INVITED PAPER

Smart Grids: A Cyber–Physical Systems Perspective

This paper presents an overview of challenges for smart grids in the context of CPSs, outlines potential contributions that CPSs can make to smart grids, and points out the implications of current technological advances to smart grids.

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ABSTRACT | Smart grids are electric networks that employ advanced monitoring, control, and communication technologies to deliver reliable and secure energy supply, enhance operation efficiency for generators and distributors, and provide flexible choices for prosumers. Smart grids are a combination of complex physical network systems and cyber systems that face many technological challenges. In this paper, we will first present an overview of these challenges in the context of cyber-physical systems. We will then outline potential contributions that cyber-physical systems can make to smart grids, as well as the challenges that smart grids present to cyber-physical systems. Finally, implications of current technological advances to smart grids are outlined.

KEYWORDS | Big data; cloud computing; complex networks; control; cyber-physical systems; intelligent systems; modeling; multiagent systems; optimization; renewable energy; smart grids

I. INTRODUCTION

The greatest discovery of the 19th century was that of electricity which has led to revolutionary progression in our society and economy. Electricity became a fundamental form of energy carrier easier to transmit over long distance than any other form, and it has become essential to our social and economic activities. The electric grids, which are essentially massive interconnected physical networks, are the infrastructure backbone for energy supply and use of today [1].

In recent years, there have been increasing demands for cleaner energy generation and more efficient use of energy due to environmental concerns as well as limited availability of nonrenewable energy sources such as coal, gas, and oil. The 2014 World Energy Outlook Report [2] indicates that the global energy demand is set to grow by 37% by 2040, and energy efficiency is critical to relieve pressure on energy supply while accommodating increasing demands without severing the environments. While renewable energy (RE) sources such as hydro, biomass, solar, geothermal, and wind are in abundance, they are much harder to harvest. Advanced technologies are needed in order to make these energy supplies more reliable and secure. Internationally, governments of many countries have adopted/are adopting new energy policies and incentives, and larger scale deployments of smart technologies are now in place. In the United States, the all-of-the-above energy strategy has been launched by President Obama. RE generation from wind, solar, and geothermal sources has doubled since 2008, and a 20% RE target by 2020 has been set [3]. In Europe, a 20% RE target by 2020 has also been set by the European Commission [4]. In China, a 15% RE target was set to achieve by 2020 [5], and an even more ambitious target of 86% RE by 2050 has recently been set by the Chinese Government [6].

All the above require a revolutionary rethinking of how to supply and use electric energy in a more efficient, effective, economical, and environmentally sustainable way. Smart grids (SGs) are such a new paradigm for energy supply and use in response to the aforementioned challenges. They aim to intelligently integrate the behaviors and actions of all the stakeholders in the energy supply chain to efficiently deliver sustainable, economic, and secure electric energy, and ensure economical and environmentally sustainable use. Key to the success of SGs is the seamless integration and interaction of the power network infrastructure as the

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physical systems, and information sensing, processing, intelligence, and control as the cyber systems. Furthermore, the emerging new technology platform, called cyber–physical systems (CPSs), is exactly the answer to address the particular integration and interaction issues in SGs, focusing on effective and efficient interaction between and integration of physical systems and cyber systems. Adopting CPS technologies in SGs will make them more efficient in operations, more responsive to prosumers, more economically viable, and environmentally sustainable. Furthermore, the peculiar characteristics of SGs will present new challenges to the development of CPSs.

In this paper, we will first give an overview of these challenges in the context of CPSs. We will then outline potential contributions that CPSs can make to SGs, as well as the challenges that SGs present to CPSs. Finally, implications of current technological advances to SGs will be outlined.

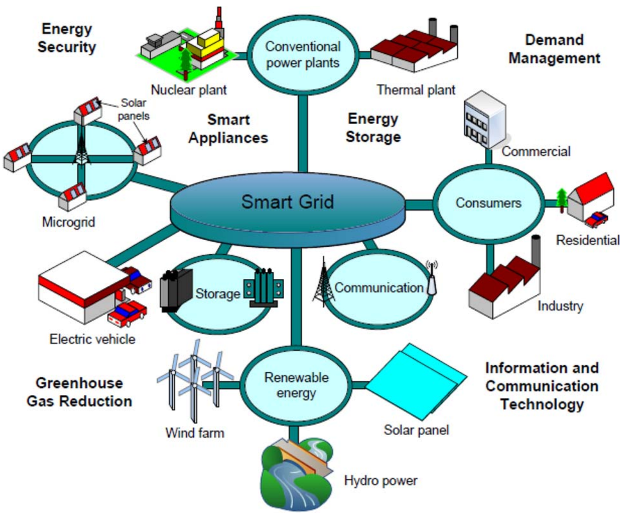

Fig. 1. *Smart grid.*

II. SMART GRIDS

The term smart grids (SGs) has been widely used with different definitions and meanings. Essential to the SG definitions is the integration of enabling ICT and other advanced technologies with the large-scale power networks to enable electric energy generation, transmission, distribution, and usage to be more efficient, effective, economical, and environmentally sustainable. The U.S. National Institute of Standards and Technology provides a conceptual model which defines seven important domains: bulk generation, transmission, distribution, customers, service provider, operations and markets. In the United States, the meaning of SGs is broad, referring to the transformation of the electric industry from a centralized, producer-controlled network to one that is more consumer interactive [7]. In Europe, SGs refer to broad society participation and integration of all European countries [8]. In China, SGs refer to a more physical-network-based approach to ensure energy supply is secure, reliable, more responsive, and economic in an environmentally sustainable manner [9]. Recently, significant attention has been paid by the Chinese Government to leverage the infrastructure to bring more socioeconomic benefits, and furthermore, introduce a market-driven national demand-side management framework and system [10].

The structure of SGs is depicted in Fig. 1, where it can be seen that there are many stakeholders and players in the highly networked and large-scale system [1]. In IEEE Grid Vision 2050 [11], the broad expectation of SGs is to have operations and control spread to the entire power systems encompassing all the present and future power technologies to enable bidirectional power flows.

The future requirements of greater flexibility, portability, safety, and security of energy supply and usage through SGs require a rethinking of how to interact between the power networks, the cyber systems, and users. Greater cooperation and interaction between physical systems (power network infrastructure) and cyber systems (ICT and advanced technologies) are a must. The technical challenges that must be addressed include intermittency of RE generation that affects electricity quality, large-scale networks of small distributed generation mechanisms, such as photovoltaic (PV) panels, batteries, wind and solar, plug-in hybrid electric vehicles (PHEVs), and uncertainties incurred due to introduction of energy market mechanism.

One key characteristic of power usage is the significant difference between the peak and average demands of electricity. For example, the ratio of peak and average demands in Australia reached around just less than 50% between 2013 and 2014 [12]. Reducing peak usage would increase the capacity of the energy supply with more margins to accommodate higher energy needs without building new power generation plants. Another way is to reduce the unnecessary waste, for example, the long distance transmission of electricity, which accounts for a substantial portion of energy generated. This supports the argument of embedded generation and siting generators close to the point of consumption (a concept usually called "distributed generation"). Another issue is how to use ICT and other advanced technologies to enhance efficiency of energy use, such as smart meters, telecommunication technologies for sensing, transmission, and processing information relating to grid conditions. To address the above issues, several key technological advances are required. 1) Control mechanisms need to be distributed, enabling lower communication needs if grid components such as source, loads, and storage units can be controlled locally or can make some decisions by themselves. 2) There should be a relatively accurate prediction of demand at the distribution level, estimating demand in any part of the grid a few hours or days in advance. 3) There should also be a relatively accurate estimation of energy generation from RE sources such as solar panels and wind turbines. This requires linkage with weather forecasting, so intermittent energy sources can be smoothly integrated with the grid. 4) Peak demand should be reduced to achieve a more efficient grid through methods such as load shedding, intelligent load management, and dynamic pricing. 5) Advanced energy storage technology is also needed that helps shave peaks in energy demands.

All the above issues and challenges require a holistic systematic approach to deal with. CPSs provide such a paradigm that can help resolve them in a systematic way. In the following, we will discuss their applications in SGs.

III. CYBER–PHYSICAL SYSTEMS

The term of cyber–physical systems (CPSs), coined in 2006 by the U.S. National Science Foundation, describes essentially a broad range of complex, multidisciplinary, physically aware next-generation engineered systems that integrate embedded computing technologies (cyber part) into the physical world (see Fig. 2). The U.S. vision of CPSs is more concentrated on connection between embedded systems and the physical world, while the European version highlights interaction with the cloud/cyberspace and human factors [13]. In China, CPSs refer to a large-scale, embedded, hybrid complex system focusing on integration of sensing, processing, intelligence, and control as a whole. Over the last few years, significant progresses have been made in CPSs, driven mainly by three emerging trends, namely, device/data proliferation, large-scale integration, and autonomy [14], even though there is still a long way to go to reach its full potential.

There have been fast developments in systems science and engineering for dealing with system analysis and synthesis such as sensing, modeling, and control, as well as computer science and engineering in programming, real-time computing, visualization, embedded design, and modeling formalisms and verification tools [15]. Systems science and engineering methods and tools excel at dealing with temporal information while computer science and engineering are good at dealing with large-scale spatial information at ease. CPSs will bring these two fields together to deal with modern industrial problems which are high in dimension and complexity and require time-critical responses.

Bridging the systems science and engineering and the computer science and engineering for CPS development faces significant technological challenges which are summarized in the following two key aspects [15], [16].

- Architecture and design. To enable seamless integration of control, communication, and computation for rapid design and deployment of CPSs, architecture and design are essential for infrastructure. Examples include communication interfaces between power networks and cyber systems, allowing heterogeneous systems to be composed in a plug-and-play fashion, and massive proliferation of technology and development of the cyber systems. Standardized abstractions and architectures that permit modular design and development of CPSs are urgently needed. Furthermore, design methodology and tools are needed to support system and network specifications, interoperability, hybrid and heterogeneous models, and modeling and analysis. Cybersecurity is another important issue for CPSs, given the intimate integration of cyber systems and physical systems where the processes and mechanisms for computing devices such as computers, smartphones, computer networks, and smart meters are essential, hence requiring protection from unauthorized access and change. New architectures and techniques are needed to ensure confidentiality, integrity, and availability of data, as well as protection of assets and humans.
- Information science and engineering. Seamless integration and interaction between cyber and physical systems demand information sensing, processing, intelligence, and control to be delivered fast and in real time. The proliferation of cost-effective sensors such as smart meters results in very large volumes of data streams which must be processed fast and efficiently in order to be useful for decision making and control, especially for the transient processes in SGs. The traditional centralized paradigms for computation, information intelligence acquisition, and control are not suitable for delivering fast real-time actions. Distributed computation, information intelligence, and control mechanisms, subject to network-based

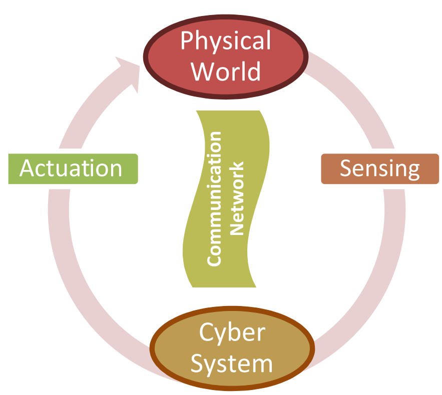

Fig. 2. *CPS framework.*

uncertainties, must be adopted in order for distributed decision making, which is especially critical for the SGs. Information sensing, processing, intelligence, and control are at the heart of all the operations.

SGs involve many stakeholders, from generator to distributor and prosumer in an interconnected world of social, economic, and technological environments. The increasing complexity of and connectivity between components such as smart meters, solar panels, wind turbines, and their sheer numbers require rethinking of how to analyze and design the CPS aspects of the SG. The applications involve components that interact through complex, highly interconnected physical environments. In the following, we will discuss the SG developments from a CPS viewpoint.

IV. SG: A CPS PERSPECTIVE

SGs integrate the physical systems (power network infrastructure) and cyber systems (sensors, ICT, and advanced technologies), and exhibit characteristics typical of CPSs, such as [17]:

- integration of real and virtual worlds in a dynamic environment where situations from the physical systems are fed to CPS control centers as input and help adjust the simulation models to influence how the physical systems perform in future times;
- dynamic connections and interactions between components in both physical and cyber systems through communication networks (e.g., *ad hoc* networks) where timely responses are essentially in their dynamic cooperation;
- real-time parallel computation and distributed information processing of big data and data streams required in order to help deliver timely decisions for SG operations across transient, distribution, and scheduling layers through the CPS;
- self-adaption, self-organization, and self-learning by which the CPS can respond to faults, attacks, and emergencies, in order to enable SG resilience and secure and safe energy supply.

An open question is whether all the currently available CPS technologies are readily applicable. The answer is not directly either “yes” or “no.” The core issue is how much integration between the cyber systems and the physical systems there should be. Often, cyber technologies such as communication networks and sensing devices are fixed on power systems without tailoring them to suit power system characteristics; a lot of calibration and patching fixtures are usually required to allow them to function together to meet the stringent SG safety and security requirements. For example, telecommunication protocols for wireless communication networks are used for retrieving measurements from smart meters installed with SIM cards and operated through public communication networks. This makes the data sensing prone to congestion, hindering decision making based on smart metering data (e.g., energy consumption reading from millions of meters at the same time) when there are competing demands on communication times during peak hours. Another example is the distributed control over communication networks which falls victim to communication time delay, packet dropouts, and packet errors, severing the control performance, and in the worst scenarios, causing the power network to collapse.

A seamless integration between these two (cyber and physical) systems will bring enormous benefits to SGs, just like what mechatronics brought to the car manufacturing industry where a blend of mechanical, electrical, telecommunications, control, and computer engineering delivers much simplified mechanical design, rapid machine setup, rapid development trials, optimized performance, productivity, reliability, and affordability.

There are peculiar characteristics of power systems that other physical systems do not have which pose new challenges to CPSs. Energy network systems require time-critical, highly connected components to work together in real time to achieve system stability, well-regulated voltage and frequency, and fast response when new energy needs are demanded. All these are done subject to various external uncertainties and disturbances. This is particular so for SGs when demands from RE sources are sought which are subject to uncertain weather conditions. A good comparison is with the acrobatic troupe performing cycling on stage from which similar characteristics can be drawn. In this team activity, real-time dynamic balancing, coordination, and cooperation between participants must be controlled optimally and distributed in order to successfully follow a performance routine designed *a priori*. In SGs, the connectivity and interdynamic reliance for maintaining network stability and functionality are more crucial than any other engineered networks such as logistic and transport networks, and even communication networks where a sudden drop of mobile coverage could occur at any time when there is traffic congestion. Such incidents cannot be allowed in SGs as time-critical control must be executed and stability be maintained in order to have uninterrupted energy supply regardless of uncertainties and disturbances. These stringent engineering requirements do beg for a conservative approach to design and management, allowing substantial redundancies which may not be necessary. CPSs can help reduce the redundancies while retaining the stability and functioning of the SG.

In order to improve cyber–physical relationship in SGs, six key functionalities are required [13], namely, 1) high dependability so that the system has to be repaired in a simple and timely manner when a fault occurs, maintaining accessibility even the fault occurs, while at the same time not causing any harm when some part is malfunctioning; 2) high reliability in open, evolving, and uncertain environments, so that the system can continue to operate even in the presence of failures without fundamental changes to its original configuration; 3) high predictability which guarantees the specified outcomes within the time span it is required to operate accurately; 4) high sustainability embedded with self-healing and adjusting mechanisms and adapting to changing environments; 5) high security so that the system has adequate means to protect itself from unauthorized access and attack; and 6) high interoperability which enables the system to provide or accept services conducive to effective communication and interoperation among system components.

There have already been some attempts to address the particular issues associated with the relationship between SGs and CPSs. The name of cyber–physical energy systems (CPESs) was used in [18] where integration of SGs and CPSs was discussed from several angles. The co-simulation environment of CPESs was proposed in [19], the communication mechanism for CPESs was discussed in [20], and a modeling analysis and control framework was proposed in [21]. However, in this paper, we will treat SGs and CPSs as two separate entities and examine the interplay and interaction between them, posing emerging mutual challenges to both fields.

In the following, we will outline the progresses and challenges in the two key broad aspects, namely, architecture and design, and information science and engineering. Fig. 3 depicts the general framework and angles that we will take to facilitate our discussions.

A. Architecture and Design

Architecture and design are concerned with how to construct the fundamental CPS infrastructure and develop design methodologies based on CPS principles so that the CPS can function seamlessly. Their key aspects are discussed below.

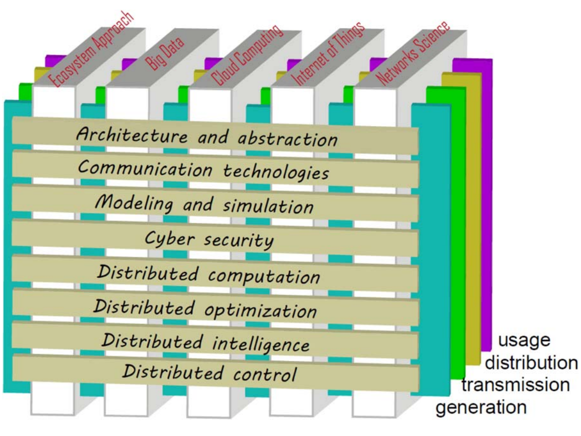

Fig. 3. *SG from a CPS viewpoint.*

Architecture and Abstraction: The physical infrastructure of power network systems demands high safety and reliability which are different from general purpose computing facilities. Furthermore, their physical characteristics make them very different from the object-oriented software components [22]. In order to have seamless integration of control, communication, and computation for rapid design and deployment of CPSs in SGs, there should be CPS architectures that are designed specifically for interfaces between power networks and cyber systems, allowing heterogeneous (dynamic) systems to talk to each other in a timely fashion and work together effectively in uncertain and sometimes highly unpredictable environments. Software-based systems must work reliably and predictably under these circumstances with concurrency which is a critical element of SGs. Common computing languages such as C can ensure the work is done right but timing is not in the semantics of C which may result in a failure of control action if the timing deadline is missed. Furthermore, most software platforms designs do not have timing properties from higher abstractions [22]. Fundamental rethinking of computer architectures taking consideration of characteristics of power systems is needed. CPS requires a unified standard framework under which the physical systems, communication protocols, computing languages, and software and hardware interfaces, which are all subject to standards in their own fields, can work together. In order for the CPS to operate seamlessly in SGs, an integrated modeling approach is required so that the physical system components (power system models) and the cyber system components (communication networks and sensing models) can be united under one framework and an overall control strategy can be developed. For SGs, such a CPS standard framework should also consider real-time responses of system transients which impose more stringent requirements [21].

Communication Technologies: Communication technologies are vital for efficient and effective interaction between the physical systems and the cyber systems. It is even more so for SGs as real-time distributed sensing and control (e.g., at the transient level) are critical for time-critical optimal performance. Two basic aspects of communication, namely, space and time, referring to the communication distance and time taken for transportation of information, should be considered when developing SG-tailored communication techniques at different levels, such as home area network, neighborhood area network, metropolitan area network, and wide area network [23]. Key factors impacting real-time performance of SGs, especially in the transient layer, are time delays, packet errors and drops, and queuing delays. Some work has already been done in this direction, for example, in [20], an on-demand communication strategy was proposed to provide real-time tracking of dynamical systems and an embedded simulation environment created to synchronize with the dynamical system to inspect communication vulnerabilities. Given the trend of market-driven energy supply and demand in the future, competition and "game playing" between various market participants may result in severe network congestions such as those occurred in India in 2012 [24]. The communication technologies as a whole need to be examined and improved upon in order for them to be used in real-time dynamic environments of SGs.

Modeling and Simulation: To support system and network specifications, interoperability, hybrid and heterogeneous modeling and operations, and modeling and simulation tools are critical to ensure that the large-scale network CPSs of SGs can operate seamlessly and components can cooperate with each other. Future SGs will deliver reliable, affordable, open, and user-friendly options for energy and utilization, which can be either large-scale and massively distributed bases in far distances or small-scale but widely distributed sources, supporting various energy demands from electric vehicles, energy conservation, and market participation. This requires multidisciplinary work involving uncertainty analysis, risk management, system security, and economic coordination [21]. New developments in reducing power consumption and spare capacity saving, including economical and effective management of massive storage of electricity, multi-dc transmission and large-scale alternating current/direct current (ac/dc) mixed-mode power networks, and wide applications of power electronic equipment require effective operation and control [19], demanding a new integrated modeling and simulation environment which is able to handle modeling to simulate the large-scale system.

So far, the boundary conditions for power network analysis, namely, the operating conditions and the disturbances, have been provided based on offline experiences, and therefore cannot be set in a realistic way following the revolutionary trends of external nonelectrical systems. This limits not only the advancement of early warning times, but also the adaptability of predecision about external environments. Future power network analysis needs to consider energy and environment as a whole. A physically secure power network can be unreliable due to the restrictions on emission, primary energy, and energy market. Preventing large-scale blackouts requires a harmonic coordination of many factors, including energy resources, financial systems, communication networks, transportation, and goods supply networks [25]. A new generation framework is needed for modeling and simulation of future SGs.

Cyber Security: Most CPSs are safety critical, and any misbehaviors due to random failures and deliberated attacks would have detrimental effects [26]. In SGs, advanced technologies such as phasor measurement units (PMUs), wide area measurement systems, substation automation, and advanced metering infrastructure (AMI) are being adopted, which present an even more increased dependency on cyber resources in real time which may be vulnerable to attacks [27], especially those sophisticated ones targeting real-time industrial control systems. The development of a trustworthy SG requires better understanding of the cyber–physical relationships in order to detect, prevent, and mitigate the cyberattacks. In computer networks, intrusion detection systems (IDSs) are the main security tools to capture, monitor, and detect various types of attacks. There are two main types of detection, the host-based IDSs and the network-based IDSs, where the former rely on known attacks with regular software updates and patching with the latter monitoring the network traffic dynamically to detect any suspicious and unknown attacks [28]. Extending the existing IDS techniques to CPSs, especially SGs, is very challenging. The existing IDS techniques are not equipped to handle the large-scaleness of the system, time-critical information exchange, and distributed and hierarchical nature of information management in CPSs. This will become even more a problem for SGs which demand real-time noninterrupted communications to exercise sensing, processing, and control especially for the transient stability of the SG. In [29], a security framework was proposed to achieve a self-healing SG which involves prevention, detection, response, recovery, and communication for cyberattacks. It aims to enable real-time monitoring and reaction, anticipation, and rapid isolation so the SG can self-heal quickly without significantly interrupting the energy supply and use. Enabling technologies and methods are needed to realize this framework.

B. Information Science and Engineering

SG is highly complex, nonlinear, and dynamical in which monitoring and control are the key to enable self-healing, self-organizing, and self-configuring capabilities. This requires much more efficient information (signal) sensing, transmission, and synthesis. The existing technologies for monitoring, assessment, and control were predominantly developed during the mid-20th century and the grid operations are rather reactive, with a number of critical tasks performed by human operators based on the raw data presented and past experiences [30]. Challenging issues include automated acquisition of field information for timely operational decision making and presentation to users in a compelling and informed way. This all becomes even more critical as the information available continues to grow exponentially with more and more sensors/meters installed. Furthermore, control centers in the current industry are set to receive measurements from sensors that interact with field devices (transmission lines, transformers, etc.). The algorithms running in the control centers process these measurements to make operational decisions. Such operations would not be feasible in the new operation environments for SGs.

Increased complexity compounded by the distributed nature of RE impacts real-time performance which is a bottleneck in deriving just-enough and just-in-time information for SG to operate efficiently [1]. The intermittent availability of RE requires consideration of the entire operational regime to deal with the associated problems such as storages and variable power quality [30]. The bidirectional electricity flow in the SG due to intermittent penetration of a large number of small generation systems and versatile usages also poses challenges. Traditional state-space-based modeling and control methodologies are no longer suitable for such tasks. A paradigm shift is needed in the way the network is dealt with. In the following, we will discuss computation, intelligence, optimization, and control requirements for SGs.

Distributed Computation: Accompanied with the deployment of large quantity of smart meters, sensing devices across the SGs at different levels of time scales are the big stream (or time-series) data that require to be processed in a timely manner in order to mine information and knowledge critical for SG operations. Furthermore, how to use this information for global optimal control of the SG is an open question. New methods are needed to automate monitoring, assessment, and control of grid operations to meet economic, social, and environmental needs. Key tasks involved in SGs include fault and stability diagnosis, reactive power control, distributed generation for emergency use, network reconfiguration, system restoration, and demand-side management analysis [31], [32]. These challenges require significant efforts in assessing whether existing theories and tools are adequate and what the limitations are. For example, the rolling out of millions of smart meters in AMI makes it possible to acquire real-time information of energy use (e.g., in 5-min intervals), connect RE to grids, manage power outages and faster restoration, fault detection, and early warning. How to fast process an extremely large volume of data streams (time series), retrieve required data intelligence, identify operational patterns, and control the SG is very challenging. Data mining technologies may be suitable for dealing with the huge dimensions of disperse data sets, but they are unable to deal with the dynamic nature of the metering data in a timely manner. Time series analysis methods may be suitable for dealing with low-dimensional metering data, but they are unable to deal with the huge dimensionality and complexity of the data sets. Bridging these two schools of thoughts together will give rise to efficient and effective data sensing, processing, and synthesis methods for SG, for example, data stream analysis can be an effective technology [33].

The capacity of a traditional centralized computer infrastructure is such that it can no longer cope with such computation requirements. The new generation of computation platforms such as grid computing [34] and cloud computing [35] can be adopted as future computation platforms for SGs, which are able to synthesize and harmonize various subcomputing tasks undertaken across SGs within local computing facilities (even smart meters can do some simple computing tasks) to deliver required computation and storage power.

Distributed Intelligence: Recently, the approach of multiagent systems (MASs) (or distributed intelligence) is shown to be an interesting solution to address the large-scaleness of the computational problem in CPS. An agent is a software entity that can represent and control a hardware component, such as a source, a storage unit, or a load. It can communicate and interact with each other and its environment, in order to cooperate or compete toward local and/or global goals. An MAS consists of a group of agents, each of which has a certain intelligence capacity, and it is a distributed intelligent agent network. Such a method has already been adopted in SG applications, for example, in [36], an application of MAS focusing on distributed state estimation, voltage coordinated control, and power flow management was made, which provides a high level of efficiency, flexibility, and intelligence. Future SG requires not only automation of operations at the micro-operational levels, but also macrolevel of decision making considering broader economic and social requirements. Distributed decision support is a key in making SGs more responsive to user demands. Another challenge is the lack of industrial grade agent-based platforms and integrated design models that are able to link the cyber–physical abstraction with the hardware-in-the-loop implementation.

Distributed Optimization: The success of SGs requires tighter integration of global optimization and local control where global optimization deals with multiple objectives such as minimum costs of energy production, maximum efficiency of electricity use, lest power network loss, and minimum carbon dioxide generation. Because of the exponentially increased number of equipment, sensors, and facilities installed and connected to the SG, traditional centralized optimization strategies are no longer adequate simply due to the computational complexity. Distributed optimization should be considered, or even hybrid distributed optimization strategies may work well, where higher level optimization is done with fewer timing tasks (e.g., scheduling) while lower level optimization is done within individual devices, each of which has a computer to process information locally, and only passes on critical information to the upper level. The challenge is how to achieve optimal global coordination by integrating global optimization and local control. MAS can be found useful to deal with the distributed optimization problems by developing communication protocols and rules to enable automatic convergence to global optimum [37], [38].

Distributed Control: SG is extremely complex with large numbers of diverse components connected through a vast and geographically extended network. Many of the controls are hierarchical and embedded in the system. The available control actions are already largely determined and have diverse timing, cost, and priority settings for action. The control goals are multiobjective with local and global requirements which vary from system operating states, for example, normal and insecure states in power systems. There is a need for a high level of distributed global control mechanism which can provide a metaview to coordinate local controllers [39]. The control system can synthesize information from physical components, adjust system models through visualization and analysis, and control the components. It can also consult various environmental databases concerning weather conditions such as temperature and wind speed to help control energy generation and dispatch [40]. Control strategies for SGs can be divided in three layers [41], the economic and planning layer, the cyber layer, and the physical and operations layer, each of which requires different time scales to impose controls, for example, the transient controllers require millisecond response time while the smart meter at the cyber layer requires less frequent regular reporting times (e.g., every 5 min). The nature of such a complex network in a hierarchical structure with different time scales at different levels poses new challenges for the existing control theory. Control of large-scale systems has been researched for many years. A common philosophy is to use a decentralized approach that decomposes the large-scale system into smaller systems based on characteristics of the problem and connectivity between them. This allows distributed control to be formulated based on local states and feedback while considering global influence [42]. An application in large-scale power systems can be found in [43]. Another effective approach is the distributed model predictive control which considers future trends into control actions [44], [45]. However, most decentralized control methods rely on modeling the systems with full states, which is not feasible in very large-scale network systems such as SGs due to their huge dimensionality and complexity. A new generation of intelligent, adaptive, robust global control strategies is needed to maintain global stability of SG against unexpected uncertainties and disturbances, in combination with wide area information sensing, data mining, and control strategy support.

V. FUTURE CHALLENGES AND OPPORTUNITIES

In this section, we will outline what we believe the key challenges and opportunities facing SGs from CPS perspective, in viewpoints of ecosystems, big data, cloud computing, Internet of Things, network science, and legislation and regulation, respectively. While they are discussed individually, they should not be considered in isolation. A system of system (or codesign) approach should be considered which will deliver optimal total system performance.

A. An Ecosystem View

SG developments cannot be done in isolation with environmental, social, and economic environments. A supply chain management (cross-functional) approach needs to be taken. For example, for coal-fired power generation, the costs and impact from mining to transporting, burning, and usage should be considered holistically. For solar panels, the costs and impact for their manufacturing from raw materials mined should also be considered. All these can be considered in a framework of "ecosystem," which is commonly defined as an ecological community interacting with the environment as a function unit [46]. Its principles can equally apply to SGs, treating it within its environments as an ecosystem consisting of many networked and interconnected elements of different life cycles, from raw materials to end-user consumption, and from physical systems to cyber systems and social–economic systems. Designing such a large-scale system requires a holistic approach taking consideration of entire life cycles of individual elements. Key elements in ecosystems are self-regulation and control through an internal feedback mechanism and resilience after disturbance, which are also shared by SGs.

In the future, operations of SGs must also be integrated with environmental, social, and economic systems, as shown in Fig. 4, which can be called energy ecosystem. Here the power system refers to the physical behaviors to be monitored, controlled, or created. The cyber system refers to the advanced embedded software and hardware, equipment, and infrastructure for information processing and communication within their distributed environments. The society and economy refer to the human dimensions of participation such as users, service providers, operators, the social dimension including community and society, and the economic dimension including energy markets, broader economic environments. The nature and environments refer to the environmental dimension including impact on flora and fauna, climate change, and natural environments. The interfaces refer to the communication networks and mediums that enable information flows between these component systems. All the key elements need to work together concurrently with key functions, namely, information

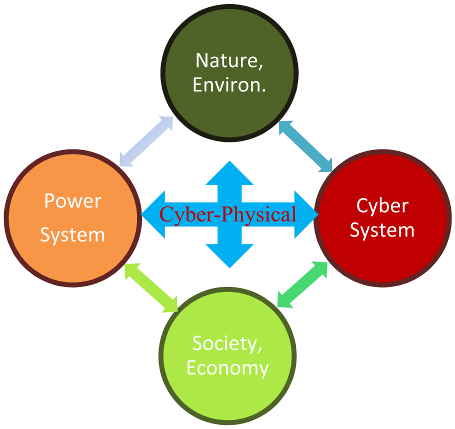

Fig. 4. *Energy ecosystem.*

retrieval, information processing, information intelligence, and intelligent control.

We believe such an energy ecosystem concept is already beyond what the SG is originally designed for, focusing on closer and more secure interactions between energy, economy, environment, and society. It also builds the safety and security of energy supply and usage on linking the primary energy sources (coal, gas, solar, wind) and energy end usage, helping develop a national strategy for energy security for each country. Such a holistic approach is being adopted by China's State Grid to build the next-generation national energy network. This super large-scale CPS of integrated subnetworks of electricity, gas, geothermal, transport, etc., will present more grand technological challenges in information sensing, processing, intelligence, and control, as well as architecture and abstraction, communications, modeling and analysis, cybersecurity, and decision support, well beyond the scopes of either SG or CPS, or both.

B. Big Data

Big data is a term that is being widely used in the data gathering and analytics. While it may have many meanings and interpretations, there are five key features, namely, volume, velocity, veracity, variance, and value [47]. Data captured by smart metering devices such as smart meters exhibit these five typical features. For example, moving from 1-m reading per month to every 5 min would transform into 308 million readings for every million consumers, resulting in a massive volume of data streams to manage. Data analytics capable of near-real-time analysis across large-volume, time-series, heterogeneous, and autonomous sources would be advantageous for both utilities and users, and if integrated with other information such as consumption data, weather, and various grid behavior-based readings, would help transform high-volume data into actionable insights that are critical for efficient operations of SGs.

The availability of large volumes of data collected in steady streams as well as other *ad hoc* occurrences such as power outages from many regions and localities makes it essential to have an integrated view of utility data and alignment of the data across disparate operational groups and lines of business. Utilities that build up this capability can gain insight into their operations and assets, enabling them to take proactive action rather than simply reacting to events after they happen. Although the increase in volume, especially in consumption data capture, is the most highlighted big data aspect with smart meters, other key aspects such as velocity and variance are equally important. This is more relevant for data generated by sensors and new grid instrumentation. Analytical algorithms which can process huge quantities of data are available. However, many of them are not able to complete such activities in a sufficiently short time period to be of practical use in SGs. For example, in real-time tasks, such as equipment reliability monitoring, outage prevention, or security monitoring, overnight is not good enough. In SG environments, data types are not necessarily from traditional sources like industrial control systems only, but also from security cameras, weather forecasting systems, maps, drawings and pictures, and the web. They are becoming increasingly important to utilities as social media and call center dialogs are also sources of critical information if considered in combination with smart meters and grid generated data for decision-making and planning processes [48]. Data analytics for those big data issues associated with SGs require developments of effective architecture and design, time-critical information science and engineering technologies with specialized semantics, computation platforms, and smart algorithms [49].

C. Cloud Computing

SG enables distributed and renewable energy generation though real-time management to meet demands in a timely manner. Cloud computing has been a very recent paradigm in which services such as computation, storage, and network are packaged as computing resources [50]. Cloud computing brings out benefits such as on-demand self-service, resource pooling, however elasticity through use of a cloud service raises security and privacy issues. This concept has already been adopted in dynamic pay-per-use pricing modeling for regulation [51], and the first cloud-based smart metering system was developed in Denmark for small utilities and communities. There are also initiatives worldwide, for example, U.K. Smart Energy Cloud, to support the United Kingdom's smart meter implementation program, which is expected to roll out more than 50 million meters throughout the country by 2016. The solution is expected to provide for more accurate billing, greater smart grid functionality, and other benefits. There have also been some cloud platforms developed for power systems, e.g., IBM Coremetrics and

Google BigQuery. A cloud-based software platform for data-driven analytics [35] was developed as a part of the Los Angeles Smart Grid Project. The benefits of cloud computing include easy management, cost reduction, uninterrupted services, disaster management, and green computing [50]. The key challenge is the security and privacy issue where confidential data may be handed over to the third party service providers resulting in exposure of confidential information to outsiders. These complex issues will need to be addressed from a broad scope of perspectives, such as legislative, regulatory, and operational viewpoints [52], which will have impact on architecture and design, information science, and engineering aspects of SG.

D. Internet of Things

Internet of Things (IoT) is considered the expansion of the Internet services due to the proliferation of RFID, sensors, smart devices, and "things" on the Internet [53]. IoT is expected to grow to 50 billion connected devices by 2020 [54].

SG has a communication network that connect all the energy-related equipment of the future, from the transmission and distribution power infrastructure, electrical, water, gas, and heat meters, to home and building automation. Effective functioning of the SG can be achieved by using the IoT computing paradigms as a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols. Here physical and virtual "things" have identities, physical attributes, virtual personalities, and user intelligent interfaces, and are seamlessly integrated into the IoT network [1]. The connectivity and accessibility that the IoT brings in further enhances customer experience and efficiencies allowing greater interaction and control for consumers. Additionally, IoT delivers more data for manufacturers and utility providers to reduce costs through diagnostics and neighborhood-wide meter reading capabilities. Ultimately, the IoT will be instrumental in building a more connected, cost-effective, and smarter SG.

There are three challenges in application of IoTs: the "things" need to be identified uniquely and tracked with their IDs through sensors and pervasive technologies. Sophisticated sensing and computing devices are required to enable various "things" to be connected globally and information/data collected be transmitted out; From the Internet viewpoint, the objects whether physical or cyber, need to work on an IP platform on which they can communicate and work together; the diverse data of homogeneous and heterogeneous types need to be interoperable under a unified semantic platform for effective data fusion [52]. Such an attempt has already been made, for example, in [56], an IoT architecture was proposed for SGs which consists of four components: intelligent electric transmission, substation, distribution, and usage, which are connected through an electric power central (wide area) network.

In SG environments, IoT represents a vast network of anything that is part of the power system. Such an environment was also named as the Internet of Energy [57]. However, due to the fact that physical laws governing electric flows are different from those for information flow, and electricity is indistinguishable between sources, and because of the physical and chemical transformation from primary sources to end use, it may be more appropriate to refer to such an environment as a cyber energy system in the context of the broader energy ecosystem to capture the landscape of the vast areas and aspects in information and physical layers covered. The information security and stringent real-time responsiveness of SG may still require closed, specialized communication networks separate from the public communication networks which are prone to cyber attacks and are poor in real-time responses. Greater integration of the Internet and specialized, closed, secure communication networks will accommodate the need for security and reliability of SG, as well as the need for effective architecture and design to enable interaction and communication between stakeholders across social, economic, and environmental domains to achieve collective goals in an optimal manner.

E. Network Science

In recent years, network science, which is defined as the study of network representations of physical, biological, and social phenomena leading to predictive models of these phenomena by the U.S. National Research Council, has attracted increasing attention. It studies complex networks found in natural and man-made systems such as communication networks, biological systems, social networks, computer networks, and power networks. Complex networks research draws theories and methodologies from a wide range of areas such as graph theory, statistics, mechanics, data mining, and sociology [58]. The essence of this theory is to study the subject system from the aspects of structure, topology, and dynamical function of a collection of nodes and links without relying heavily on the dimensionality of the system which is usually focused on in existing theories such as control and optimization theories. Typical complex networks include regular networks, random networks, small-world networks, and scale-free networks. Such a theory has found its application in the vulnerability analysis of the power network [59], [60].

The new way of thinking embedded in the complex network theories is to consider the connectivity, topological structures, and strengths of connections as key factors to understand, model, and manage the networks without bogging down with the huge dimensionality and complexity, which are usually NP-hard problems [58]. This may result in achieving close-to-ideal modeling or control effects focusing only on few drive nodes [61] or few smaller subnetworks so that modeling, optimization, and control tasks for complex networks can be performed much faster and simpler. Some exploitation of this idea has been implemented in pinning control of complex networks (taking advantage of the topological structure of the network to simplify the analysis and control design) [62]. However, the existing results suffer from several problems: 1) the node dynamics are homogeneously simplistic, usually linear systems of same dimensions which are far from reality; 2) the links are static where in SGs the links can be dynamic; 3) the complex networks themselves are not heterogeneous where in SGs there are mixes of dynamic, static, nonlinear models interconnected; and 4) there is also an aspect of network of network where the power networks have different layers of functional networks acting upon the physical energy network system such as telecommunication, smart meter, and demand-side management networks, which have not been studied before. The aforementioned issues are frontiers in complex networks, SGs, and CPSs; solving them will have significant impact on these areas individually and as a whole. For example, SG architecture design can use network topological information for differential treatment of components upon their importance. Such information can also be used to discriminate less important components to deliver time-critical feasible solutions.

F. Legislation and Regulation

As SG becomes an increasingly important development across the globe, legislators and regulators in various countries are considering possible implementation barriers based on numerous analyses done, which are different from country to country and have different focuses. For example, in the United States and Europe, the barriers are both legislative and regulative [63], [64], while in developing countries such as China, the focus is placed more on regulations and standards which aim to enable the SG to function seamlessly.

There are a broad range of issues concerning SG's uptake as a national infrastructure, most of which are closely related to cyber–physical aspects of SGs, for example, stakeholder participation and incentives for demand-side response, legal barriers to the SG development, regulatory instruments to facilitate it. In here, we mainly focus on legislative and regulatory issues closely related to the two key central aspects of this paper: architecture and design, and information science and engineering. For architecture and design, the challenges include legislative encouragement for SG development, regulatory requirements for standards, models, and architectures that enable interoperability and interconnectivity, data collection and handling, cyber and network security, and compliances of enabling ICT such software platforms, hardware infrastructure and devices, as well as legal responsibilities of various stakeholders such as vendors and prosumers. For information systems and engineering, there are outstanding legal and regulatory issues concerning data access, data provision, data privacy, software/hardware liabilities, and automated decision making. They are expected to be treated differently within the legislative and regulatory frameworks of individual countries. ■

VI. CONCLUSION

In this paper, we have presented an overview of the challenges in SGs from a CPS perspective. We have outlined potential contributions that CPSs can make to SGs, as well as the challenges that SGs present to CPSs. We have particularly discussed the impact of the latest frontier technologies on SGs, including big data, cloud computing, the Internet of Things, and network science as well as challenges in legislation and regulation A number of open questions have also been posed which will be important for future developments of SGs, CPSs, as well as the energy ecosystem as a whole.

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