls the rotor voltage magnitude and phase angle, partial control of active and reactive power is also possible.

Finally, another approach, which will probably dominate in offshore applications, is the multipole synchronous generator connected to the grid through a power electronic converter that handles the full power production. This concept, also called the direct-drive machine, takes advantage of the wide speed range allowed by the full-scale frequency converter. The generator can operate at any rotational speed, allowing operation to track the optimal speed for each wind condition. Among the main advantages of this approach are low maintenance costs and high reliability due to omission of the gearbox, improved aerodynamic efficiency, and the ability to assist grid voltage control.

A generic qualitative power curve for a variable-speed pitch-controlled wind turbine is shown in Fig. 4. Four zones and two areas are indicated in the figure [12]. The rated power P_r of the wind turbine (that is, the actual power supplied to the grid at wind speed greater than V_r) separates the graph into two main areas. Below rated power, the wind turbine produces only a fraction of its total design power, and therefore an optimization control strategy needs to be performed. Conversely, above rated power, a limitation control strategy is required.

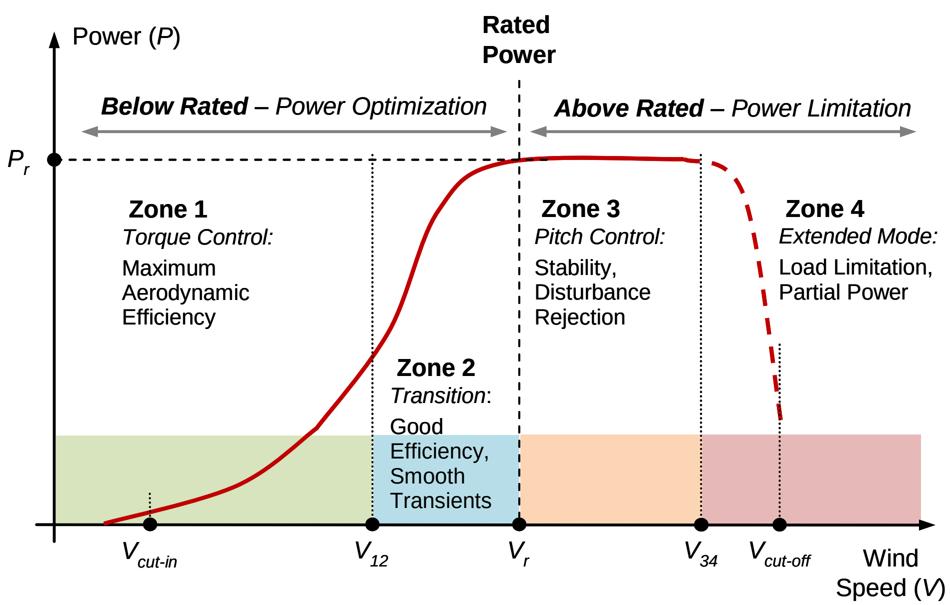

Figure 4. Power curve of a wind turbine and control zones.

For passive-stall-controlled wind turbines, in which the rotor blades are fixed to the hub at a specific angle, the generator reaction torque regulates rotor speed below rated operation to maximize energy capture. Above a specific wind speed, the geometry of the rotor induces stall. In this manner, the power delivered by the rotor is limited in high wind conditions thanks to a particular design of the blades that provokes loss of efficiency.

In pitch control, the power delivered by the rotor is regulated either by pitching the blades toward the wind to maximize energy capture or by pitching to feather to discard the excess power and ensure that the mechanical limitations are not exceeded. At rated operation, the aim is to maintain power and rotor speed at their rated value. To achieve this, the torque is held constant and the pitch is continually changed following the demands of a closed-loop rotor speed controller that optimizes energy capture and follows wind speed variations. In contrast, below rated operation there is no pitch control; the blade is set to a fine pitch position to yield higher power capture values while the generator torque itself regulates the rotor speed.

Active stall control is a combination of stall and pitch control. It offers the same regulation possibilities as the pitch-regulated turbine but uses the stall properties of the blades. Above rated operation, the control system pitches the blades to induce stall instead of feathering. In this technique, the blades are rotated only by small amounts and less frequently than for pitch control.

Solar Energy

A handful of thermal solar energy plants, most of them experimental, have been developed over the last two decades. The Solar One power tower [13], developed in Southern California in 1981, was in operation from 1982 to 1986. It used 1,818 mirrors, each 40 m^2, for a total area of 72,650 m^2. The plant was transformed into Solar Two by adding a second ring of larger (95 m^2) heliostats and molten salts as a storage medium. This gave Solar Two the ability to produce 10 MW and helped with energy storage, not only during brief interruptions in sunlight due to clouds, but also to store sufficient energy for use at night. Solar Two was decommissioned in 1999 but proved it could produce power continuously around the clock.

The Solar Tower Power Plant SSPS was developed in 1980 in the Plataforma Solar de Almeria (PSA) on the edge of the Tabernas Desert in Spain (Fig. 5). The plant had 92 heliostats (40 m^2) producing 2.7 MWth at the focal point of the 43-m-high tower where the heat was collected by liquid sodium. The PSA has a number of experimental plants such as the CESA-1 7-MWth central receiver system and the SSPS-OCS 1.2-MWth parabolic-trough collector system with associated thermal storage.

Figure 5. Plataforma Solar de Almeria (PSA).

The Solar Energy Generating Systems (SEGS) [14] begun in 1984 in the Mojave Desert in California uses parabolic-trough technology (Fig. 6). SEGS is composed of nine solar plants and is still the largest solar-energy-generating facility in the world with a 354-MW installed capacity. The plants have a total of 936,384 mirrors and cover more than 6.5 km^2. Lined up, the parabolic mirrors would extend more than 370 km.

Photo credit: Alan Radecki

Figure 6. SEGS plants III-VII in California, U.S.A.

The number of commercial solar power plants has been increasing in the last few years. New installations include the 10-MW (PS10) and the 20-MW (PS20) power tower (Fig. 7) plants; the 50-MW Solnova 1 and Solnova 3 trough plants designed, built, and operated by Abengoa Solar near Seville in Southern Spain; and the 50 MW Andasol 1 and Andasol 2 plants owned by ACS Group.

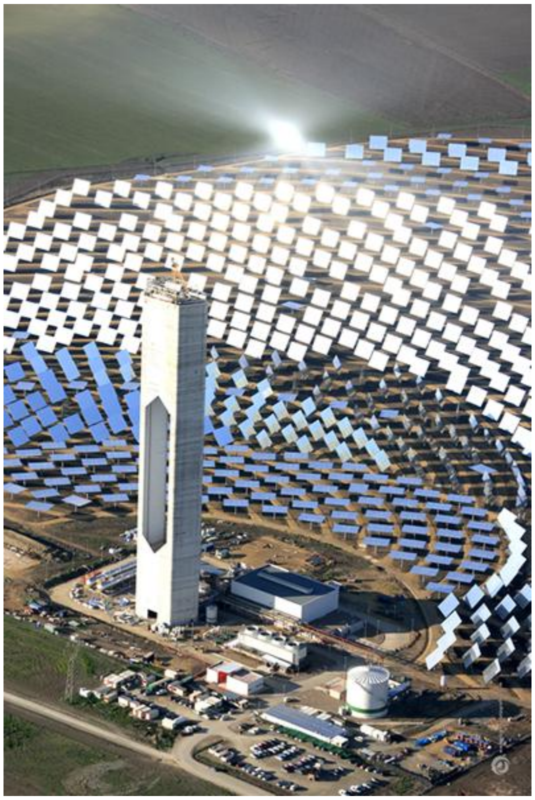

Figure 7. Abengoa Solar PS 20 power tower (Sevilla, Spain).

Solar power plant systems cannot be controlled with simple control strategies; they require advanced algorithms to compute the solar reflector positions as well as for self-calibration and prediction of the reflectors [15]. The sun vector needs to be computed, and for each heliostat, the normal vector is computed such that it divides the angle formed by the sun vector and the vector joining the center of the heliostat with the receiver. The current trend in solar concentrator tracking systems is to use open-loop controllers that compute the direction of the solar vector based on location and time. Nevertheless, error sources such as time of day, sun model, latitude and longitude of the site, heliostat position in the field, and control interval increase the complexity of the control system. Structural and mechanical sources of error, mainly due to tolerances (joints, encoder) and incorrect mirror facet alignment (optical errors), further add to the approximations in calculating solar position and other variables.

Heuristic control algorithms and CCD cameras have been used [16] to cope with some of these errors. The sunbeam centroid position errors are used to calibrate heliostat tracking parameters. The system can also be used during operation, as an individual heliostat can be deviated from its spot to correct its offset in real time.

To avoid deterioration due to excessive thermal gradients in central volumetric receivers, multi-aiming strategies are used [17] to obtain an appropriate flux distribution. Individual heliostats are deliberately aimed at different aiming points in such a way that more uniform irradiance is obtained in the central receiver.

Parabolic trough systems concentrate sunlight onto a receiver pipe located along the focal line of a trough collector. A heat transfer fluid, typically synthetic oil, is heated as it flows along the receiver pipe. For maximum efficiency, a constant supply of hot oil is required at some prespecified temperature, despite variations in the ambient temperature, inlet temperature, and direct solar radiation. Over the last 25 years, considerable research has been devoted to improving the efficiency of solar thermal power plants with distributed collectors in terms of control and optimization. Activities performed by control groups related to this field cover modeling, identification and simulation, classical proportional-integral-derivative control (PID), feedforward control (FF), model-based predictive control (MPC), adaptive control (AC), gain-scheduled control (GS), cascade control (CC), internal model control (IMC), time delay compensation (TDC), optimal control (LQG), nonlinear control (NC), robust control (RC), fuzzy logic control (FLC), and neural network control (NNC) . Most of this work is summarized in [12]. The control of steam-generating parabolic trough systems is a more challenging problem [18].

Smart Grids

Power systems are fundamentally reliant on control, communications, and computation for ensuring stable, reliable, efficient operations. Generators rely on governors and automatic voltage regulators (AVRs) to counter the effects of disturbances that continually buffet power systems, and many would quickly lose synchronism without the damping provided by power system stabilizers (PSSs). Flexible AC transmission system (FACTS) devices, such as static var compensators (SVCs) and high-voltage DC (HVDC) schemes, rely on feedback control to enhance system stability. At a higher level, energy management systems (EMSs) use supervisory control and data acquisition (SCADA) to collect data from expansive power systems and sophisticated analysis tools to establish secure, economic operating conditions. Automatic generation control (AGC) is a distributed closed-loop control scheme of continental proportions that optimally reschedules generator power setpoints to maintain frequency and tie-line flows at their specified values.

Historically, distribution systems have had a minimal role in power system operation and control. Many distribution utilities have employed demand management schemes that switch loads such as water heaters and air conditioner to reduce load during peak conditions or emergency situations. The controllability offered by such schemes has been rather limited, however. This lack of involvement of distribution is largely a consequence of the technical difficulties involved in communicating (with sufficient bandwidth) with consumers. Smart grids promise cost-effective technology that overcomes these limitations, allowing consumers to respond to power system conditions and hence actively participate in system operations.

Smart grid concepts encompass a wide range of technologies and applications. We describe a few below that are currently in practice with the caveat that, at this early stage in the development of smart grids, the role of control, especially advanced control, is limited:

- Advanced metering infrastructure (AMI) is a vision for two-way meter/utility communication. Two fundamental elements of AMI have been implemented. First, automatic meter reading (AMR) systems provide an initial step toward lowering the costs of data gathering through use of real-time metering information. They also facilitate remote disconnection/reconnection of consumers, load control, detection of and response to outages, energy theft responsiveness, and monitoring of power quality and consumption. Second, meter data management (MDM) provides a single point of integration for the full range of meter data. It enables leveraging of that data to automate business processes in real time and sharing of the data with key business and operational applications to improve efficiency and support decision making across the enterprise.

- Distribution management system (DMS) software mathematically models the electric distribution network and predicts the impact of outages, transmission, generation, voltage/frequency variation, and more. It helps reduce capital investment by showing how to better utilize existing assets, by enabling peak shaving via demand response (DR), and by improving network reliability. It also facilitates consumer choice by helping identify rate options best suited to each consumer and supports the business case for renewable generation solutions (distributed generation) and for electric vehicles and charging station management.

- Geographic information system (GIS) technology is specifically designed for the utility industry to model, design, and manage their critical infrastructure. By integrating utility data and geographical maps, GIS provides a graphical view of the infrastructure that supports cost reduction through simplified planning and analysis and reduced operational response times.

- Outage management systems (OMSs) speed outage resolution so power is restored more rapidly and outage costs are contained. They eliminate the cost of manual reporting, analyze historical outage data to identify improvements and avoid future outages, and address regulatory and consumer demand for better responsiveness.

- Intelligent electronics devices (IEDs) are advanced, application-enabled devices installed in the field that process, compute, and transmit pertinent information to a higher level. IEDs can collect data from both the network and consumers' facilities (behind the meter) and allow network reconfiguration either locally or on command from the control center.

- Wide-area measurement systems (WAMS) provide accurate, synchronized measurements from across large-scale power grids. They have been implemented in numerous power systems around the world, following initial developments within the Western Electricity Coordinating Council (WECC) through the early 1990s [19]. WAMS consist of phasor measurement units (PMUs) that provide precise, time-stamped data, together with phasor data concentrators that aggregate the data and perform event recording. WAMS data plays a vital role in post-disturbance analysis, validation of system dynamic models, FACTS control verification, and wide-area protection schemes. Future implementation of wide-area control schemes are expected to build on WAMS.

- Energy management systems (EMSs) at customer premises can control consumption, onsite generation and storage, and potentially electric vehicle charging. EMSs are in use today in large industrial and commercial facilities and will likely be broadly adopted with the rollout of smart grids. Facility energy management can be seen as a large-scale optimization problem: Given current and (possibly uncertain) future information on pricing, consumption preferences, distributed generation prospects, and other factors, how should devices and systems be used optimally?

Smart grid implementations are occurring rapidly, with numerous projects under way around the world. Fortum's "intelligent management system of electric consumption" uses advanced metering devices to gather customer's consumption data and metering management systems to store and analyze this information. Vattenfall's "automatic household electricity consumption metering system" is another example of a European project that is focused on remote measurement of consumers. Also, projects such as Elektra's "distribution management system" improve quality of service by implementing next-generation devices to manage and control information (SCADA), DMS to plan and optimize distribution system operations, and ArcFM/Responder to improve outage response times.

Market Sizes and Investment [15], [20], [21]

Wind Energy

With many thousands of wind turbines in operation, the total worldwide installed capacity is currently about 160 GW. According to the World Wind Energy Association, the net growth rate is expected to be more than 21% per year. The top five countries, the United States, Germany, Spain, China, and India, currently share about 73% of the world capacity.

The cost of electricity from utility-scale wind farms has dropped by more than 80% over the last 20 years, reaching values of about $2.2 and $4.6 million per megawatt for onshore and offshore applications, respectively, in 2010. According to the U.S. Department of Energy, the capital cost of onshore applications can be further reduced to about 10% of current cost over the next two decades. In addition, several countries have adopted special programs to subsidize and promote wind energy. Among the most successful ones are the feed-in-tariff (FiT) programs and the production tax credit (PTC) programs.

The FiT programs have been adopted by more than 60 countries and states all over the world, including some of the top-producing countries: Germany, Spain, Canada, and Denmark. They typically include: (1) guaranteed grid access for the wind farm, (2) long-term contracts to sell the electricity produced by the wind turbines, and (3) purchase prices for distributed renewable generation that are substantially higher than the retail price of electricity (and will gradually be reduced toward grid parity).

A production tax credit program has been adopted in the United States. This federal incentive provides a credit of a varying number of cents per kilowatt-hour (currently 2.1 cents). Since its establishment in 1992, the PTC has had an "on-again/off-again" status, which has contributed to boom-bust cycles of the wind energy industry in the U.S.

More wind power was installed in the EU in 2008 than any other electricity-generating technology [22]. In leading the EU power sector for the first time, wind accounted for 36%, or 8,484 MW, of new capacity based on investments of €11 billion in the EU alone. By comparison, the gas sector created 6,932 MW (29%) of new capacity, new solar photovoltaic installation capacity was 4,200 MW (18%), new capacity from oil was 2,495 MW (10%), from coal, 762 MW (3%), and from hydro, 473 MW (2%). The 65 GW of EU wind energy capacity installed by the end of 2008 will avoid the emission of 108 million tons (Mt) of CO_2 annually—equivalent to taking 55 million cars off the road and equaling 24% of the EU-27's Kyoto obligation.

The EU wind energy sector directly employed approximately 108,600 people in 2007 [23]. Including indirect employment, the wind energy sector employs 154,000 in the EU. On average, 12,047 new direct wind energy jobs have been created per year in the five-year period 2002-2007.

Solar Energy

Solar photovoltaic generation installed capacity has grown about 40% since 2002. Thermal power plants are growing rapidly, with more than 2 GW under construction and some 14 GW announced through 2014. Spain is the epicenter of solar thermal power development with 22 projects under development for 1,081 MW capacity [24]. In the United States, 5,600 MW of solar thermal power projects have been announced. Currently (as of July, 2010), 679 MW of CSP capacity are installed worldwide. The U.S. is the market leader in terms of installed capacity with 63% market share, followed by Spain with 32%. These two markets will continue to be crucial for the development of the industry into the next decade, with Spain accounting for the largest share of projects under construction with almost 89%. Solar generation is taking off in emerging regions as well; both China and India have announced plans for large-scale solar plants.

On July 3, 2010, U.S. President Obama announced that "the Department of Energy is awarding nearly $2 billion in conditional commitments to two solar companies. The first is Abengoa Solar, a company that has agreed to build one of the largest solar plants in the world right here in the United States. Once completed, this plant will be the first large-scale solar plant in the U.S and it will generate enough clean, renewable energy to power 70,000 homes. The second company is Abound Solar Manufacturing, which will manufacture advanced solar panels at two new plants. When fully operational, these plants will produce millions of state-of-the-art solar panels each year" [25]. The Solar Energy Technologies Program (SETP, or Solar Program) launched by the U.S. Department of Energy works to develop cost-competitive solar energy systems for America. More than $170 million is spent each year in research and development (R&D) on both photovoltaics and concentrating solar power. The greatest R&D challenges are reducing costs, improving system performance, and finding new ways to generate and store energy captured from the sun [26].

In terms of the technology employed, the market is dominated by parabolic trough technology, which accounts for 88% of operating plants and 97.5% of projects under construction.

The China Renewable Energy Scale-up Programme (CRESP) recently released a report on solar power generation economic incentive policies. The report suggested measures such as taxation and financial preference, discounted loans, and direct financial subsides and included information on preferential price policies and management, increasing technical research and development investment, strengthening R&D capacity, establishing technical standards, management regulations, and an authentication system. The Chinese National Development and Reform Commission’s 11th 5-year plan (2006-2010) includes 200 MW of commercial CSP plants [24]. China is currently the market leader in the PV manufacturing industry. A licensing agreement to build at least 2 GW of solar thermal power plants in China over the next 10 years was recently announced [6]. The deal represents the country’s first major move into concentrating solar thermal power. The Chinese government also recently announced aggressive plans to increase the country’s renewable power generation capacity to 15% by 2020 [27].

India's “New Solar Mission” [28] is the most ambitious solar energy development plan in the world. Its goal is for the country to be generating 20 GW of energy from sunlight by 2022. Going by International Energy Agency forecasts, this will make India the producer of almost three-quarters of the world's total solar energy output. The “New Solar Mission” has set forward a three-stage approach to hitting the 2022 target. The first stage will comprise 1,100 MW of grid-connected power and up to 200 MW of nongrid capacity by 2013.

Smart Grid

The smart grid’s technology market is expected to see 20% annual growth, going from $70 billion in 2009 to about $171 billion by 2014, according to market reports by Specialist in Business Information (SBI). In 2010 alone, the U.S. and China will spend more than $7 billion on smart grid technology and implementation, according to the research and consulting firm Zpryme. Due to these and many other initiatives, the smart grid communication market is expected to have opportunities of $16 to $20 billion per year, and transmission and distribution infrastructures will see investment of $41 billion through 2015.

The European Electricity Grid Initiative (EEGI) is one of many European projects focused on smart grid research and implementation. One of the EEGI’s main goals is to achieve the 20-20-20 climate package challenge: a 20% cut in emissions of greenhouse gases by 2020 (compared with 1990 levels), a 20% increase in renewable energy use by 2020, and a 20% cut in energy consumption by 2020. The total budget for this program is estimated at €2 billion ($2.54 billion). U.S. initiatives include the “Grid 2030 Vision,” which consists of achieving three major elements: a national electricity backbone, regional interconnections, and local distribution. To achieve this vision, the U.S. government plans on investing more than $38 billion to create the first “smart grid with continental dimensions.”

Application Challenges/Opportunities for Research [5], [20], [29]

Wind Energy

The enormous and unique worldwide possibilities for large-scale wind energy development over the next few decades depend greatly on how critical technology challenges are addressed. New ideas and control engineering solutions are needed to open virgin global markets. Among others, we emphasize the seven technology challenges (TCs) listed in Table 1.

Table 1. Wind Energy Challenges

TC.1	Cost reduction for a zero-incentive situation
TC.2	Efficiency maximization
TC.3	Mechanical load attenuation
TC.4	Large-scale grid integration and penetration
TC.5	Extreme weather conditions
TC.6	Offshore wind turbines
TC.7	Airborne wind energy systems

- **TC.1.** Although the cost of utility-scale wind farms has dropped by more than 80% over the last 20 years, most wind energy systems, including all offshore applications, still need significant government support to be feasible. However, that subsidy cannot be sustained long term at large scale. Thus, the long-term economic sustainability of wind energy imperatively requires improving the wind energy business model so that costs are similar to conventional power generation. This important objective will be achieved by (1) the development of new control systems, materials, blades, electromechanics, and power systems for the wind turbine, and (2) automatic low-cost blade and tower manufacturing systems for mass production.

- **TC.2.** Efficiency maximization implies generating more energy over the low-to-medium operating wind spectrum. Research opportunities for efficiency maximization include: (1) smart blades with advanced airfoils, new sensors and actuators, and specific control systems; (2) new rotor configurations; (3) variable-diameter rotors, which could significantly increase the efficiency of the turbine by presenting a large area to capture more energy in low winds and a reduced area to protect the system in high winds; and (4) turbines with taller towers to capture more energy in regions with high wind shear. In all cases, advanced control strategies to damp out tower motion by using blade pitch and generator torque control are critical.

- **TC.3.** Large multi-megawatt machines need very large rotor diameters. To allow the rotor to grow larger and capture more energy, new active and independent pitch control and torque control systems must be developed to reduce towertop motion, power fluctuations, asymmetric rotor loads, mechanical fatigue, and individual blade loads, achieving higher reliability and lower maintenance [5],[29],[30]. These developments will also help improve gearbox reliability.

- **TC.4.** In a large-scale wind energy scenario, the wind farms will have to support the grid by providing (1) fault ride-through capability; (2) voltage regulation and reactive power control; (3) primary frequency control; (4) oscillation damping; (5) low harmonics content; and by (6) avoiding power flickers and (7) carrying a share of power control capability for the grid. There is no generally accepted "maximum" level of wind penetration. The limit for a particular grid will depend on existing generating plants, wind turbine technology, wind turbine control systems, grid demand management, pricing mechanisms, grid capacity and topology, storage type and availability, and wind resource reliability and diversity [31]-[33].

- **TC.5.** Extreme cold and humid weather conditions can stop the wind turbines from working during winter months due to ice formation on the blades in quantities that would degrade the turbine performance and cause blade imbalance. By integrating ice protection systems in the blades and managing them with an appropriate control system, the wind turbines will produce a greater amount of power during winter, opening new markets at northern latitudes and many offshore locations such as the freshwater Great Lakes in the U.S. and Canada.

- **TC.6.** Offshore wind power is a promising technology with enormous energy potential. With fewer logistic constraints than onshore applications, over the next few years offshore turbines will reach a typical size of 5 to 8 MW and a rotor diameter of more than 150 m, adopting tip speeds slightly higher than those of onshore turbines. The offshore foundation system depends on the water depth. Most of the projects installed so far have been in water less than 22 m deep, with a demonstration project in Scotland at a depth of 45 m. Shallow-water technology currently uses monopiles for about 20-m depths. Very deep water applications, with floating foundations, still need reliable solutions, including advanced control systems to deal with wind, ocean waves, tides, ice formation, and water currents simultaneously. In addition, research opportunities for offshore applications include: (1) new ideas to reduce the cost from the current 20 cents/kWh to 7-9 cents/kWh by 2030, according to U.S. Department of Energy goals; (2) remote, intelligent turbine condition monitoring and self-diagnostic systems; (3) dedicated deployment vessels; (4) analytical models to characterize wind, ocean currents, tides, ice, and ocean waves; (5) high reliability; (6) predictive maintenance techniques; and (7) grid technologies for electricity transmission back to shore.

- **TC.7.** An airborne wind energy system is a wind turbine that is supported in the air without a tower. Two technologies have been proposed: ground generator systems and aloft generator systems. In both cases, the wind turbines have the advantages of an almost constant and high wind speed and a low-cost structure without the expense of tower construction. Advanced multivariable robust control strategies for attitude and position control of the flying structure and reliable control algorithms to govern the system under bad weather conditions, such as lightning or thunderstorms, are critical. No commercial airborne wind turbines are in regular operation yet.

Solar Energy

One of the 21st Century's Grand Challenges for Engineering identified by the U.S. National Academy of Engineering is to make solar energy economical: “Overcoming the barriers to widespread solar power generation will require engineering innovations in several arenas—for capturing the sun’s energy, converting it to useful forms and storing it for use when the sun itself is obscured” [34].

Solar energy can be made more economical by reducing investment and operating costs and by increasing solar plant performance. The solar field represents the largest share of the cost of any CSP plant. Depending on the technology, this cost could vary from about 43% for tower and Fresnel technology to almost 60% for parabolic trough and dish Stirling CSP plants. The most significant cost reductions are likely to come from innovations in solar field design, which could bring down the levelized cost of energy (LCOE) by 15% to 28%, depending on the technology.

Advanced control can help reduce operating costs and increase solar plant performance. The main control challenges are:

- Optimal robust control techniques able to maintain the operating temperature as close to optimum as possible despite disturbances such as changes in solar irradiance level (caused by clouds), mirror reflectivity, and other operating conditions.
- Optimal and hybrid control algorithms that determine optimal operating points and modes and take into account the production commitments, expected solar radiation, state of energy storage, and electricity tariffs.
- Modes and methods for forecasting solar radiation using heterogeneous information (cameras, satellites, weather forecasts).
- Algorithms to estimate main process variables and parameters from heterogeneous and distributed measurements (oil temperature and solar radiation at different parts of the field, mirror reflectivity, thermal losses).
- Automatic mirror cleaning devices. The main factor degrading the optical performance of concentrating mirrors is accumulation of dirt on the mirror surface. Cleaning mirrors represents a considerable expense in manpower and water, usually a scarce resource where solar plants are located. Automatic devices need to be developed that minimize the use of water and degradation of the reflective surface.
- Heliostat self-calibration mechanisms. Heliostats need to be retuned periodically because of errors in the sun model, latitude and longitude of the site, heliostat position in the field, mechanical errors, optical errors, and the like. Heliostat recalibration may represent an important cost in manpower and time when done manually. Methods are needed for fast, automatic, online recalibration of heliostats.
- Fault detection and isolation in solar power plants. Algorithms are needed to detect and isolate faults and malfunctions in power plants, such as detection of hot spots, receivers with broken glass covers or vacuum losses, and heliostat faults.

Smart Grids

A significant challenge associated with smart grids is the integration of renewable generation. Traditionally, power systems have addressed the uncertainty of load demand by controlling supply. With renewable energy sources, however, uncertainty and intermittency on the supply side must also be managed. Demand response and load control—direct and indirect mechanisms to adjust consumption—are required. Direct load control—load adjustments made directly by the utility—must be nondisruptive in the sense that consumers are unaware of the control actions. Indirect demand response, such as providing price signals or other incentives for consumers to modify their loads, is already being practiced in commercial and industrial facilities, and some pilot projects are under way for homes as well. Modeling, optimization, and control issues are crucial. For example, instability may result in both the market side and the grid side if real-time pricing is implemented without adequate understanding of control principles. With slower time scales for price adjustment (a more likely scenario), instability will not be a primary concern, but the cost of suboptimal performance may be considerable. For example, slow price adjustment limits the ability for demand to track variations in renewable generation output, increasing the reliance on storage and nonrenewable sources for power balance.

Also on the consumer side, the integration of storage, distributed generation, and plug-in (possibly hybrid) electric vehicles all present both opportunities and challenges. Any local storage or generation can, at least in principle, help with managing varying grid supply. But each component has characteristics that must be considered and incorporated in the control scheme. Plug-in vehicles, when broadly deployed, are especially notable in that they represent a large load (charging rates for individual vehicles may be higher than typical peak load in a home), and consumers will expect full (or at least commute-sufficient) state of charge by morning. Some neighborhood or higher level control will likely be necessary to regulate the overnight load. Given that wind generation is typically at maximum overnight, such controls will play a vital role in achieving optimal use of wind resources.

As noted above, price signals are already being communicated to users by utilities or service providers with media ranging from advanced metering infrastructure (AMI) to the Internet. Here, too, control-relevant issues arise, and on both the supply and demand sides. Thus, a utility needs to generate control signals (a simple example is time-of-use prices, which impose different consumption costs at different times of the day according to a fixed and broadcast schedule) that, based on models of expected consumer behavior, will maximize the utility's objective—incorporating profitability, renewable energy use, stability/loadability requirements, and other criteria. Conversely, consumers must determine how to schedule their load and, where available, how and when to operate distributed generation and storage resources to best satisfy their objectives. Furthermore, large consumers and utilities will sometimes negotiate together for load profiles and prices, thereby combining two already large optimization problems into a multi-objective problem.

Another promising focus for the controls community related to the smart grid is power electronics, which is playing an increasingly important role in grid connection of loads and generation. Devices that use power electronics for grid connection include plug-in electric vehicles, variable-frequency drives, and many of the newer forms of renewable generation. Power electronic interfaces tend to decouple device behavior from grid disturbances. This decoupling can have a detrimental effect on the response of the grid frequency and can accentuate voltage collapse. Power electronic interfaces can be controlled in ways that alleviate these undesirable effects, within the bounds of physical capabilities. The required controls are location-specific and also vary with system conditions.

Complexities abound across the transmission and distribution infrastructure, with inherent interactions between continuous dynamics and discrete events. Power systems should therefore be modeled as large-scale hybrid dynamical systems, where the continuous dynamics are best represented by differential-algebraic models. State dimension is frequently in the tens of thousands. Smart grids imply incorporating cyberinfrastructure into this physical model, and doing so in a way that is computationally feasible yet preserves the dominant characteristics of the cyber-physical interactions. Furthermore, smart grids will add large numbers of devices that actively participate in systemwide control actions. Modeling each individual device is infeasible, yet their consolidated response must be accurately represented. The overall modeling problem is multiscale in terms of both time and model fidelity.

Finally, on the architectural front, smart grids will require new distributed control structures to fully exploit the new, and widely distributed, sensors and actuators. It is infeasible for a centralized controller to address every controllable load individually, yet actions taken by local controllers must be consistent with global performance objectives.

Conclusions

Most national energy policies worldwide aim at ensuring an energy portfolio that supports a cleaner environment and stronger economy and that strengthens national security by providing a stable, diverse, domestic energy supply. Clean energy is a global and urgent imperative. Renewable generation, especially from wind and solar, and smart grid concepts are critical technologies needed to address global warming and related issues. The key challenge is to reduce the cost of renewable energies to affordable levels. Control and related technologies will be essential for solving these complex problems.

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Selected recommendations for research in the control of renewable generation and smart grids:

- For concentrated solar power plants, integrated control systems are needed that incorporate advanced estimation and forecasting, heliostat self-calibration, and hybrid/robust closed-loop control.
- Novel high-altitude systems promise tremendous improvement in wind power generation—but the associated, complex modeling and control challenges must first be addressed.
- Control is critical for realizing visions for smart grids—in particular, distributed decentralized control system architectures encompassing end-to-end communication and power flows are needed.

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