Smart Grids: A Cyber–Physical Systems Perspective

Ujas Bhadani

Cyber Security Expert
Gujarat Technological University
Gujarat, India

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Abstract - *Smart grids are electric networks that use cutting-edge monitoring, controlling, and communication technology to deliver a safe and stable energy supply, improve the efficiency of operation for generators and distributors, and offer consumers various options. The mix of sophisticated physical network systems and cyber systems that make up smart grids presents various technical difficulties. This paper will give a general overview of these difficulties in the context of cyber-physical systems. After that, we'll discuss the potential benefits that cyber-physical systems could provide to smart grids, as well as the difficulties that smart grids pose for these systems. Finally, the effects of recent technological developments on smart grids are addressed.*

Key Words: Smart Grids, Cyber–Physical Systems, Complex Networks, Renewable Energy, Multiagent Systems

1. INTRODUCTION

The invention of electricity, which revolutionized our culture and economy, was the biggest discovery of the 19th century. Considering electricity is capable of traveling over great distances more easily than any other form of energy carrier, it has become important to our economic and social functioning. Electric grids, which are essentially huge interconnected physical networks, serve as the foundation of today's energy supply and consumption systems. [1]

Due to environmental concerns and the limited supply of nonrenewable energy sources like coal, gas, and oil, there have been growing demands for cleaner energy generation and more efficient energy use in recent years. Although there are many sources of renewable energy (RE), such as hydro, biomass, solar, geothermal, and wind, they are far more difficult to extract. Since 2008, the amount of RE generated by wind, solar, and geothermal sources has increased, and a 20% RE target has been planned for 2020 [2]. According to the 2014 World Energy Outlook Report [3], by 2040, the world's energy demand is expected to increase by 37%. At the global level, several governments have implemented or are implementing new energy laws and incentives, and larger-scale deployments of smart technology are now in place.

In response to the issues mentioned, smart grids (SGs) are a technological evolution for energy supply and consumption. Smart grids are designed to effectively deliver sustainable, affordable, and secure electric energy by integrating the behaviors and activities of all the contributors in the energy supply chain. The growing new technological platform known as cyber-physical systems (CPSs), which focuses on the seamless integration of physical systems and cyber systems, is the perfect solution to handle the specific integration and interaction difficulties in SGs. The consistent integration and interaction of information sensing, processing, intelligence, and control as cyber systems with the power network infrastructure as the physical systems are essential to the success of SGs. SGs will become more operationally effective, consumer-responsive, commercially viable, and environmentally sustainable by implementing CPS technologies.

This paper will provide an outline of these constraints in the context of CPSs. The issues that SGs provide to CPSs will next be discussed, along with the potential contributions that CPSs can make to SGs. The effects of recent technological advancements on SGs will be explored in the last section.

2. SMART GRIDS

The term "smart grids" (SGs) has been used frequently and has been given various definitions. The integration of enabling ICT and other cutting-edge technologies with large-scale power networks is extremely important to the SG definitions because it makes it possible for electric energy generation, transmission, distribution, and usage to be more effective, efficient, affordable, and environmentally sustainable. Seven crucial domains are defined under the U.S. NIST conceptual model, which includes bulk generation, transmission, distribution, customers, service providers, operations, and markets [4].

Different nations have their own interpretations of what the SGs mean. In China, SGs refer to a more physical-network-based strategy to ensure energy supply is safe, reliable, responsive, and cost-effective while also being environmentally sustainable [5]. The technical difficulties that must be addressed include the intermittent nature of renewable energy generation, massive networks of small, distributed generation systems, and the uncertainty imposed by the implementation of an energy market mechanism.

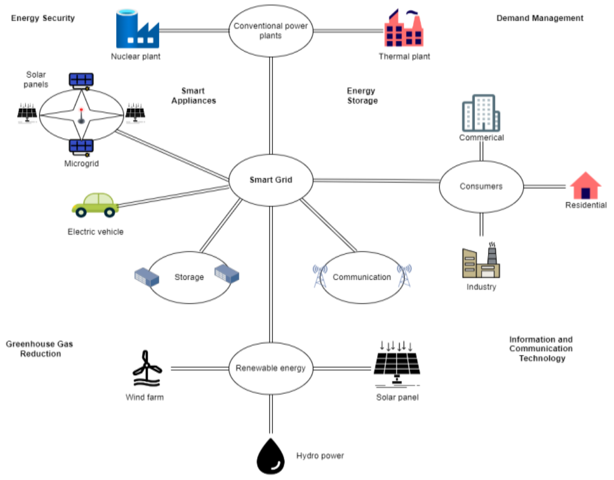

Chart -1: Smart grid network

According to Fig. 1, which shows the SGs' organizational structure, the complex, highly interconnected system contains a wide range of stakeholders and participants [1]. According to IEEE Grid Vision 2050 [6], SGs should have operations and control dispersed across the whole power systems, including all current and emerging power technologies, in order to facilitate bidirectional power flows. Future energy supply and usage through SGs needs to be more flexible, portable, safe, and secure, which requires rethinking the way consumers, cyber systems, and power networks interact.

The stark contrast between the peak and average electricity demand is one of the fundamental characteristics of power usage. Increasing the capacity of the energy supply with greater capacity to satisfy rising energy needs without constructing additional power generation facilities would derive from reducing peak usage. Another concern is how to employ ICT and other cutting-edge technology, like smart meters and telecommunications technologies for sensing, transmitting, and processing data about grid conditions, to improve energy consumption efficiency. Several significant technological improvements are needed to address the problems such as,

- To create a more effective grid, peak demand should be decreased through techniques like load shedding, intelligent load management, and dynamic pricing.
- If grid components like sources, loads, and storage units can be controlled locally or can make some decisions on their own, control methods need to be decentralized in order to reduce communication requirements.
- Energy production from RE sources like solar cells and wind turbines should also be fairly accurately estimated.
- Demand at the distribution level should be rather accurately predicted, with demand in any area of the grid estimated a few hours or days in advance.
- Innovative energy storage technology is also required to reduce energy demand peaks.

A comprehensive, systematic approach is needed to address all of the mentioned problems and challenges. CPSs offers a paradigm that can help in standardizing its solutions. We will talk about how they are used in SGs in the sections that follow.

3. CYBER-PHYSICAL SYSTEMS

The U.S. National Science Foundation first used the term "cyber-physical systems" (CPSs) in 2006 to refer to a broad category of sophisticated, multidisciplinary, and physically aware next generation designed systems that incorporate embedded computing technology (the "cyber part") into the real world (see Fig. 2). While the European form of CPSs emphasizes contact with the cloud/cyberspace and human factors, the American version is more focused on the relationship between embedded systems and the physical world [7]. Significant advancements in CPSs have been made in recent years, mostly due to three rising trends: the proliferation of devices and data, significant integration, and autonomy [8]. For dealing with system analysis and syntheses like 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, there have been rapid progressions in systems science and engineering [15]. While computer science and engineering are able to handle large-scale geographic information with ease, systems science and engineering methodologies and tools excel at managing temporal information. These two disciplines will come together through CPSs to address the complex, time-sensitive issues facing the modern industry today.

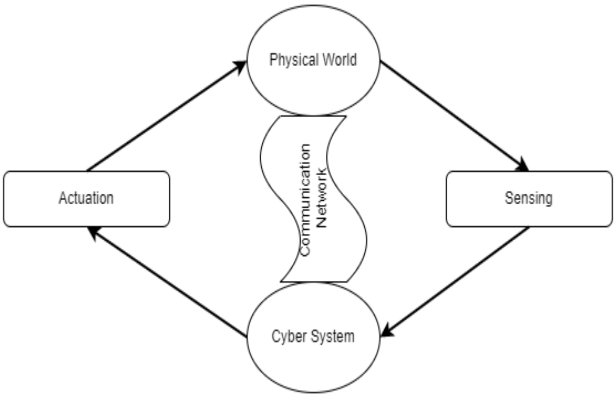

Chart -2: CPS framework

For the development of CPS, bridging systems science and engineering and computer science and engineering presents technological difficulties, which are articulated in the two key features below [9], [10].

- Architecture and design. Infrastructure architecture and design are important for providing seamless integration of control, communication, and computing for quick CPS design and deployment. Examples include the development of communication interfaces between electricity networks and cyber systems, the ability to plug and play heterogeneous systems together, and the rapid spread of technology. There is a critical need for standardized abstractions and architectures that allow for the modular design and development of CPSs.

- Information science and engineering. Information sensing, processing, intelligence, and control must be delivered instantly and in real-time to ensure seamless integration and interaction between cyber and physical systems. In order to be relevant for decision-making and control, especially for the transient processes in SGs, very high volumes of data streams must be analyzed quickly and efficiently because of the widespread use of affordable sensors like smart meters.

The applications contain elements that communicate via sophisticated, heavily interconnected physical environments. We will explore the SG developments from a CPS perspective in the sections that follow.

4. SG: A CPS PERSPECTIVE

Sensors, information and communication technologies, and other cutting-edge technologies are integrated with physical and cyber systems in SGs, which display CPS-specific traits like [11]:

- The merging of the real and virtual worlds in a dynamic environment where events from the physical systems are sent into the CPS control centers as input and help modify the simulation models to affect how the physical systems behave in the future

- Dynamic connections and interactions between elements in physical and virtual systems via communication networks (such as ad hoc networks), where prompt actions are largely determined by their dynamic collaboration.

- To support SG activities spanning transitory, distribution, and scheduling layers through the CPS, real-time parallel computation and distributed information processing of huge data and data streams are necessary.

- The ability of the CPS to respond to faults, attacks, and emergencies through self-adaptation, self-organization, and self-learning in order to increase SG resilience and provide a secure and safe energy supply.

As with mechatronics, which combines mechanical, electrical, telecommunications, control, and computer engineering to produce considerably simpler mechanical design, quick machine setup, faster development trials, optimized performance, productivity, dependability, and cost, a seamless integration between these two (cyber and physical) systems will be extremely beneficial to SGs.

The specific properties of power systems present new difficulties for CPSs that other physical systems do not have. For energy network systems to provide system stability, well-regulated voltage and frequency, and quick response when new energy needs are requested, time-critical, highly connected components must cooperate in real time. All of these things are done with numerous outside uncertainties and interruptions in consideration. This is especially true for SGs when requests from RE sources are made that are dependent on erratic weather.

As opposed to other designed networks like logistic and transport networks, or even communication networks, where a sudden reduction in mobile coverage could happen at any time when there is traffic congestion, in SGs, connectivity and inter-dynamic dependency for sustaining network stability and functionality are more important. Such occurrences are not permitted in SGs because stability and time-critical control must be maintained to ensure an uninterrupted energy supply despite uncertainties and interruptions. These demanding engineering specifications do require a cautious approach to design and management, allowing for significant redundancy that may not be required. CPSs can assist in reducing redundancies while maintaining the SG's stability and functionality.

Six critical characteristics are needed to optimize the cyber-physical interaction in SGs [7], including

- High dependability, which enables quick and easy repairs to be made.

- High reliability in open, dynamic, and uncertain contexts, allowing the system to function even in the event of failures.

- High predictability, which ensures the desired results within the timeframe needed to operate correctly.

- High sustainability built into self-healing and adjusting mechanisms that can adjust to shifting environmental conditions

- High security so that the system has sufficient defenses against attack and illegal access
- High interoperability allows the system to accept services that support efficient communication and cooperation among subsystem.

The specific problems related to the interaction between SGs and CPSs have already been addressed. However, we will treat SGs and CPSs as two distinct entities in this work and examine how they interact with one another, creating additional problems to both domains. Following, we will discuss the developments and difficulties in the two major, all-encompassing fields of architecture and design and information science and engineering. The general framework and perspectives that we will use to support our conversations are shown in Fig. 3.

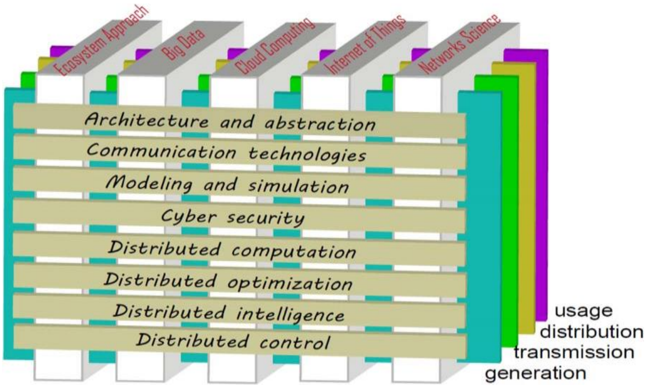

Chart -3: Smart grid from a CPS viewpoint

4.1 Architecture & Design

For the CPS to operate effectively, architecture and design are concerned with how to build the essential CPS infrastructure and create design approaches based on CPS principles. These crucial elements are covered here.

Architecture and Abstraction: Compared to general purpose computer facilities, the physical infrastructure of power network systems has higher safety and reliability requirements. Likewise, they differ significantly from the components of object-oriented software in terms of their physical features [12]. There should be CPS architectures that are specifically created for interfaces between power networks and cyber systems in order to have seamless integration of control, communication, and computation for rapid design and deployment of CPSs in SGs. This will enable heterogeneous (dynamic) systems to communicate with one another promptly and collaborate effectively in uncertain and occasionally highly unpredictable environments.

Communication Technologies: The efficient and successful connection between physical systems and cyber systems depends on communication technology. For SGs, it is particularly important because time-critical optimal performance depends on distributed real-time sensing and control (for example, at the transient level). When developing SG-tailored communication techniques at various levels, such as HAN, NAN, MAN, and WAN, two fundamental aspects of communication, namely, space and time, should be taken into consideration, referring to the communication distance and time taken for the transportation of information [13]. Time delays, packet errors and losses, and queuing delays are important variables affecting the real-time performance of SGs, particularly in the transient layer.

Modeling and Simulation: Interoperability, hybrid and heterogeneous modeling and operations, as well as modeling and simulation tools, are essential to support system and network requirements and guarantee that the large-scale network CPSs of SGs can run smoothly and components can communicate with one another. Future SGs will provide dependable, affordable, open, and user-friendly options for energy and utilization. These options can be large-scale bases that are broadly distributed over large distances or small-scale sources that are widely dispersed, supporting a variety of energy demands from electric vehicles, energy conservation, and market participation [14]. This necessitates interdisciplinary work including risk management, system security, uncertainty analysis, and economic cooperation.

Cyber Security: Due to the safety-critical nature of the majority of CPSs, any improper actions brought on by arbitrary errors and malicious attacks would be disastrous [15]. Phasor measurement units (PMUs), wide area measurement systems (WAMS), substation automation, and advanced metering infrastructure (AMI) are examples of advanced technologies being adopted in SGs. These technologies present an even greater dependency on real-time cyber resources that may be vulnerable to attacks, particularly those sophisticated ones targeting real-time industrial control systems [16]. For the purpose of detecting, preventing, and mitigating intrusions, the creation of a trustworthy SG demands a greater knowledge of the cyber-physical connections. Intrusion detection systems (IDSs) are the primary security tools for capturing, monitoring, and detecting different forms of intrusions in computer networks. Host-based IDSs and network-based IDSs are the two primary types of detection; the former relies on known attacks and routine software upgrades and patching, whereas the latter dynamically monitors network traffic to detect any suspicious and unidentified attacks [17].

4.2 Information Science & Engineering

Monitoring and control are essential to facilitating SG's self-healing, self-organizing, and self-configuring capabilities because SG is highly complex, nonlinear, and dynamic. Sensing, transmitting, and processing of information (signals) must be much more effective. The monitoring, evaluation, and control technologies currently in use were mostly developed in the middle of the 20th century, and grid operations are mostly reactive, with a number of crucial jobs being carried out by human operators based on the raw data supplied and prior experiences [18]. Automated collection of information for timely operational decision-making and presentation to users in a compelling and informative way are challenging concerns. With additional sensors and meters being deployed, this all becomes even more crucial as the amount of information available continues to expand exponentially.

Real-time performance is impacted by increased complexity compounded by the distributed nature of RE, which acts as a bottleneck in obtaining just-enough and just-in-time information for SG to function effectively [1]. Because of RE's inconsistent availability, the entire operational regime must be taken into account in order to address related issues like storage and fluctuating power quality [18].

Distributed Computation: Sensing devices across the SGs at various levels of time scales are installed along with vast numbers of smart meters, creating a big stream (or time-series) of data that must be analyzed quickly in order to mine data that is essential for SG operations. Furthermore, it is unclear how to apply this knowledge to the SG's overall optimal control. To meet requirements for economic, social, and environmental objectives, new techniques are required to automate monitoring, assessment, and control of grid operations. Fault and stability diagnosis, reactive power regulation, distributed generation for emergency usage, network reconfiguration, system restoration, and demand-side management analysis are some of the major responsibilities involved with SGs [19], [20].

Distributed Intelligence: The use of multiagent systems (MASs) is proven to be an effective solution to the computational problem's huge scale in CPS. A software entity known as an agent can represent and control a piece of hardware, such as a source, a storage device, or a load. It can converse with one another and interact with its surroundings in order to work together or compete to achieve local and/or global goals. An MAS is a distributed intelligent agent network made up of a number of agents, each of which has a specific level of intelligence. Applications for SG have already included such a methodology [21]. Future SG calls for both macrolevel decision-making that takes into account greater economic and social requirements in addition to micro-operational level automation. Distributed decision support is essential for improving the user responsiveness of SGs.

Distributed Optimization: The success of SGs necessarily involves a closer pairing of global optimization and local control, where global optimization deals with a variety of goals including minimum costs of energy production, maximum efficiency of electricity use, least amount of power network loss, and minimal carbon dioxide generation. Due to the exponentially increased computational complexity brought on by the installation and connection of a growing number of devices, sensors, and facilities to the SG, conventional centralized optimization methodologies are no longer suitable.

Distributed Control: SG is immensely complicated, with numerous unique components interconnected by a huge, globally distributed network. A large number of the controls are incorporated into the system and are hierarchical. The available control actions have a variety of timing, cost, and priority settings for execution and have already been decided in significant part. The control objectives are multi objective, with local and global specifications that differ depending on the system operating states, such as secure and unsecure states in power systems [22]. Through visualization and analysis, the control system can modify system models and control the components while also synthesizing data from the physical components. It may also look for weather information in several environmental databases [23].

5. FUTURE CHALLENGES & OPPORTUNITIES

We will discuss what we perceive to be the main obstacles and potential for SGs from a CPS standpoint in this section, from the perspectives of ecosystems, big data, cloud computing, the Internet of Things, network science, and, respectively, legislation and regulation.

5.1 An Ecosystem View

Environmental, social, and economic factors must be considered in SG developments. For instance, when considering coal-fired power generation, it is important to consider all costs and effects, from mining to transporting, burning, and using the fuel. The costs and effects of extraction for the raw minerals needed to make solar panels should also be considered. All of these can be viewed within the context of an "ecosystem," which is typically understood as an ecological community interacting with its surroundings as a functional unit [24].

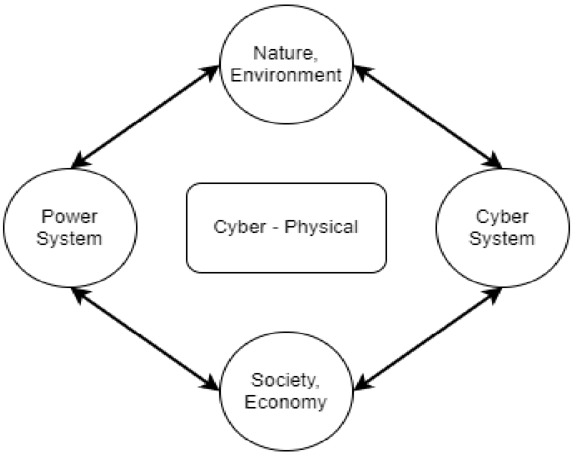

Chart -4: Energy ecosystem

Future SG operations must also be connected with social, economic, and environmental systems, as shown in Fig. 4, which is referred to as the energy ecosystem. In this context, the power system refers to the physical behaviors that must be observed, managed, or produced. The term "cyber system" describes the sophisticated embedded software, hardware, tools, and infrastructure used in distributed systems for information processing and communication. The terms "society" and "economy" are used to describe the human aspects of participation, such as users, service providers, and operators, as well as the social dimension, which includes community and society, and the economic dimension, which includes energy markets and broader economic environments. The energy ecosystem concept, which emphasizes closer and safer interactions between energy, economics, environment, and society, goes beyond what the SG was initially intended for. Additionally, it strengthens the security of energy usage and supply by connecting the main energy sources (coal, gas, solar, and wind) and energy end uses, supporting the development of each nation's national energy security policy.

5.2 Big Data

The phrase "big data" is frequently used in the context of data collection and analytics. Although it may be interpreted and given many different meanings, there are five essential characteristics: volume, velocity, veracity, variation, and value [25]. These five common characteristics can be seen in the data collected by smart metering devices, such as smart meters. For instance, if measurements were changed from being taken once a month to being taken every five minutes, there would be 308 million readings for every million users, creating a huge amount of data streams to manage. Both utility companies and users would benefit from data analytics that can perform near real-time analysis across large-volume, time-series, heterogeneous, and autonomous sources. When combined with additional data like consumption data, weather, and different grid behavior-based readings, high-volume data can be transformed into actionable insights that are important for the efficient operation of SGs.

5.3 Cloud Computing

Through real-time management, SG enables distributed and renewable energy generation to efficiently meet demand. A relatively new concept called cloud computing bundles services including compute, storage, and networking as computing resources [26]. On-demand self-service and resource pooling are two advantages of cloud computing, however elasticity brought on by using a cloud service raises concerns about security and privacy. Dynamic pay-per-use pricing modeling for regulation has already incorporated this idea [27], and the first cloud-based smart metering system was created in Denmark for local utilities and towns. More precise billing, improved smart grid operation, and other advantages are anticipated from the system. Furthermore, several cloud platforms, such as Google Big Query and IBM Core metrics, have been designed exclusively for power systems. Easy management, lower costs, uninterruptible services, disaster management, and green computing are a few advantages of cloud computing [26]. The main difficulty is the security and privacy issue, because giving personal data to third-party service providers could expose sensitive data to the public.

5.4 Internet of Things

The transmission and distribution of electricity infrastructure, electrical, water, gas, and heat meters, as well as home and building automation, are all connected by a communication network at SG. The IoT computing paradigms can be used to create a dynamic global network infrastructure with self-configuring capabilities based on open-standard and interoperable communication protocols, which will enable the SG to function effectively. In this scenario, both real and virtual "things" are seamlessly incorporated into the IoT network and have identities, physical characteristics, virtual personalities, and user-intelligent user interfaces. Consumer interaction and control are increased because to the IoT's connectivity and accessibility, which also improve efficiency and the customer experience [1]. Additionally, the Internet of Things (IoT) provides additional data to manufacturers and utility companies, allowing them to reduce expenses by diagnosing problems and enabling neighborhood-wide meter reading. In the end, the IoT will be crucial to creating a more interconnected, economical, and intelligent SG.

IoT in SG environments refer to a huge network of anything connected to the power infrastructure. The “Internet of Energy" was another term for such a system [28]. Private, specialized communication networks are separate from the open communication networks, which are vulnerable to cyberattacks and have poor real-time reaction times and are required to maintain the information security and strict real-time responsiveness of SG.

5.5 Network Science

The U.S. National Research Council defines network science as the study of network representations of physical, biological, and social events that results in predictive models. It has gained popularity in recent years. It examines complicated networks that can be found in both natural and artificial systems, including communication, biological, social, computer, and power networks. Research on complex networks involves theories and techniques from many other disciplines, including graph theory, statistics, mechanics, data mining, and sociology [29]. Regular networks, random networks, small-world networks, and scale-free networks are examples of common complex networks. The investigation of the power network's vulnerabilities has made use of such a hypothesis.

5.6 Legislation and Regulation

Legislators and regulators in various nations are taking into consideration potential implementation barriers based on numerous analyses that have been conducted, each of which differs from country to country and has a different focus as SG becomes an increasingly significant development around the world. For instance, in the United States and Europe, the barriers are both statutory and regulatory [30], [31]. In emerging nations like China, the emphasis is more on rules and standards intended to ensure the SG operates without interruption.

There are many concerns with SG adoption as a national infrastructure, most of which are directly tied to cyber-physical features of SGs, such as stakeholder engagement and demand-side response incentives, legislative restrictions on SG development, and regulatory tools to support it. Here, we primarily concentrate on legal and administrative matters that are directly related to the two primary foundations of this paper: architecture and design and information science and engineering.

6. CONCLUSIONS

From a CPS perspective, we have provided an overview of the difficulties with SGs in this study. We have discussed the possible benefits that CPSs can provide to SGs as well as the difficulties that SGs pose for CPSs. We have specifically covered how the newest cutting-edge technologies, including as big data, cloud computing, the Internet of Things, and network science, impact SGs as well as issues with legislation and regulation. Also, a number of unanswered questions have been raised that are crucial for the future expansion of CPSs, SGs, and the entire energy ecosystem.

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