Smart Grid – The New and Improved Power Grid: A Survey

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***Abstract*—The Smart Grid, regarded as the next generation power grid, uses two-way flows of electricity and information to create a widely distributed automated energy delivery network. In this article, we survey the literature till 2011 on the enabling technologies for the Smart Grid. We explore three major systems, namely the smart infrastructure system, the smart management system, and the smart protection system. We also propose possible future directions in each system. Specifically, for the smart infrastructure system, we explore the smart energy subsystem, the smart information subsystem, and the smart communication subsystem. For the smart management system, we explore various management objectives, such as improving energy efficiency, profiling demand, maximizing utility, reducing cost, and controlling emission. We also explore various management methods to achieve these objectives. For the smart protection system, we explore various failure protection mechanisms which improve the reliability of the Smart Grid, and explore the security and privacy issues in the Smart Grid.**

***Index Terms*—Smart grid, power grid, survey, energy, information, communications, management, protection, security, privacy.**

I. INTRODUCTION

TRADITIONALLY, the term *grid* is used for an electricity system that may support all or some of the following four operations: electricity generation, electricity transmission, electricity distribution, and electricity control.

A *smart grid (SG)*, also called smart electrical/power grid, intelligent grid, intelligrid, futuregrid, intergrid, or intragrid, is an enhancement of the 20th century power grid. The traditional power grids are generally used to carry power from a few central generators to a large number of users or customers. In contrast, the SG uses two-way flows of electricity and information to create an automated and distributed advanced energy delivery network. Table I gives a brief comparison between the existing grid and the SG.

TABLE I
A BRIEF COMPARISON BETWEEN THE EXISTING GRID AND THE SMART GRID [70]

Existing Grid	**Smart Grid**
Electromechanical	Digital
One-way communication	Two-way communication
Centralized generation	Distributed generation
Few sensors	Sensors throughout
Manual monitoring	Self-monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptive and islanding
Limited control	Pervasive control
Few customer choices	Many customer choices

By utilizing modern information technologies, the SG is capable of delivering power in more efficient ways and responding to wide ranging conditions and events. Broadly stated, the SG could respond to events that occur anywhere in the grid, such as power generation, transmission, distribution, and consumption, and adopt the corresponding strategies. For instance, once a medium voltage transformer failure event occurs in the distribution grid, the SG may automatically change the power flow and recover the power delivery service. Let us consider another example of demand profile shaping. Since lowering peak demand and smoothing demand profile reduces overall plant and capital cost requirements, in the peak period the electric utility can use real-time pricing to convince some users to reduce their power demands, so that the total demand profile full of peaks can be shaped to a nicely smoothed demand profile.

More specifically, the SG can be regarded as an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption to achieve a system that is clean, safe, secure, reliable, resilient, efficient, and sustainable. This description covers the entire spectrum of the energy system from the generation to the end points of consumption of the electricity [80]. The ultimate SG is a vision. It is a loose integration of complementary components, subsystems, functions, and services under the pervasive control of highly intelligent management-and-control systems. Given the vast landscape of the SG research, different researchers may express different visions for the SG due to different focuses and perspectives. In keeping with this format, in this survey, we explore three major systems in SG from a technical perspective:

- *Smart infrastructure system*: The smart infrastructure system is the energy, information, and communication infrastructure underlying of the SG that supports 1) advanced electricity generation, delivery, and consumption; 2) advanced information metering, monitoring, and management; and 3) advanced communication technologies.
- *Smart management system*: The smart management sys-

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tem is the subsystem in SG that provides advanced management and control services.

- *Smart protection system*: The smart protection system is the subsystem in SG that provides advanced grid reliability analysis, failure protection, and security and privacy protection services.

Other surveys on SG were done in [3], [17], [29], [41], [42], [90], [97], [211], [247], [251], [254], [267]. Chen *et al.* [41], Yu *et al.* [267], and Hassan and Radman [97] briefly reviewed the basic concepts of SG and some technologies that could be used in SG. The authors of [211], [247] reviewed the existing SG standardizations and gave concrete recommendations for future SG standards. Vasconcelos [251] outlined the potential benefits of smart meters, and provided a short overview of the legal framework governing metering activities and policies in Europe. Brown and Suryanarayanan [29] determined an industry perspective for the smart distribution system and identified those technologies that could be applied in the future research in the smart distribution system. Baumeister [17] presented a review of the works related to SG cyber security. Chen [42] explored the security and privacy issues in SG and related these issues to cyber security in the Internet. Gungor and Lambert [90] explored communication networks for electric system automation and attempted to provide a better understanding of the hybrid network architecture that can provide heterogeneous electric system automation application requirements. Akyol *et al.* [3] analyzed how, where, and what types of wireless communications are suitable for deployment in the electric power system. Wang *et al.* [254] provided a survey on the communication architectures in the power systems, including the communication network compositions, technologies, functions, requirements, and research challenges. They also discussed the network implementation considerations and challenges in the power system settings.

Our survey complements these existing surveys in that we: 1) comprehensively survey the literature till 2011, and systematically classify the works for the smart infrastructure system (energy, information, and communications), the smart management system, and the smart protection system; and 2) outline challenges and future research directions for each of these three major systems. The novelty of this survey is in the classification, volume of information provided, and outlining of future research in these three major systems.

This survey is structured as follows. In Section II, we present an overview of SG. In Section III, we review the legislations, the standards, the projects, the programs, and the trials of SG. We then describe three subsystems of the smart infrastructure system in Sections IV-VI, respectively. We next describe the smart management system and the smart protection system in Sections VII and VIII, respectively. In Section IX, we conclude this survey and present some lessons learned. In addition, refers to Appendix A for the abbreviations used in this survey.

II. What is Smart Grid?

The initial concept of SG started with the idea of advanced metering infrastructure (AMI) with the aim of improving demand-side management and energy efficiency, and constructing self-healing reliable grid protection against malicious sabotage and natural disasters [204]. However, new requirements and demands drove the electricity industries, research organizations, and governments to rethink and expand the initially perceived scope of SG. The U.S. Energy Independence and Security Act of 2007 directed the National Institute of Standards and Technology (NIST) to coordinate the research and development of a framework to achieve interoperability of SG systems and devices. Although a precise and comprehensive definition of SG has not been proposed yet, according to the report from NIST [177], the anticipated benefits and requirements of SG are the following:

1) Improving power reliability and quality;
2) Optimizing facility utilization and averting construction of back-up (peak load) power plants;
3) Enhancing capacity and efficiency of existing electric power networks;
4) Improving resilience to disruption;
5) Enabling predictive maintenance and self-healing responses to system disturbances;
6) Facilitating expanded deployment of renewable energy sources;
7) Accommodating distributed power sources;
8) Automating maintenance and operation;
9) Reducing greenhouse gas emissions by enabling electric vehicles and new power sources;
10) Reducing oil consumption by reducing the need for inefficient generation during peak usage periods;
11) Presenting opportunities to improve grid security;
12) Enabling transition to plug-in electric vehicles and new energy storage options;
13) Increasing consumer choice;
14) Enabling new products, services, and markets.

In order to realize this new grid paradigm, NIST provided a conceptual model (as shown in Fig. 1), which can be used as a reference for the various parts of the electric system where SG standardization works are taking place. This conceptual model divides the SG into seven domains. Each domain encompasses one or more SG *actors*, including devices, systems, or programs that make decisions and exchange information necessary for performing applications. The brief descriptions of the domains and actors are given in Table II. Refer to the appendix of the NIST report [177] for more detailed descriptions. Note that NIST proposed this model from the perspectives of the different roles involved in the SG.

In contrast, our survey, which looks at SG from a technical view point, divides SG into three major systems: smart infrastructure, smart management and smart protection systems.

1) *Smart infrastructure system*: The smart infrastructure system is the energy, information, and communication infrastructure underlying the SG. It supports two-way flow of electricity and information. Note that it is straightforward to understand the concept of "two-way flow of information." "Two-way flow of electricity" implies that the electric energy delivery is not unidirectional anymore. For example, in the traditional power grid, the electricity is generated by the generation plant,

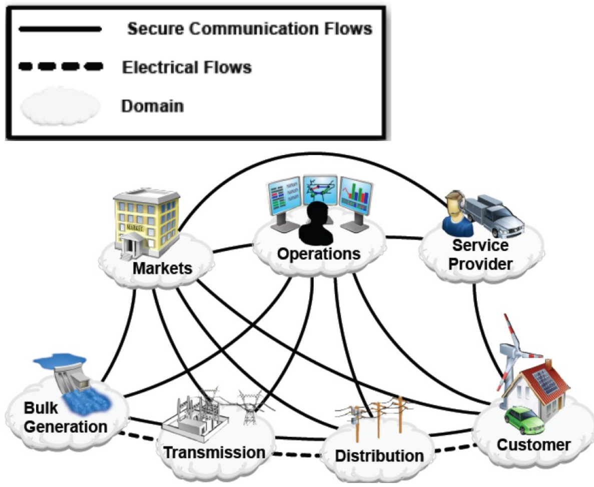

Fig. 1. The NIST Conceptual Model for SG [177]

then moved by the transmission grid, the distribution grid, and finally delivered to users. In an SG, electricity can also be put back into the grid by users. For example, users may be able to generate electricity using solar panels at homes and put it back into the grid, or electric vehicles may provide power to help balance loads by "peak shaving" (sending power back to the grid when demand is high). This backward flow is important. For example, it can be extremely helpful in a microgrid (described in Section IV-D) that has been 'islanded' due to power failures. The microgrid can function, albeit at a reduced level, with the help of the energy fed back by the customers. In this survey, we further divide this smart infrastructure into three subsystems: the *smart energy subsystem*, the *smart information subsystem*, and the *smart communication subsystem*.

- The smart energy subsystem is responsible for advanced electricity generation, delivery, and consumption.
- The smart information subsystem is responsible for advanced information metering, monitoring, and management in the context of the SG.
- The smart communication subsystem is responsible for communication connectivity and information transmission among systems, devices, and applications in the context of the SG.

Note that the reason why we separate information subsystem and communication subsystem is to get a handle on the involved complexity of the SG as a system of systems. This also makes our survey compliant with IEEE P2030 [109] to meet the interoperability requirements. We will briefly describe IEEE P2030 in Section III.

2) *Smart management system*: The smart management system is the subsystem in SG that provides advanced management and control services and functionalities. The key reason why SG can revolutionize the grid is the explosion of functionality based on its smart infrastructure. With the development of new management applications and services that can leverage the technology and capability upgrades enabled by this advanced infrastructure, the grid will keep becoming "smarter." The smart management system takes advantage of the smart infrastructure to pursue various advanced management objectives. Thus far, most of such objectives are related to energy efficiency improvement, supply and demand balance, emission control, operation cost reduction, and utility maximization.

3) *Smart protection system*: The smart protection system is the subsystem in SG that provides advanced grid reliability analysis, failure protection, and security and privacy protection services. By taking advantage of the smart infrastructure, the SG must not only realize a smarter management system, but also provide a smarter protection system which can more effectively and efficiently support failure protection mechanisms, address cyber security issues, and preserve privacy.

TABLE II
DOMAINS AND ACTORS IN THE NIST SG CONCEPTUAL MODEL [177]

Domain	Actors in the Domain
Customers	The end users of electricity. May also generate, store, and manage the use of energy.
Markets	The operators and participants in electricity markets.
Service Providers	The organizations providing services to electrical customers and utilities.
Operations	The managers of the movement of electricity.
Bulk Generation	The generators of electricity in bulk quantities. May also store energy for later distribution.
Transmission	The carriers of bulk electricity over long distances. May also store and generate electricity.
Distribution	The distributors of electricity to and from customers. May also store and generate electricity.

Fig. 2 shows the detailed classification of these three major systems. In this paper, we will describe SG using this classification. We encourage the readers to refer back to this classification in case of any confusion while reading the text.

III. AN OVERVIEW OF LEGISLATIONS, STANDARDS, PROJECTS, PROGRAMS AND TRIALS

In 2001, the U.S. Department of Energy (DOE) began a series of Communications and Controls Workshops focused on the integration of distributed energy resources [146]. The broad view of a transformation to SG was reflected in DOE's GridWise [51], [200]. The U.S. federal government has also established its policy for SG, which is reflected in two Acts of Congress. The first one is the Energy Independence and Security Act of 2007 [239] which specifies studies on the state and security of SG; establishes a federal advisory committee and intergovernment agency task force; frames technology research, development and demonstration; directs the advancement of interoperability; and creates a matching fund program to encourage investment in SG [146]. The second one is the American Recovery and Reinvestment Act of 2009 [240], which includes $3.4 billion in funding for the SG Investment Grant Program and $615 million for the SG Demonstration Program. The result of these programs is expected to lead to a combined investment of over $8 billion in SG capabilities.

Several standardizations have also come up in different areas, countries, or organizations. We list several major SG standardization roadmaps and studies in the following:

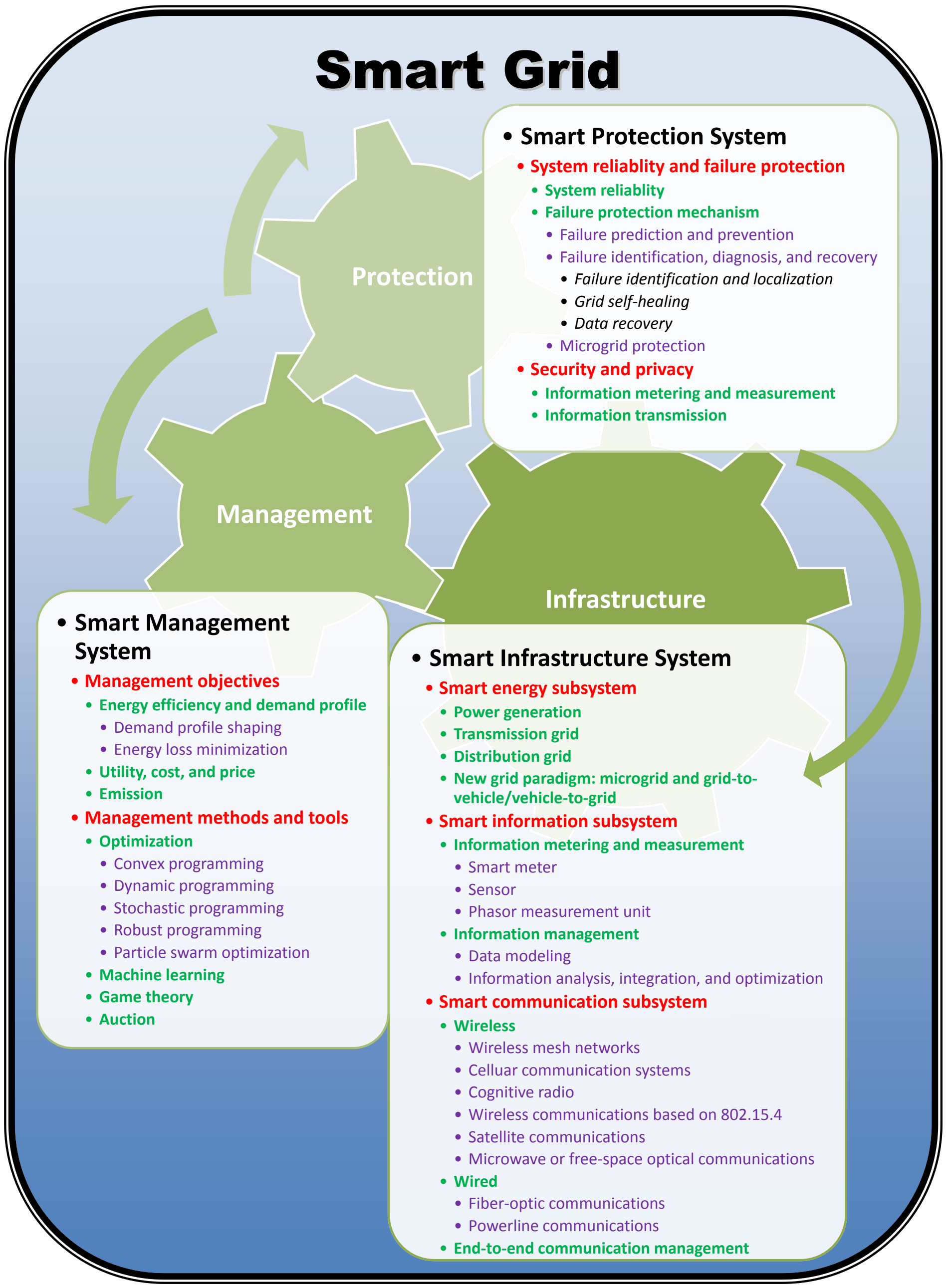

Fig. 2. The Detailed Classification of the Smart Infrastructure System, the Smart Management System, and the Smart Protection System: In Sections IV-VI, we will describe the smart energy subsystem, the smart information subsystem, and the smart communication subsystem, respectively. In Section VII, we will describe the smart management system. In Section VIII, we will describe the smart protection system.

1) United States: NIST IOP Roadmap [177];
2) European Union: Mandate CEN/CENELEC M/441 [67];
3) Germany: BMWi E-Energy Program [187], BDI initiative -Internet der Energie [111];
4) China: SGCC Framework [233];
5) Japan: METI Smart Grid roadmap [118];
6) Korea: Smart Grid Roadmap 2030 [247];
7) IEEE: P2030 [109];
8) IEC SMB: SG 3 Roadmap [227];
9) CIGRE: D2.24 [113];
10) Microsoft: SERA [167].

A detailed study comparing them and an overview of other SG roadmaps (e.g. Austria [209], UK [65], and Spain [75]) can be found in [211], [247]. In order to drive all the dimensions of the future standards of SG, a cooperative standardization roadmap crossing different areas, countries, and organizations is desired. In the meantime, those existing standards may need to be developed and revised to adapt to the changes within technical, political, and regulatory aspects. Considering the importance of IEEE standards, we briefly describe IEEE P2030 [109]. IEEE P2030 focuses on a system level approach to the guidance for interoperability components of communications, power systems, and information technology platforms. SG interoperability provides organizations the ability to communicate effectively and transfer meaningful data, even though they may be using a variety of different information systems over widely different infrastructures,

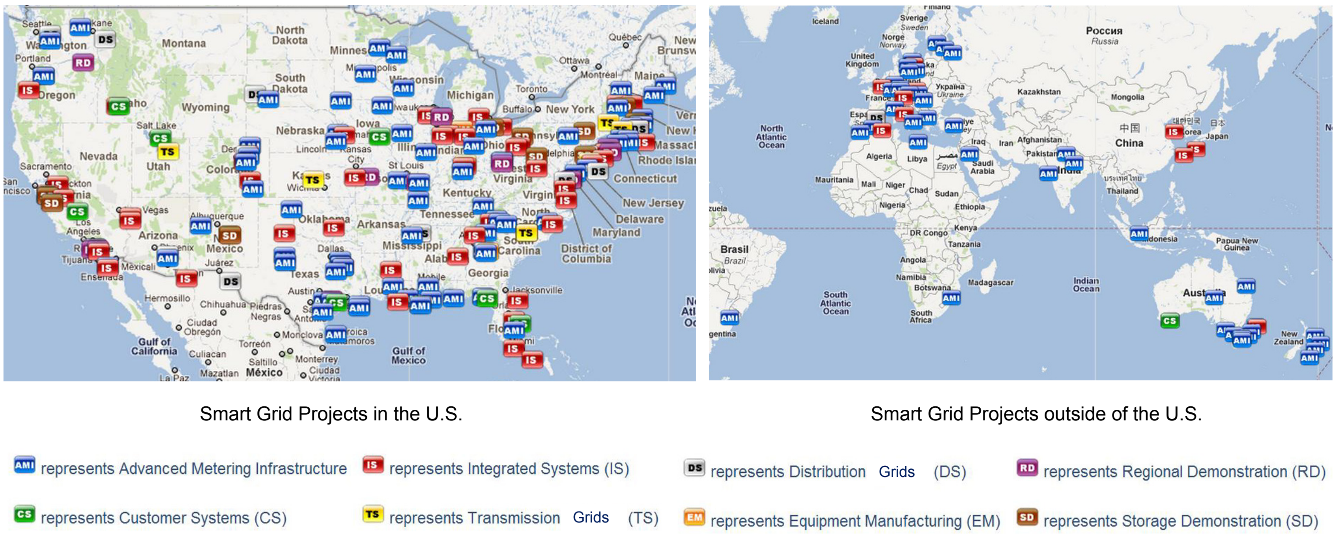

Fig. 3. Smart Grid Project Map [226]

sometimes across different geographic regions and cultures. P2030 views the SG as a large, complex "system of systems" and provides guidance to navigate the numerous SG design pathways throughout the electric power system and end-use applications.

In order to promote the development of SG, governments, academia, industry, and research organizations have put a great deal of effort in pilot projects, programs, and field trials. In order to help the readers assess the recent progress, especially in the industrial sector, we summarize 17 major projects, programs, and trials, shown in Table IV of Appendix B. They cover smart meter, AMI, transmission grid, distribution grid, distributed resource, virtual power plant, home application, microgrid, electric vehicle, and integrated systems. These concepts will be described in the following sections. In addition, in order to give the readers a direct impression, we use Fig. 3 to show the map of the SG projects collected by Smart Grid Information Clearinghouse [226]. This map roughly shows the locations and the objectives of these SG projects. We can observe that in the U.S., Europe, and East Asia, there already exist several integrated system projects, although we are just at the beginning of the SG transition. As pointed out by Giordano *et al.* [84], in almost all countries, a significant amount of investments is devoted to projects which address the integration of different SG technologies and applications. Most of the technologies are known, but their integration is the new challenge.

IV. Smart Infrastructure System I - Smart Energy Subsystem

Two-way flows of electricity and information lay the infrastructure foundation for the SG. The smart infrastructure can be subdivided into the smart energy subsystem, the smart information subsystem, and the smart communication subsystem, respectively. In this section, we explore existing works on the smart energy subsystem and outline some future research directions and challenges.

The traditional power grid is unidirectional in nature [70]. Electricity is often generated at a few central power plants by

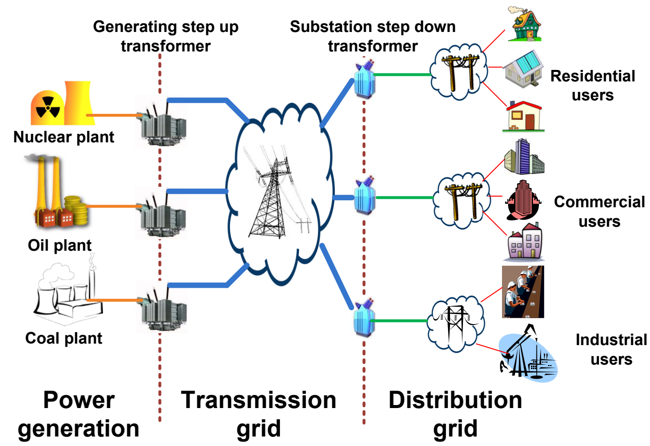

Fig. 4. An Example of the Traditional Power Grid

electromechanical generators, primarily driven by the force of flowing water or heat engines fueled by chemical combustion or nuclear power. In order to take advantage of the economies of scale, the generating plants are usually quite large and located away from heavily populated areas. The generated electric power is stepped up to a higher voltage for transmission on the *transmission grid*. The transmission grid moves the power over long distances to substations. Upon arrival at a substation, the power will be stepped down from the transmission level voltage to a distribution level voltage. As the power exits the substation, it enters the *distribution grid*. Finally, upon arrival at the service location, the power is stepped down again from the distribution voltage to the required service voltage(s). Fig. 4 shows an example of the traditional power grid.

In contrast with the traditional power grid, the electric energy generation and the flow pattern in an SG are more flexible. For example, the distribution grid may also be capable of generating electricity by using solar panels or wind turbines. In this survey, we still divide the energy subsystem into *power generation*, *transmission grid*, and *distribution grid*.

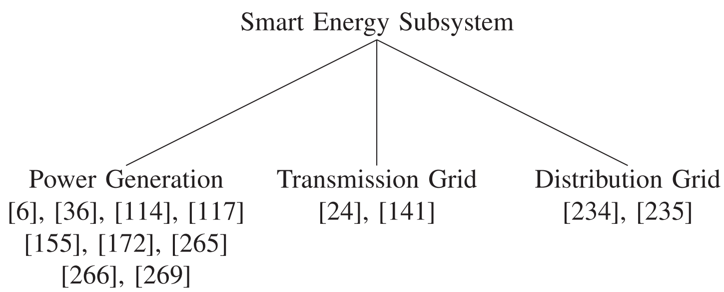

Fig. 5. Classification of the Works on the Smart Energy Subsystem

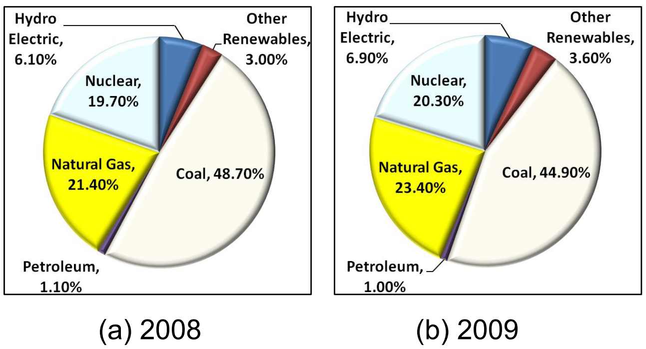

Fig. 6. U.S. Electricity Generation by Source [58]

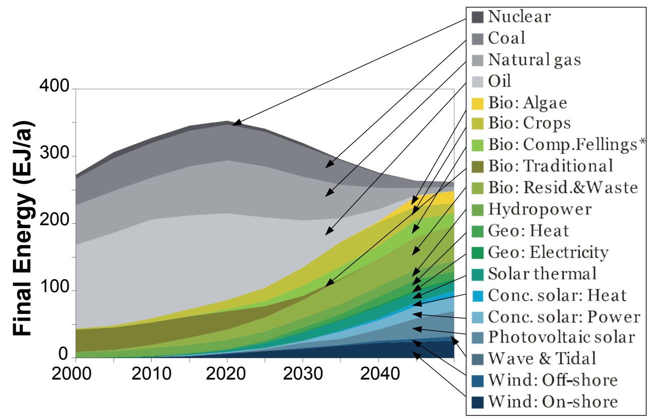

Fig. 7. World Energy Supply by Source [259]

Fig. 5 shows a classification of the works on the smart energy subsystem.

A. Power Generation

Electricity generation is the process of generating electricity from other forms of energy, such as natural gas, coal, nuclear power, the sun, and wind. During the 1820s and early 1830s, British scientist Michael Faraday discovered the fundamental principles of electricity generation: electricity can be generated by the motion of a loop of wire or a disc of copper between the poles of a magnet, a principle still being used today. There are many energy sources used to generate electric power. Fig. 6 shows the U.S. electricity generation by source in 2008 and 2009 [58]. As fossil fuels get depleted and generally get more expensive, it is expected that renewable energy will play a more important role in the future power generation. Fig. 7 shows the predicted world energy supply by source [259].

In contrast to the power generation in the traditional power grid, *smarter* power generation becomes possible as the two-way flows of electricity and information are supported. A key power generation paradigm enabled by SG will be the *distributed generation* (DG). DG takes advantage of *distributed energy resource* (DER) systems (e.g. solar panels and small wind turbines), which are often small-scale power generators (typically in the range of 3 kW to 10,000 kW), in order to improve the power quality and reliability. For example, a microgrid (discussed in Section IV-D), which is a localized grouping of electricity generators and loads, can disconnect from the macrogrid so that distributed generators continue to power the users in this microgrid without obtaining power from outside. Thus, the disturbance in the macrogrid can be isolated and the electric power supply quality is improved. A study [114] from the International Energy Agency pointed out that a power system based on a large number of reliable small DGs can operate with the same reliability and a lower capacity margin than a system of equally reliable large generators. A review of different distributed energy technologies such as microturbines, photovoltaic, fuel cells, and wind power turbines can be found in [269].

However, implementing DG(s) in practice is not an easy proposition due to several reasons. *First*, DG involves large-scale deployments for generation from renewable resources, such as solar and wind, whose yield is, however, subject to wide fluctuations. In general, the generation patterns resulting from these renewables and the electricity demand patterns are far from being equal [172]. Therefore, effective utilization of the DG in a way that is cognizant of the variability of the yield from renewable sources is important. *Second*, the authors of [114], [269] indicated that the usual operation costs of distributed generators for generating one unit of electricity are high compared with that of traditional large-scale central power plants. Considering the DG's potential benefits on power quality, a systematic research on how to balance the high capital costs and the reliable power supplies brought by DG is essential.

Although we can only see a limited penetration of DG in today's power system, the future SG is expected to adopt a large number of distributed generators to form a much more decentralized power system. As predicted in [114], it may evolve from the present system in three stages:

1) Accommodating DGs in the current power system;
2) Introducing a decentralized system of DGs cooperating

with the centralized generation system;

3) Supplying most power by DGs and a limited amount by central generation.

Note that as DG enables the users to deploy their own generators, the large-scale deployment of DG will also change the traditional power grid design methodology, in which the generators are connected to the transmission grid (see Fig. 4).

The development and deployment of DG further leads to a concept, namely *Virtual Power Plant* (VPP), which manages a large group of distributed generators with a total capacity comparable to that of a conventional power plant [172]. This cluster of distributed generators is collectively run by a central controller. The concerted operational mode delivers extra benefits such as the ability to deliver peak load electricity or load-aware power generation at short notice. Such a VPP can replace a conventional power plant while providing higher efficiency and more flexibility. Note that more flexibility allows the system to react better to fluctuations. However, a VPP is also a complex system requiring a complicated optimization, control, and secure communication methodology.

Traditional VPPs are studied in [6], [36], [155], [265], [266]. Anderson *et al.* [6] aimed to find and describe a suitable software framework that can be used to help implement the concept of a VPP in future power systems, and emphasized the importance of Service Oriented Architecture in implementing the VPP. Caldon *et al.* [36] proposed a cost based optimization procedure for harmonizing the concurrent operation of distribution system operator and VPP which, although acting in an independent manner, can be coordinated by means of suitable economic signals. Lombardi *et al.* [155] focused on the optimization of the structure of the VPP. By using an energy management system, a VPP can be controlled in order to minimize the electricity production costs and to avoid the loss of renewable energy. You *et al.* [265] proposed a market-based VPP, which uses bidding and price signal as two optional operations, and provides individual distributed energy resource units with the access to current electricity markets. You *et al.* [266] proposed a generic VPP model running under liberalized electricity market environment, and attempted to provide an outline of the main functions that are necessary for the efficient operation of this generic VPP.

In addition, recently the integration of Vehicle-to-Grid (V2G) technology (explained in Section IV-D) and VPP was investigated in [117], which outlined an architecture of V2G integrating VPP, provided a sketch of the trip-prediction algorithm, and the associated optimization problem for the overall system architecture.

Similar ideas of "virtual" have also been used for other applications, such as virtual energy buffers [245] and virtual energy provisioning systems [119].

B. Transmission Grid

On the power transmission side, factors such as infrastructure challenges (increasing load demands and quickly aging components) and innovative technologies (new materials, advanced power electronics, and communication technologies) drive the development of smart transmission grids. As stated in [141], the smart transmission grid can be regarded as an integrated system that functionally consists of three interactive components: *smart control centers*, *smart power transmission networks*, and *smart substations*.

Based on the existing control centers, the future smart control centers enable many new features, such as analytical capabilities for analysis, monitoring, and visualization.

The smart power transmission networks are conceptually built on the existing electric transmission infrastructure. However, the emergence of new technologies (e.g new materials, electronics, sensing, communication, computing, and signal processing) can help improve the power utilization, power quality, and system security and reliability, thus drive the development of a new framework architecture for transmission networks.

The vision of the smart substation is built on the existing comprehensive automation technologies of substations. Although the basic configurations of high-voltage substations have not changed much over the years, the monitoring, measurement, and control equipment have undergone a sea change in recent years [24]. Major characteristics of a smart substation shall include digitalization, autonomization, coordination, and self-healing. By supporting these features, a smart substation is able to respond rapidly and provide increased operator safety.

In brief, with a common digitalized platform, in the smart transmission grid it is possible to enable more flexibility in control and operation, allow for embedded intelligence, and foster the resilience and sustainability of the grid.

C. Distribution Grid

For the distribution grid, the most important problem is how to deliver power to serve the end users better. However, as many distributed generators will be integrated into the smart distributed grid, this, on one hand, will increase the system flexibility for power generation, and on the other hand, also makes the power flow control much more complicated, in turn, necessitating the investigation of smarter power distribution and delivery mechanisms.

An interesting research work was done by Takuno *et al.* [235]. Takuno *et al.* proposed two in-home power distribution systems, in which the information is added to the electric power itself and electricity is distributed according to this information. The first one is a circuit switching system based on alternating current (AC) power distribution, and the other is a direct current (DC) power dispatching system via power packets. Note that the packetization of energy is an interesting but challenging task since it requires high power switching devices. Researchers have shown that silicon carbide junction gate field-effect transistors are able to shape electric energy packets [234]. Hence, the system proposed in [235] has the potential as an intelligent power router. More specifically, supplied electricity from energy sources is divided into several units of payload. A header and a footer are attached to the unit to form an electric energy packet. When the router receives packets, they are sorted according to the addresses in the headers and then sent to the corresponding loads. Using energy packet, providing power is easily regulated by controlling the number of sent packets. In addition, many in-home electric devices are driven by DC power and have built-in power conversion circuits to commutate AC input voltage. Thus, DC-based power distribution is feasible. These systems will make in-home power distribution systems more efficient and easier to control energy flow.

D. Some New Grid Paradigms

In this subsection, we describe two of the most important new grid paradigms, which benefit from smart energy subsystem technologies and also further promote the development of SG. These two paradigms are widely regarded as important components of the future SG. Note that these two paradigms also take advantage of other SG technologies as we will explain in the corresponding sections.

1) Microgrid: Distributed generation promotes the development of a new grid paradigm, called *microgrid*, which is seen as one of the cornerstones of the future SG [68]. The organic evolution of the SG is expected to come through the plug-and-play integration of microgrids [70]. A microgrid is a localized grouping of electricity generations, energy storages, and loads. In the normal operation, it is connected to a traditional power grid (macrogrid). The users in a microgrid can generate low voltage electricity using distributed generation, such as solar panels, wind turbines, and fuel cells. The single point of common coupling with the macrogrid can be disconnected, with the microgrid functioning autonomously [122]. This operation will result in an *islanded* microgrid, in which distributed generators continue to power the users in this microgrid without obtaining power from the electric utility located in the macrogrid. Fig. 8 shows an example of the microgrid. Thus, the multiple distributed generators and the ability to isolate the microgrid from a larger network in disturbance will provide highly reliable electricity supply. This intentional islanding of generations and loads has the potential to provide a higher local reliability than that provided by the power system as a whole [136]. Note that although these users do not obtain the power from outside in the islanding mode, they may still exchange some information with the macrogrid. For instance, they may want to know the status of the macrogrid and decide whether they should reconnect to the macrogrid and obtain power from the electric utility.

Lasseter [135] also pointed out that using microgrids in the distribution system is straightforward and also simplifies the implementation of many SG functions. This includes improved reliability, high penetration of renewable sources, self-healing, active load control, and improved efficiencies. For example, in order to realize self-healing during outages, microgrids can switch to the islanding mode and as a result the users in microgrids will not be affected by outages.

2) G2V and V2G: An electric vehicle is a vehicle that uses one or more electric motors for propulsion. As fossil fuels diminish and generally get more expensive, fully electric vehicles or plug-in hybrid electric vehicles will rise in popularity. In the following, we use EV to represent both fully electric vehicle and plug-in hybrid electric vehicle. The wide use and deployment of EVs leads to two concepts, namely *Grid-to-Vehicle (G2V)* and *Vehicle-to-Grid (V2G)*.

In **G2V**, EVs are often powered by stored electricity originally from an external power source, and thus need to be charged after the batteries deplete. This technology is conceptually simple. However, from the perspective of the grid, one of the most important issues in G2V is that the charging operation leads to a significant new load on the existing distribution grids. In the literature, many works have studied the impact of EVs on the power grid.

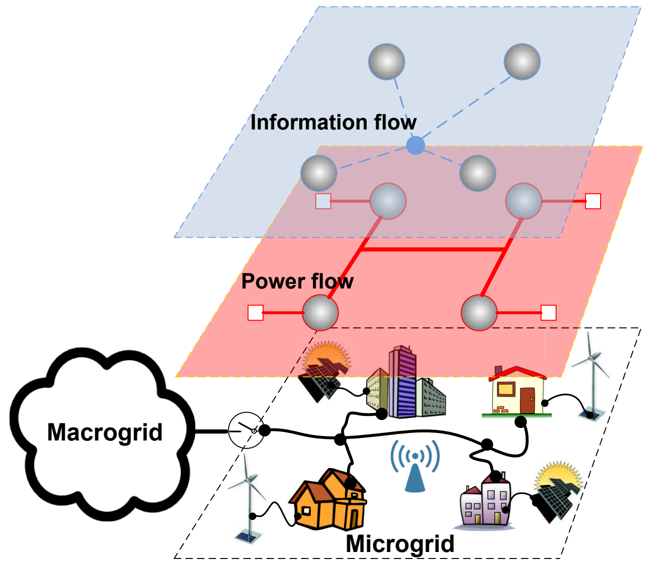

Fig. 8. An Example of a Microgrid: The lower layer shows a physical structure of this microgrid, including four buildings, two wind generators, two solar panel generators, and one wireless access point (AP). These buildings and generators exchange power using powerlines. They exchange information via an AP-based wireless network. The blue (top) layer shows the information flow within this microgrid and the red (middle) layer shows the power flow.

Schneider *et al.* [224] pointed out that the existing distribution grid infrastructure in the Pacific Northwest is capable of supporting a 50% penetration of EVs with the 120V smart-charging profile, which equates to approximately 21.6% of the light duty vehicle fleet. This level of penetration exceeds the known capability of the existing generation resources, which is approximately 18%. The authors of [92], [210], [228] further pointed out that serious problems (e.g.significant degradation of power system performance and efficiency, and even overloading) can arise under high penetration levels of uncoordinated charging.

One solution to mitigate the impact of EVs on the grid is to optimize their charging profile. In other words, we need to keep the peak power demand as small as possible, taking into account the extra power consumption from the vehicle charging. This can be done by coordinating the charging operations of different EVs so that they are not charged at the same time. For example, Clement *et al.* [48] show that the coordinated charging of EVs can improve power losses and voltage deviations by flattening out peak power.

In **V2G**, EVs provide a new way to store and supply electric power. V2G-enabled EVs can communicate with the grid to deliver electricity into the grid, *when they are parked and connected to the grid.* Note that as reported by Kempton *et al.* [127], in the U.S. the car is driven only one hour a day on average. In other words, these cars are parked most of the time doing nothing. There exist three major delivery setups:

1) A hybrid or fuel cell vehicle, which generates power

from storable fuel, uses its generator to produce power for a utility at peak electricity usage times. These vehicles serve as a distributed generation system producing energy from conventional fossil fuels or hydrogen.

2) A battery-powered or plug-in hybrid vehicle uses its excess rechargeable battery capacity to supply power for a utility at peak electricity usage times. These vehicles can then be recharged during off-peak hours at cheaper rates. These vehicles serve as a distributed battery storage system to store power.
3) A solar vehicle which uses its excess charging capacity to provide power to the power grid when the battery is fully charged. These vehicles serve as a distributed small renewable energy power system.

Thus far, researchers have focused on the connection between batteries and the power grid [126], [244], the validity of the V2G system [123], the feasible service [244], its environmental and economic benefits [186], its new markets [125], [124], and system integration [258]. Utilities currently also have V2G technology trials. For example, Pacific Gas and Electric Company tried to convert a number of company-owned Toyota Prius to V2G plug-in hybrids at Google's campus [28]. Xcel Energy performed the nation's first large test of V2G-enabled EVs in Boulder, Colorado, as part of its internationally recognized SmartGridCity project [260].

Note that G2V and V2G are not fully separated concepts in the vision of SG. For example, V2G-enabled EVs are often used to provide power to help balance loads by "peak shaving" (sending power back to the grid when demand is high) but also "valley filling" (charging when demand is low). Therefore, a key question is how to determine the appropriate charge and discharge times throughout the day. Hutson *et al.* [107] studied this problem and used a binary particle swarm optimization algorithm to look for optimal solutions that maximize profits to vehicle owners while satisfying system and vehicle owners' constraints. Note that particle swarm optimization is an iterative stochastic optimization algorithm. The solution search is performed in a stochastic nature allowing the algorithm to overcome nonlinear, non-differentiable, and discontinuous problems.

E. Summary and Future Research

In this subsection, we have reviewed the works on the smart energy subsystem, more specifically, power generation, transmission, and distribution. We have also described two new grid paradigms: microgrid and G2V/V2G. In the following, we list several research challenges and possible future research worth exploring.

1) **Effective utilization of intermittent and fluctuant renewables**: It is believed that distributed renewable energy generation will be widely used in SG. However, the utilization of distributed renewable energy resources also poses many challenges and opens up many new research topics.

The key problem is how to model renewable energy source. The intermittent and fluctuant nature of wind and solar generation requires much more complicated forecasting and scheduling. Both long-term and short-term renewable source patterns and likely behavior must be understood and explored [198].

For example, He *et al.* [100] divided a 24-hour period into M slots of length T_1 each; and each T_1-slot, in turn, consists of K slots, each of length T_2. The wind generation can be modeled as a non-stationary Gaussian random process across the T_1-slots, i.e., the wind generation amount in the kth T_2-slot of the mth T_1-slot follows $N(\theta, \sigma^2)$, where N is the Gaussian distribution, θ is the mean, and σ^2 is the variance. In addition, finite-state Markov models have also been used as an effective approach to characterize the correlation structure of the renewable energy outputs [66], [181]. Since we may not fully observe the system transition state, hidden Markov models are also used in modeling renewable energy systems [32], [33], [175], [230]. Considering that in practice the power pattern of renewable resources may not follow any simple distribution or Markov process, Fang *et al.* [69] further used non-stochastic multi-armed bandit online learning technique to learn the evolution of power pattern of renewable energy source. Note that online learning is a model of induction that learns the label of one instance at a time. The goal in online learning is to predict labels for instances. A typical application could be that the instances are able to describe the current conditions of the renewable sources, and an online algorithm predicts tomorrow's value of a particular source. In summary, in order to effectively utilize the renewable energy, more thorough mathematical analysis on modeling renewable energy is desirable.

Another possible research topic is the optimal deployment of the additional ancillary services (e.g. energy reserves) to maintain reliability and meet operational requirements, taking into account the uncertainty and variability of renewable energy resources.

2) **Utilization of G2V/V2G:**

In G2V, the challenge is that vehicle charging will lead to a significant new load on the existing distribution grids, with many of these circuits not having any spare capacity. In V2G, the challenge is the availability of EVs, since an EV can only deliver power to the grid when it is parked and connected to grid. As a result, this increases the uncertainty of the power supplied by EVs.

It is easy to see that the above two challenges lead to an urgent need for an analysis of large-scale EV stochastic behavior. More specifically, we can use probability theory or experiments to model the power request profile for a large number of EVs charging operations, and the total available power profile provided by a large number of EVs. Although we cannot accurately predict the behavior of each EV, it is very likely that over a large dataset, the overall profile must follow some distribution. Let us recall the normal distribution, one of the most famous distributions. According to the central limit theorem [63], the mean of a sufficiently large number of independent random variables, each with finite mean and variance, follows the normal distribution. This analysis can help the operator pre-design the system capacity margins.

In addition, queueing theory [87] could also play an important role in G2V analysis. Assume that an EV charging station works as a queue, i.e., serving EVs sequentially. Queueing theory [87] enables mathematical analysis of several related processes, including arrival of EVs at the queue, waiting in the queue for being served, and being served at the front of the queue. Thus, we can predict the expected number of EVs waiting or receiving service, and the probability of encountering the charging system in certain states, such as empty, full, having an available server, or having to wait a certain amount of time to be served.

3) **Challenges in large-scale deployment**: A deployed large-scale commercial SG may have tens of millions of nodes. So far we have little experience in large-scale distributed control approaches to addressing the complex power system component interactions, and in large-scale deployment of new technologies, such as batteries, thermal storages, DGs, and EVs [146]. This challenge requires us to think about how to organize so many devices in a large-scale SG. Two approaches may be applicable: *top-down* and *bottom-up*.

In the top-down approach, the high-level framework of the system is formulated by a powerful grid operator, and each subsystem is then refined in greater details. For example, a group of users in a microgrid can refine their own connection structure based on the high-level framework defined by an upper supervisor. However, this approach needs a powerful operator to initially design the whole architecture, which is not an easy task.

The bottom-up approach is the piecing together of systems to give rise to grander systems. For example, a group of users first link together to form a system. Then these systems link together to form a larger system. Although this methodology does not need a powerful operator to initially design the whole architecture, the final system grows up from many individually formed subsystems. Therefore, the performance of the whole system may not be good enough.

The advantages and disadvantages of both top-down and bottom-up approaches need to be investigated. Furthermore, self-organization is a topic worth exploring. For example, in the bottom-up approach, one question is how a group of users or devices can be self-organized to form a system.

In addition, open, scalable, and instructive standards will play an important role in the large-scale deployment of SG. Let us take the IEEE P2030 guide for SG interoperability [109] as an example. Using a system of systems approach, this guide defines three perspectives: power systems, information technology, and communications. Moreover, these interoperability architectural perspectives are comprised of domains, entities, interfaces, and data flows. The domains are the same as the seven domains mentioned in Section II. Entities (devices, communication networks, computer systems, software programs, etc.) are generally located inside a domain and are connected to each other through one or more interfaces. Interfaces are logical connections from one entity to another that support one or more data flows implemented with one or more data links. These data flows are application-level communications from entities that provide data to entities that consume data.

This guide does not specify which particular technology should be used. Instead, it aims to establish both entities and relationships within the environment of the SG and define interfaces in a technology-agnostic manner. For example, it defines 20 entities and 81 interfaces among the major entities in each of the domains. The methodology of this guide is applicable to all SG implementations. It is general enough to allow the implementation of newer technologies and changing conditions in the utility's operational environment. This methodology is of great importance for the large-scale deployment and interoperability of the SG. For example, each entity can design its own implementation. As long as its implementation follows the standards, the whole system will work. In other words, the large-scale deployment task is hence divided into several small basic tasks, while these small tasks can be coordinated based on the well-defined interfaces and relationships. Different functions of SG can be realized by using different combinations of basic tasks. [109] shows several such examples. In this way, the complexity of building a large-scale SG is significantly reduced. Therefore, designing a highly scalable, open, and instructive standard is of great importance, albeit difficult.

V. Smart Infrastructure System II - Smart Information Subsystem

The evolution of SG relies on not only the advancement of power equipment technology, but also the improvement of sophisticated computer monitoring, analysis, optimization, and control from exclusively central utility locations to the distribution and transmission grids. Many of the concerns of distributed automation should be addressed from an information technology perspective, such as interoperability of data exchanges and integration with existing and future devices, systems, and applications [109]. Therefore, a smart information subsystem is used to support information generation, modeling, integration, analysis, and optimization in the context of the SG.

In this section, we concentrate on the smart information subsystem. We first explore the information metering and measurement, which generates information from end entities (e.g. smarter meters, sensors, and phasor measurement units) in an SG. This information is often used for billing, grid status monitoring, and user appliance control. We then explore the information management, including data modeling, information analysis, integration, and optimization. We finally outline some future research directions and challenges.

A. Information Metering and Measurement

Study in information metering and measurement can be classified into smart metering, and smart monitoring and measurement as shown in Fig. 9. In the following, we describe this classification in detail.

1) Smart Metering: Smart metering is the most important mechanism used in the SG for obtaining information from end users' devices and appliances, while also controlling the behavior of the devices. *Automatic metering infrastructure* (AMI) systems [96], which are themselves built upon *automatic meter reading* (AMR) systems [208], are widely regarded as a logical strategy to realize SG. AMR is the technology of automatically collecting diagnostic, consumption, and status data from energy metering devices and transferring that data to a central database for billing, troubleshooting, and analyzing. AMI differs from traditional AMR in that it enables two-way communications with the meter. Therefore nearly all of this information is available in real time and on demand,

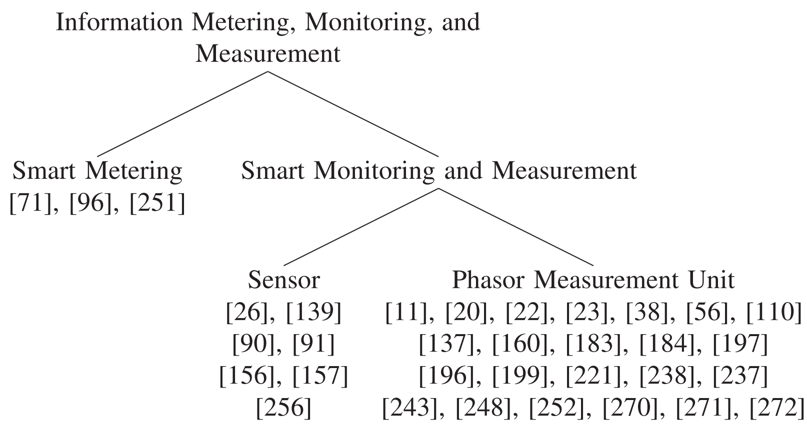

Fig. 9. Classification of the Works on the Information Metering and Measurement

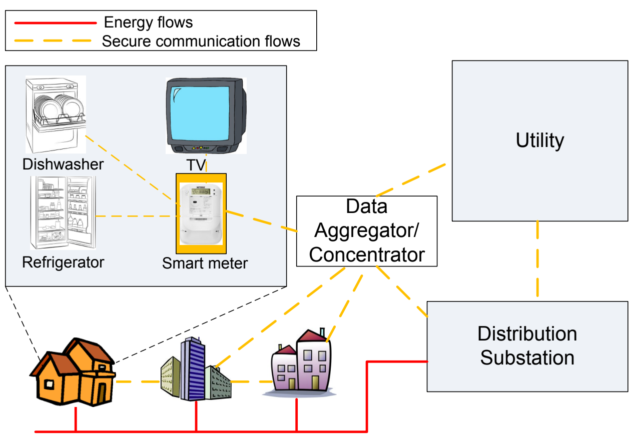

Fig. 10. An Example of the Smart Metering Structure: The smart meter collects the power consumption information of the dishwasher, TV, and the refrigerator, and also sends the control commands to them if necessary. The data generated by the smart meters in different buildings is transmitted to a data aggregator. This aggregator could be an access point or gateway. This data can be further routed to the electric utility or the distribution substation. Note that the smart communication subsystem, described in Section VI, is responsible for the information transmission.

allowing for improved system operations and customer power demand management.

Smart meters, which support two-way communications between the meter and the central system, are similar in many aspects to AMI meters, or sometimes are regarded as part of the AMI. A smart meter is usually an electrical meter that records consumption in intervals of an hour or less and sends that information at least daily back to the utility for monitoring and billing purposes [71]. Also, a smart meter has the ability to disconnect-reconnect remotely and control the user appliances and devices to manage loads and demands within the future "smart-buildings." Fig. 10 shows a typical usage scenario for smart meters.

From a consumer's perspective, smart metering offers a number of potential benefits. For example, end users are able to estimate bills and thus manage their energy consumptions to reduce bills. From a utility's perspective, they can use smart meters to realize real-time pricing, which tries to encourage users to reduce their demands in peak load periods, or to optimize power flows according to the information sent from demand sides.

2) Smart Monitoring and Measurement: An important function in the vision of SG is monitoring and measurement of grid status. We review the following two major monitoring and measurement approaches, namely *sensors* and *phasor measurement units*.

Sensors: Sensors or sensor networks have already been used as a monitoring and measurement approach for different purposes [1]. In order to detect mechanical failures in power grids such as conductor failures, tower collapses, hot spots, and extreme mechanical conditions, Leon *et al.* [139] proposed that sensor networks should be embedded into the power grid and help to assess the real-time mechanical and electrical conditions of transmission lines, obtain a complete physical and electrical picture of the power system in real time, diagnose imminent as well as permanent faults, and determine appropriate control measures that could be automatically taken and/or suggested to the system operators once an extreme mechanical condition appears in a transmission line.

Wireless sensor networks (WSNs) in particular, given their low cost, can provide a feasible and cost-effective sensing and communication platform for remote system monitoring and diagnosis. Gungor *et al.* [91] reviewed the application of WSNs for electric power systems along with their opportunities and challenges and presented a comprehensive experimental study in different electric power system environments. They concluded that with the help of WSN, a single system contingency in the power grid could be detected and isolated before it causes cascading effects and leads to more catastrophic system-wide breakdowns.

Other research works on applying WSNs for SG are [26], [156], [157]. Bressan *et al.* [26] explored the implementation of a smart monitoring system over a WSN, with particular emphasis on the creation of a solid routing infrastructure using the routing protocol for low-power and lossy networks, whose definition is currently being discussed within the IETF ROLL working group. Lu *et al.* [156] proposed a closed-loop energy management scheme with a WSN, which was applied as the architecture of an industrial plant energy management system. The importance of the proposed scheme lies in its nonintrusive, intelligent, and low cost nature. Later, Lu *et al.* [157] extended the previous work [156], and studied the overall system architecture.

However, the use of sensor networks in the SG has many requirements: [90], [91], [256]:

1) *Quality-of-Service (QoS) requirements*: The information generated by sensor networks may be associated with some data QoS requirements, such as reliability, latency, and network throughput. For example, the critical sensed data related to grid failures should be received by the controller in a timely manner. The communication subsystem (described in Section VI) supporting sensor networks must provide mechanisms to satisfy these QoS requirements.
2) *Resource constraints*: Sensor nodes are often low cost and resource limited devices. Thus the control programs for sensor networks should be energy efficient.
3) *Remote maintenance and configuration*: Sensors must be remotely accessible and configurable, so that the sensor networks could be maintained remotely, conveniently, and promptly.
4) *High security requirements*: Security is very important for electric power systems. By compromising sensors, attackers can jeopardize the power grid operation.
5) *Harsh environmental conditions*: In SG environments, sensors may be subject to radio frequency (RF) interference, highly caustic or corrosive environments, high humidity levels, vibrations, dirt and dust, or other conditions that may cause a portion of sensor nodes to malfunction. Hence sensor network design must consider the survivability requirement, i.e., the sensor network is still connected or the critical areas are still monitored if some sensors fail.

Phasor Measurement Unit: Recent developments in the SG have spawned interest in the use of *phasor measurement units* (PMUs) to help create a reliable power transmission and distribution infrastructure [11]. A PMU measures the electrical waves on an electrical grid to determine the health of the system. Technically speaking, a phasor is a complex number that represents both the magnitude and phase angle of the sine waves found in electricity. Phasor measurements that occur at the same time are called *synchrophasor*, as are the PMU devices that allow their measurement. Typically, PMU readings are obtained from widely dispersed locations in a power system network and synchronized using the global positioning system (GPS) radio clock. With a large number of PMUs and the ability to compare shapes from alternating current (AC) readings everywhere on the grid, system operators can use the sampled data to measure the state of the power system and respond to system conditions in a rapid and dynamic fashion. Refer to [56] for a technical introduction to the PMU.

Phasor measurements using GPS based time synchronization were introduced in the mid-1980s [22], [197], [196], [252]. A Virginia Tech research team developed the first prototype PMU in 1988 [271]. Later, the frequency monitoring network (FNET) project utilized a network of low-cost, high-precision frequency disturbance recorders to collect synchrophasor data from the U.S. power grid [184]. Recently Zhang *et al.* [271] presented some of the latest implementations of FNET's applications by using PMUs, which are significantly better at observing power system problems than the earlier implementations. The current FNET system hierarchy is suitable for high volume data transfer, processing, storage, and utilization. A variety of applications, especially with regards to real-time dynamic monitoring, have been developed and integrated into the system. FNET is growing into a mature, multifunctional, and low-cost phasor measurement system with stable performance and high accuracy.

Early research on the applications of PMU technology was mainly focused on validation of system models and accurate postmortem analysis. However, now with wide-scale real-time PMU data being obtainable, system operators have the capability of deploying system state estimation procedures and system protection functionalities in power grids, with the goal of making the power system immune to catastrophic failures. Several countries, such as Brazil, China, France, Japan, South Korea, Mexico, Norway, and the U.S., have installed PMUs on their power grid systems for research or are developing prototypes [270]. The installation of PMUs on transmission grids of most major power systems has become an important activity.

In addition, the investigation of PMUs is an exciting area being explored by both industry and academia. Industry is investigating how to install the PMUs, collect the data, and establish communication transfers of this data to the utility control centers [110], [183]. In academia, typical research fields are the applications of PMU for grid protection functions, such as providing loss-of-mains protection [137], monitoring fault event [221], [237], [238], [243], [272], locating disturbance [160], estimating grid state [199], [248], studying synchronous islanded operation [20], monitoring power quality [38], and devising experimental applications for the monitoring of active distribution grids [23].

B. Information Management

In SG, a large amount of data and information will be generated from metering, sensing, monitoring, etc. SG must support advanced information management. The task of the information management is data modeling, information analysis, integration, and optimization.

1) Data Modeling: As stated by IEEE P2030 [109], the goal of SG information technology data modeling is to provide a guide to creating persistent, displayable, compatible, transferable, and editable data representation for use within the emerging SG. In other words, the objective is to make it as interoperable as possible using relevant standards. That is specifically addressing the data that represents state information about the grid and individual items in it. This would include nearly all connected items from generation down to individual consuming devices. They all have state information that may need to be read, stored, transmitted, etc.

Why is data modeling important? Let us look at the following two reasons. First, the information exchange between two application elements is meaningful only when both of them can use the information exchanged to perform their respective tasks. Therefore, the structure and meaning of the exchanged information must be understood by both application elements. Although within the context of a single application, developers can strive to make the meaning clear in various user interfaces, when data is transferred to another context (another system), the meaning could be lost due to incompatible data representation. Considering that the SG is a complicated system of systems, design of a generally effective data representation is very important.

Second, the data modeling is also related to the system forward compatibility and backward compatibility. On one hand, a well-defined data model should make legacy program adjustments easier. We hope that the data representation designed for SG can also be (or at least partially) understood by the current power system, in order to take advantage of the existing infrastructure as much as possible. On the other hand, thus far SG is more like a vision. Its definition and functionality keep evolving. Suppose that in the current implementation, all the data is particularly designed to be stored in an optimized way that can be understood by a current application *X*. After some time, a new application *Y* is integrated into SG. Data modeling is the key to whether this new application can understand the historical data and obtain enough information from the historical data.

IEEE P2030 [109] pointed out that ontology may be a good option, because it is becoming an increasingly popular way of providing a data model with formal semantics based on a shared understanding that is machine-readable. Ontology helps convey knowledge in a formal fashion, just like a programming language conveys mathematics in a formal fashion. With ontology, one speaks of concepts in a subject area, and relationships between them. Like a programming language, it helps define, clarify, and standardize what is being discussed. Another reason that ontology-based strategies are commonly used with success in creating and manipulating data models is that they provide easy export or translation to Extensible Markup Language (XML) or Unified Modeling Language (UML), which provides for a great deal of information interoperability.

2) Information Analysis, Integration, and Optimization: Information analysis is needed to support the processing, interpretation, and correlation of the flood of new grid observations, since the widely deployed metering and monitoring systems in SG will generate a large amount of data for the utility. As mentioned in [109], one part of the analytics would be performed by existing applications, and another part of the analytics dimension is with new applications and the ability of engineers to use a workbench to create their customized analytics dashboard in a self-service model.

Information integration aims at the merging of information from disparate sources with differing conceptual, contextual, and typographical representations. In SG, a large amount of information has to be integrated. **First**, the data generated by new components enabled in SG may be integrated into the existing applications, and metadata stored in legacy systems may also be used by new applications in SG to provide new interpretations. IEEE P2030 [109] indicated that data integrity and name services must be considered in information integration. Data integrity includes verification and cross-correlation of information for validity, and designation of authoritative sources. Name service addresses the common issue of an asset having multiple names in multiple systems.

Second, as stated in [115], [212], currently most utility companies have limited installed capability for integration across the applications associated with system planning, power delivery, and customer operations. In most cases, this information in each department is not easily accessible by applications and users in other departments or organizations. These "islands of information" correspond to islands of autonomous business activities. Therefore, the emerging SG calls for enterprise-level integration of these islands to improve and optimize information utilization throughout the organization.

Information optimization is used to improve information effectiveness. The data size in the future SG is expected to be fairly large as a result of the large-scale monitoring, sensing, and measurement. However, the generated data may have a large amount of redundant or useless data. Therefore, we need to use advanced information technology to improve the information effectiveness, in order to reduce communication burden and store only useful information. This problem has been studied, among others, by [180], [257]. In order to compress the size of disturbance signals and reduce sinusoidal and white noise in the signals, Ning *et al.* [180] proposed a wavelet-based data compression approach for SG. The proposed method can be implemented in SG to mitigate data congestion and improve data transmission and quality. Wang *et al.* [257] applied the singular value decomposition analysis to examine the coupling structure of an electrical power grid in order to highlight opportunities for reducing the network traffic, by identifying what are the salient data that need to be communicated between parts of the infrastructure to apply a control action. They found that typical grid admittance matrices have singular values and vectors with only a small number of strong components.

C. Summary and Future Research

In this section, we reviewed the works on the smart information subsystem, especially information metering, measurement, and management in SG. We list the following challenges and possible directions worth exploring.

1) **Effective information store:** A large amount of information, such as the data from smart meters, sensors, and PMUs, will be sampled in SG, and sent to the control system. One important problem is what information should be stored in the control system so that meaningful system or user history can be constructed from this data. Note that system history is important for analyzing system operations, and user history is important for analyzing user behaviors and bills. Considering that the amount of information received by the control system is huge, solving this problem is challenging.

We suggest using data mining, machine learning, and information retrieval techniques to analyze the information and thus obtain the representative data. Furthermore, the correlation among some data may be high. For example, the smart meter readings must be similar when no activity takes place at home. This opens a door for significantly reducing the amount of information needed to store by using data compression. In addition, database tools should be used to organize, store, and retrieve this data.

2) **The utilization of cloud computing:** Cloud computing has been envisioned as the next-generation computing paradigm for its major advantages in on-demand self-service, ubiquitous network access, location independent resource pooling, and transference of risk [99]. The basic idea of cloud computing is that the cloud providers, who operate large data centers with massive computation and storage capacities, deliver computing as a service, whereby shared resources, software and information are provided to computers and other devices as a utility over a network. Integrating cloud computing may improve the information management in SG.

First, since cloud providers have massive computation and storage capacities, they can design some basic and generic information management services for electric utilities. Therefore, electric utilities can focus on more advanced and complicated information management functions, while outsourcing the basic and generic information management functions to the cloud. As a result, electric utilities do not have to develop the information management functions from scratch. This is especially useful for small utilities or even personal users who provide power service. Let us consider an example. Since distributed renewable generations are expected to be widely used in the emerging SG, a user equipped with a distributed renewable generator may want to sell his excess energy to other users nearby. This user can outsource the basic information storage and management to the cloud, and thus has no need to design his own information management system.

Second, cloud computing may be able to improve the information integration level in SG. For example, as mentioned before in most cases, the information in each department is not easily accessible by applications and users in other departments or organizations. These "islands of information" correspond to islands of autonomous business activities. If all the information is stored and managed by a cloud, it actually provides a relatively cost-effective way to integrate these islands of information. As stated by Rusitschka *et al.* in [215], the ease-of-interfacing with the cloud has the potential to create usable de facto standards while enabling interoperability and extensibility.

Although using cloud computing may improve the information management in SG, it also poses many challenges. First, information security and privacy must be the major concern of electric utilities, since the information storage and management is out of the control of electric utilities. Rusitschka *et al.* [215] discussed the confidentiality and privacy issues, and proposed some solutions, including designing multi-tenant data architectures, and applying pseudonymization or cryptographic hashes. Second, it is unlikely that an electric utility outsources all the information management functions to the cloud. Therefore, we ask two questions:

1) From the cloud provider's perspective, which information management services should be provided to maximize its own profit?
2) From the electric utility' perspective, which information management functions should be outsourced and which should be operated by itself to maximize its own profit?

VI. Smart Infrastructure System III - Smart Communication Subsystem

The third part in the smart infrastructure system is the smart communication subsystem. This subsystem is responsible for communication connectivity and information transmission among systems, devices, and applications in the context of the SG.

In this section, we first give an overview of the smart communication subsystem in SG. We then describe wireless and wired communication technologies in Sections VI-B and VI-C, respectively. In Section VI-D, we describe how to manage end-to-end communications in this heterogenous communication system, where various communication technologies, network structures, and devices may be used. We finally outline some future research directions and challenges.

A. An Overview

The most important question in the communication subsystem is, *"What networking and communication technology should be used?"* While there is a general agreement on the need for communication networks to support a two-way flow of information between the various entities in the electric grid, there is still much debate on what specific technologies should be used in each SG application domain and how they should be implemented [231]. One reason why this is still not clear is that the SG consists of many different types of networks, including for example

1) *Enterprise bus* that connects control center applications, markets, and generators;
2) *Wide area networks* that connect geographically distant sites;
3) *Field area networks* that connect devices, such as intelligent electronic devices that control circuit breakers and transformers;
4) *Premises networks* that include customer networks as well as utility networks within the customer domain.

Although thus far the answer is not clear, since reliable and effective information exchange is a key to the success of the future SG, a communication subsystem in an SG must at least satisfy the following basic requirements:

1) The communication subsystem must support the quality of service (QoS) of data [144]. This is because the critical data (e.g. the grid status information) must be delivered promptly.
2) The communication subsystem must be highly reliable. Since a large number of devices will be connected and different devices and communication technologies will be used, guaranteeing the reliability of such a large and heterogeneous network is not a trivial task.
3) The communication subsystem must be pervasively available and have a high coverage. This is mandated by the principle that the SG can respond to any event in the grid in time.
4) The communication subsystem must guarantee security and privacy. In Section VIII, we will discuss the security and privacy issues of information transmission in SG.

In the rest of this section, we focus on the communication and networking technologies which are applicable in SG. We

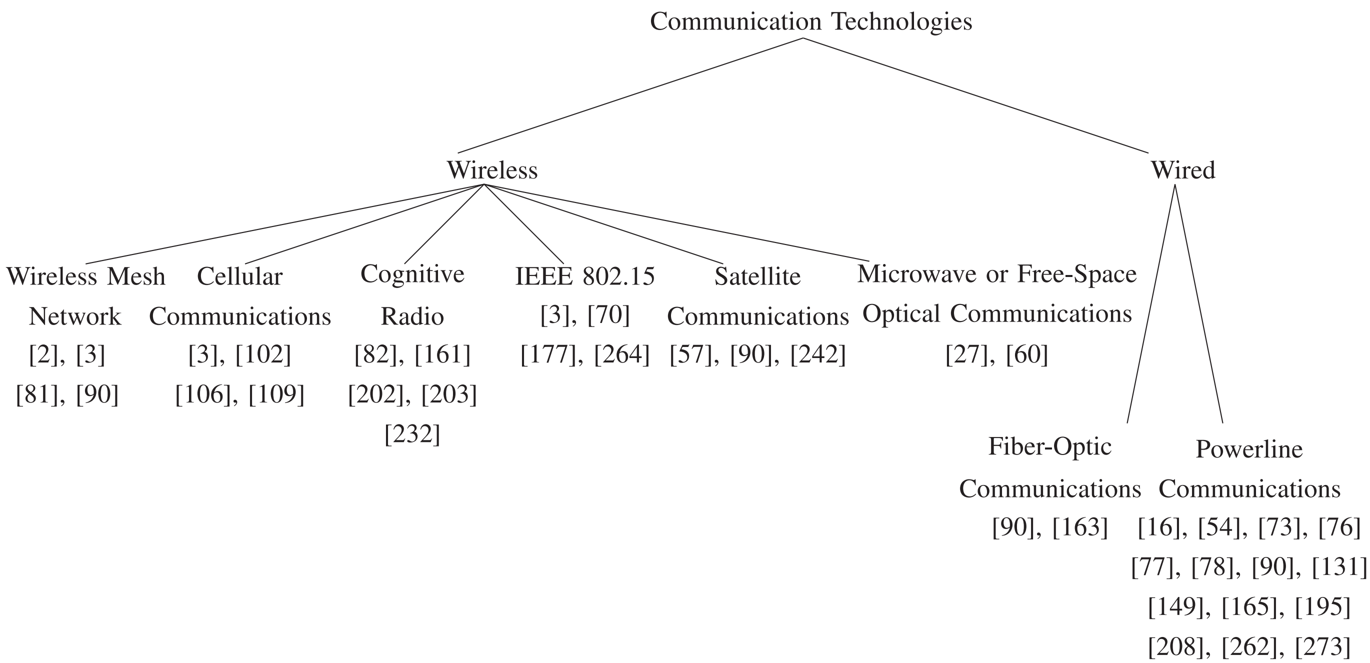

Fig. 11. Classification of Relevant Research in Communication Technologies in SG

describe wireless and wired communication technologies in Sections VI-B and VI-C, respectively. Fig. 11 shows a classification of the works related to communication technologies in SG. Fig. 12 shows an example of a communication network used in SG.

B. Wireless Technologies

Wireless technologies not only offer significant benefits over wired technologies, such as low installation cost, rapid deployment, mobility, etc., but are also more suitable for remote end applications [193]. Wireless communication has already been widely used in our daily life and can be deployed anywhere and anytime. We list the following important wireless communication and networking technologies which may be applicable in future SG.

Wireless Mesh Network: *Wireless mesh network* (WMN), which is a communication network made up of radio nodes organized in a mesh topology, has emerged as a key technology for next-generation wireless networking [2]. Industrial standards groups, such as IEEE 802.11 and 802.16, are all actively working on new specifications for WMNs. A WMN also provides basic networking infrastructure for the communications in SG. Some of the benefits of using WMNs in SG are highlighted as follows:

1) *Increased communication reliability and automatic network connectivity*: Since redundant paths usually exist in WMNs, network robustness against potential problems, e.g., node failures and path failures, can be improved. Furthermore, generally speaking a WMN is self-organized and self-configured. This feature is crucial for electric system automation, since it enables electric utilities to cope with new connectivity requirements driven by customer demands [90].
2) *Large coverage and high data rate*: WiMAX mesh network can enable both long distance and high data rate communications. In the SG, a large amount of data, such as the information from smart meters, sensors, and phasor measurement units (PMUs), will be generated and sent to the control system. A communication network with large coverage and high data rate is necessary.

Traditionally, electricity power grid and WMN are two parallel concepts. In the literature, there exists a large amount of works focused on WMN technologies. An excellent survey on the general concepts of WMNs can be found in [2]. The emerging SG will attempt to integrate WMN into power grid.

Recently, some researchers have conducted some studies along this line. Gharavi and Hu [81] presented a multi-gate mesh network architecture to handle real-time traffic for the last mile communication. The multigate routing is based on a flexible mesh network architecture that expands on the hybrid tree routing of the IEEE 802.11s. The network is specifically designed to operate in a multi-gateway structure in order to meet the SG requirements in terms of reliability, self-healing, and throughput performance. More detailed studies on wireless mesh technologies used in electric power system can be found in [3], [90].

Cellular Communication Systems: A cellular communication system, such as GSM [174] and 3G (WCDMA [103] and CDMA-2000 [263]), is a radio network distributed over land areas called cells, each served by at least one fixed-location transceiver known as a cell site or base station. It has been a proven mature technology for data transmission for several decades. By using the existing 3G (or even 4G [105]) cellular communication systems, it is quick and inexpensive to obtain data communications coverage over a large geographic area [3].

Researchers have also conducted some studies on cellular communications for the SG. For example, Hung *et al.* [106] studied a new network model in which sensor/relay nodes can also communicate with other back-end nodes using a

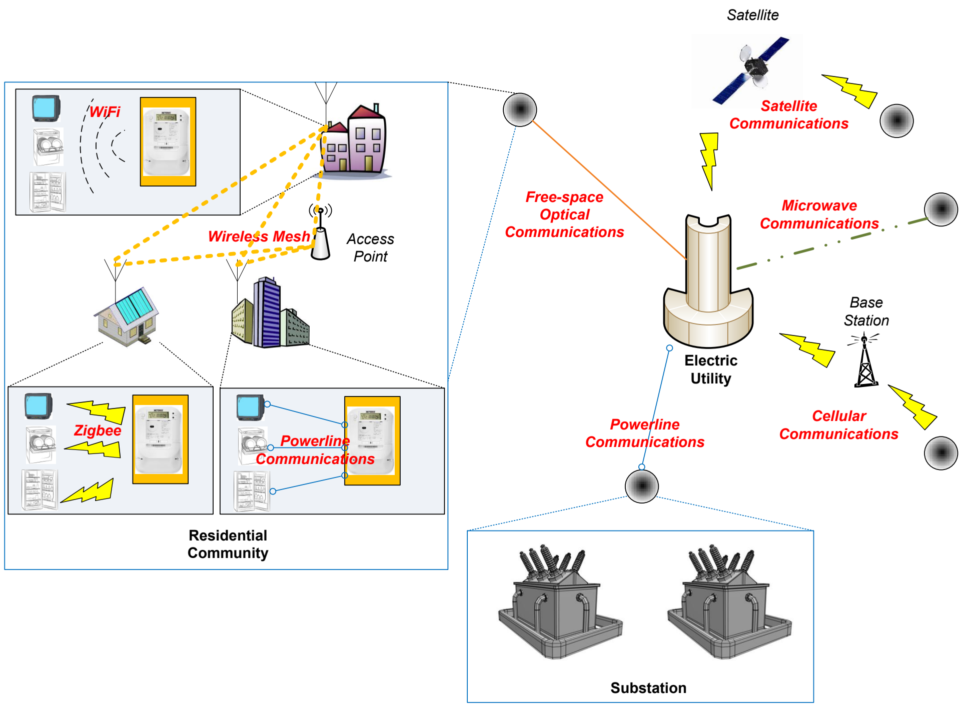

Fig. 12. An example of a communication network in SG: User devices and smart meters use ZigBee, WiFi, and powerline communications. Wireless mesh networks are used for information exchanges between users. Communities are connected to their electric utility via free-space optical, satellite, microwave, or cellular systems. A substation communicates with an electric utility over the powerline.

wide area network such as the cellular network, and proved that the delay and cost of transmitting data can be reduced. Hochgraf *et al.* [102] proposed to use the GSM network and Short Message Service (SMS) messages as an option for SG communications, and presented a system that provides the control of thousands of mobile electric vehicle (EV) chargers using a simple SMS message interface. In addition, using 3G cellular communication system as the backhaul network has also been recommended by IEEE P2030 [109]. Compared with WMN, the biggest strength of cellular communication systems is the pervasiveness of this mature technology.

Cognitive Radio: The communication system in SG needs to be designed to accommodate the current management requirements as well as the potential demand of future applications. It is likely that unlicensed spectrum will also be used when SG is in large-scale commercial use.

Ghassemi *et al.* [82] proposed an application of cognitive radio for the SG based on the IEEE 802.22 standard. In rural areas, the standalone option can provide broadband access to the geographically spread customers. In urban areas, IEEE 802.22 transceivers can be used as secondary radios to handle high volumes of non-critical data and also act as backup radios in emergency situations. Ma *et al.* [161] proposed to communicate through a cognitive radio link between the sensors at the consumer side and the control center of the SG. Therefore, the state estimator needs to adjust to this new communication link as the link is affected by primary users. This link is governed by multiple semi-Markov processes each of which can capture and model one channel of the cognitive radio system. Sreesha *et al.* [232] proposed a multi-layered approach to provide energy and spectrum efficient designs of cognitive radio based wireless sensor networks at the smart grid utility. Their design provides a reliable and low-latency routing support for large-scale cognitive SG networks. Qiu *et al.* [202] built a real-time CR network testbed, which can help tie together CRs in the next-generation SG network. Later, Qiu *et al.* [203] systematically investigated the idea of applying CR for SG, studied system architecture, algorithms, and hardware testbed, and proposed a microgrid testbed supporting both power flow and information flow.

Wireless Communications based on 802.15.4: Three wireless communication technologies based on IEEE 802.15.4 protocol stack are recommended to be used in SG [3]. They are ZigBee, WirelessHART, and ISA100.11a. ZigBee is a wireless technology which is designed for radio-frequency applications that require low data rate, long battery life, and secure networking. It might be one of the most widely used communication technologies in the customer home network. The ZigBee and ZigBee Smart Energy Profile (SEP) have been defined as one of the communication standards for use in the customer premise network domain of the SG by the U.S. National Institute of Standards and Technology (NIST) [177]. It has also been selected by many electric utilities as the communication technology for the smart metering devices [70], since it provides a standardized platform for exchanging data between smart metering devices and appliances located on customer premises. The features supported by the SEP include demand response, advanced metering support, real-time pricing, text messaging, and load control [264].

WirelessHART utilizes a time synchronized, selforganizing, and self-healing mesh architecture, and supports operation in the 2.4 GHz band using IEEE 802.15.4 standard radios. Developed as a multi-vendor, interoperable wireless standard, WirelessHART was defined for the requirements of process field device networks. ISA100.11a is an open wireless networking technology standard developed by the International Society of Automation. The official description is "Wireless Systems for Industrial Automation: Process Control and Related Applications." For wireless sensor network applications in SG, such as a substation or a generation plant, it is recommended to use WirelessHART or ISA100.11a. These two standards are similar in functionality, and therefore either standard is suitable for deployment [3].

Satellite Communications: Satellite communication is a good solution for remote control and monitoring, since it provides global coverage and rapid installation [90]. In some scenarios where no communication infrastructure exists, especially for remote substations and generation deployments, satellite communication is a cost-effective solution. For example, Deep *et al.* [57] pointed out that with remote generation deployments, such as those based on wind energy, a cost-effective communication system with global coverage using satellite technology would be advantageous. Such communication can be easily set up by only acquiring the necessary satellite communication equipment. Note that some utilities have already installed such equipment for rural substations monitoring [242]. Furthermore, a terrestrial-only architecture is vulnerable to disasters or communication system failures on the ground. Therefore, in order to ensure the fail-safe operation and the delivery of critical data traffic in disasters or terrestrial communication system failures, satellites can be used as a backup for the existing grid communication networks.

However, we should also note the disadvantages of satellite communications. There are two major shortcomings. First, a satellite communication system has a substantially higher delay than that of a terrestrial communication system. This makes some protocols (e.g. TCP), which are originally designed for terrestrial communication, unsuitable for satellite communications [90]. Second, satellite channel characteristics vary depending on the effect of fading and the weather conditions. This property can heavily degrade the performance of the whole satellite communication system [104].

Microwave or Free-Space Optical Communications: Microwave technologies are widely used for point-to-point communications, since their small wavelength allows use of conveniently sized directional antennas to obtain secure information transmission at high bandwidths. The report by Donegan [60] pointed out that over 50% of the world's mobile base stations are connected using point-to-point microwave technologies. For over 20 years, microwave has been the primary solution for rapidly rolling out cost-effective mobile backhaul infrastructure worldwide [148].

Free-space optical communication is an optical communication technology that can use light propagating in free space to transmit point-to-point data. It provides high bit rates with low bit error rates. Furthermore, it is very secure due to the high directionality and narrowness of the beams. In addition to providing long-distance point-to-point communication in remote or rural areas, these "optical wireless" technologies also provide point-to-point solutions suitable for use in dense urban areas where microwave solutions are impractical from an interference standpoint [27].

Therefore, one important application of microwave or free-space optical point-to-point communications is to build up SG communication backhaul networks. This is especially important in rural or remote areas, where using other wireless or wired technologies is costly or even impossible. However, both microwave communication and free-space optical communication are line of sight communication technologies. Therefore, their communication qualities are greatly affected by obstacles (e.g. buildings and hills) and environmental constraints (e.g. rain fade).

Remarks: It is clear that wireless communication technologies are important for future SG, and that different technologies might be applicable. In order to assess the suitability of various wireless technologies for meeting the communication requirements of SG applications, Souryal *et al.* [231] presented a methodology to evaluate wireless technologies. The proposed approach to modeling wireless communications first identifies the various applications utilizing a specific link. Second, it translates the requirements of these applications to link traffic characteristics in the form of a link layer arrival rate and average message size. Third, it uses coverage analysis to determine the maximum range of the technology under an outage constraint and for a given set of channel propagation parameters. Finally, using the link traffic characteristics and coverage area determined above, it employs a model to measure link performance in terms of reliability, delay, and throughput.

C. Wired Technologies

It is also believed that wired communication technologies will be integrated into SG. We list the following important wired communication technologies.

Fiber-optic Communications: There is a long history of the use of fiber communications by large power companies to connect their generation network with their network control facilities. Furthermore, its electromagnetic and radio interference immunity make fiber-optic communication ideal for high voltage operating environment [163].

Due to its high bandwidth capacity and immunity characteristics, it is believed that optical fibers will play an important role for the information network backbones in future SG [90]. Although it is well-known that the installment cost of optical fibers may be expensive, fiber optic network is still a cost-effective communication infrastructure for high speed communication network backbones in future SG, since such fibers are already widely deployed in today's communication network backbones, with a large amount of spare capacity being unused.

Powerline Communications: *Powerline communications* (PLC) is a technology for carrying data on a conductor also used for electric power transmission. In the last decades, utility companies around the world have been using PLC for remote metering and load control applications [73]. The debate on what is the actual role of PLC in future SG is still open.

Some advocate that PLC is a very good candidate for some applications [78], [208], while others express concerns on PLC (e.g. the security issue due to the nature of powerlines) [149], [195]. Although the SG could use many different communications technologies, without a doubt, PLC is the only wired technology that has deployment cost comparable to wireless technologies since the lines are already there [78].

Technically, in PLC power electronics are used to manipulate high-voltage waveforms for signal and information oriented applications [262]. For example, a thyristor or similar device is used to create a waveform disturbance such as a very small but detectable voltage sag. The existence of the sag implies digital "1" and no sag implies digital "0."

Although how to most effectively utilize PLC is still not clear, Galli *et al.* [78] predicted that PLC may be more suitable for the distribution grid. Traditional substations in the medium voltage distribution grids are not equipped with communications capabilities. Thus using the existing powerline infrastructure represents an appealing alternative to the installation of new communication links. This enables the information about state and event to flow among substations within a grid. In low voltage distribution grids (close to the homes), there also exist a large number of applications of PLC. First, narrowband PLC is well suited for smart metering infrastructure [208]. Second, PLC enables the communications between electric vehicles and power grid via powerline without introducing other wired or wireless equipments. Third, broadband PLC can provide the service of transferring data seamlessly from SG controllers to home networks and vice versa.

The most urgent task for the research on PLC might be a comprehensive theoretical understanding. Most of the works are focused on the ultimate performance that can be achieved over the powerline channel [90]. In order to further utilize PLC, we need to have a better understanding of the powerline channel, since it is a complicated and noisy medium disturbed by noise, external emissions, and frequent impedance alterations. Some researchers have investigated channel modeling and analysis methods for PLC, such as [16], [54], [76], [77], [131], [165], [273].

Barmada *et al.* [16] studied load-time variation in PLC systems and analyzed asynchronous impulsive noise and related channel variations due to switch commutations. Corripio *et al.* [54] analyzed the properties of indoor PLC channels when they are used for broadband transmission. It is shown that these channels exhibit a short-term variation. Galli [76] reported for the first time some statistical properties of indoor powerline channel that exhibit some interesting similarities to the wireless channel. He also reported for the first time that both channel gain and root-mean-square delay spread of indoor channels are lognormally distributed, leptokurtic, and negatively correlated, thus suggesting that channels which introduce severe multipath fading are also characterized by large attenuation. Konaté *et al.* [131] studied both frequency (100 kHz-30 MHz) and time-domain channel modeling in inverter driven electrical drives. Meng *et al.* [165] presented an approach to model the transfer function of electrical powerlines for broadband PLCs. In this approach, the powerline is approximated as a transmission line, and the two intrinsic parameters–the characteristic impedance and the propagation constants–are derived based on the lumped-element circuit model. Zimmermann and Dostert *et al.* [273] analyzed and tried to model impulsive noise in broadband PLC. Refer to [73] for more works along the research on channel modeling and analysis methods for PLC.

D. End-to-end Communication Management

One important issue in the communication subsystem is the end-to-end communication management. More specifically, in this heterogenous communication subsystem where various communication technologies, network structures, and devices may be used, we need to identify each entity (probably by giving a unique ID for each one), and solve the problem of how to manage end-to-end communications (perhaps between any pair of entities).

Recently, there is a growing trend towards the use of TCP/IP technology (usually based on IPv6 address) as a common and consistent approach in order to achieve end-to-end communications [18], [46], [129], [153], [154], [177], [223]. TCP/IP is an easy solution to the problem of managing systems based on incompatible lower layer technologies. Therefore electric utilities can deploy multiple communication systems, while using TCP/IP technology as a common management platform for maintaining end-to-end communications, and enjoy the high rate of innovation (and competition) focused around the TCP/IP protocol suite.

NIST also indicated that there are a number of benefits that make TCP/IP an important SG technology, including the maturity of a large number of standards, the availability of tools and applications that can be applied to SG environments, and its widespread use in both private and public networks [177]. If an application does not support TCP/IP natively, it may still be possible to implement encapsulation, gateway, or semi-transparent tunneling by providing a special communication interface for this application.

E. Summary and Future Research

In this section, we reviewed the works on the smart communication subsystem, including wireless technologies, wired technologies, and end-to-end communication management. We list the following challenges and possible directions worth exploring.

1) **Interoperability of communication technologies:** Since many different communication protocols and technologies will be used in SG, and each of them probably will use its own protocols and algorithms, materializing interoperability is not easy.

Although the framework architecture in the classic layer model (e.g. the famous Open Systems Interconnection model) could provide a promising conceptual solution to this problem, it is well-known that this model suffers in some modern applications. For example, the performance of the pure TCP may be very bad in wireless networks since it cannot differentiate packet loss due to wireless fading from that due to a real congestion in the network. In order to improve the quality of service, under various operational conditions, some functions or services are not tied to a given layer, but can affect more than one layer. This often requires cross-layer design and optimization, which may be essential in the SG. However, interoperability among different communication technologies, a precursor to cross-layer approaches, is difficult. We suggest studying the advantages and disadvantages of cross-layer design in SG communication subsystem considering interoperability, especially the trade-offs between cross-layer optimization and the need for interoperability.

2) **Dynamics of the communication subsystem:** The communication subsystem underlying an SG may be dynamic, with topology changes being unpredictable. For example, both the operation of connecting (or disconnecting) the electric vehicle (EV) to (or from) the grid and the motion of vehicle may result in the change of communication network topology. Note that these operations may not follow a predictable pattern. The dynamics of an SG communication subsystem have not been fully explored.

The following two research directions are worth exploring. First, systematic protocol designs are needed to support topology dynamics. For example, communication protocols should deal with topology reconfiguration in the connect-disconnect operation of EVs. Second, dynamic resource allocation algorithms are needed to support topology dynamics. For example, due to the topology change, the network resources (e.g. bandwidth) may need to be reallocated to optimize performance.

3) **Smoothly updating existing protocols:** The current power grid has used several protocols to realize simple data communications. For example, the currently used metering and Supervisory Control and Data Acquisition Systems (SCADA) [176] protocols are based on a simple request/response scheme with their own addressing [223]. One problem is how to smoothly update existing protocols to the ones which are applicable in future SG. For example, as stated in Section VI-D, for the end-to-end communication management, even if an application does not support TCP/IP natively, it may still be possible to implement the encapsulation, gateway, or semi-transparent tunneling for this application. However, encapsulating such SCADA and metering protocols into mature TCP/IP protocols generates an overhead without additional benefit, and thus is deliberately not considered [223]. How to smoothly transit the systems using these protocols to the ones applicable in future SG is still an open question.

For this open question, we may be able to borrow from industry the idea of how to smoothly update old IPv4 networks to new IPv6 networks. For example, this transition can be done in two stages: 1) the system can communicate using pre-existing old protocols and also TCP/IP and 2) the system operates by only using TCP/IP. A complete solution along this line is desired.

VII. Smart Management System

In SG two-way flows of electricity and information are supported, which lay the foundation for realizing various functions and management objectives, such as energy efficiency improvement, operation cost reduction, demand and supply balance, emission control, and utility maximization. A common superficial understanding about SG is that only the energy, information and communication infrastructure underlying the SG is smart. This is not true. The more accurate

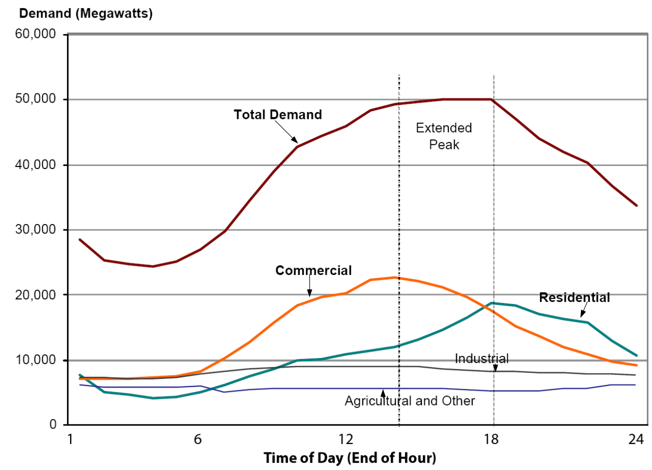

Fig. 13. Total California Load Profile for a Hot Day in 1999 [214].

assessment is: With the development of new management applications and services that can leverage the technology and capability upgrades enabled by this advanced infrastructure the grid will keep becoming "smarter."

For example, let us consider *demand response*, one of the most important concepts supported by SG. Traditionally, the electric utilities try to match the supply to the demand for energy. However, this may be not only expensive but also impractical, perhaps impossible in the longer run. This is because the total amount of power demand by the users can have a very widespread probability distribution, which requires spare generating plants in standby mode to respond to the rapidly changing power usage. The last 10% of generating capacity may be required in as little as 1% of the time. The attempts to meet the demand could fail, resulting in brownouts (i.e. a drop in voltage), blackouts (i.e. electrical power outage), and even cascading failures. In SG, demand response manages the customer consumption of electricity in response to supply conditions. More specifically, by using demand response, SG does not need to match the supply to the demand, but in contrast, to match the demand to the available supply by using control technology or convincing the consumers (such as through variable pricing) thus achieving better capacity utilization.

For example, Fig.13 shows the total energy usage pattern during a twenty-four hour period for a typical hot day in California (1999) [214]. As we can see, the total demand from 14:00PM to 18:00PM is much higher than the average. In an SG, smart management by a smart meter can reduce energy consumptions by turning off non-essential devices during peak time in a way that the peak total demand can be reduced.

In this section, we explore smart management in SG. We first classify smart management techniques according to their management objectives and then according to their management methods and tools.

A. Management Objectives

Within the framework of SG, many management goals, which are difficult and possibly infeasible to realize in conventional power grids, become possible and easy. So far, the

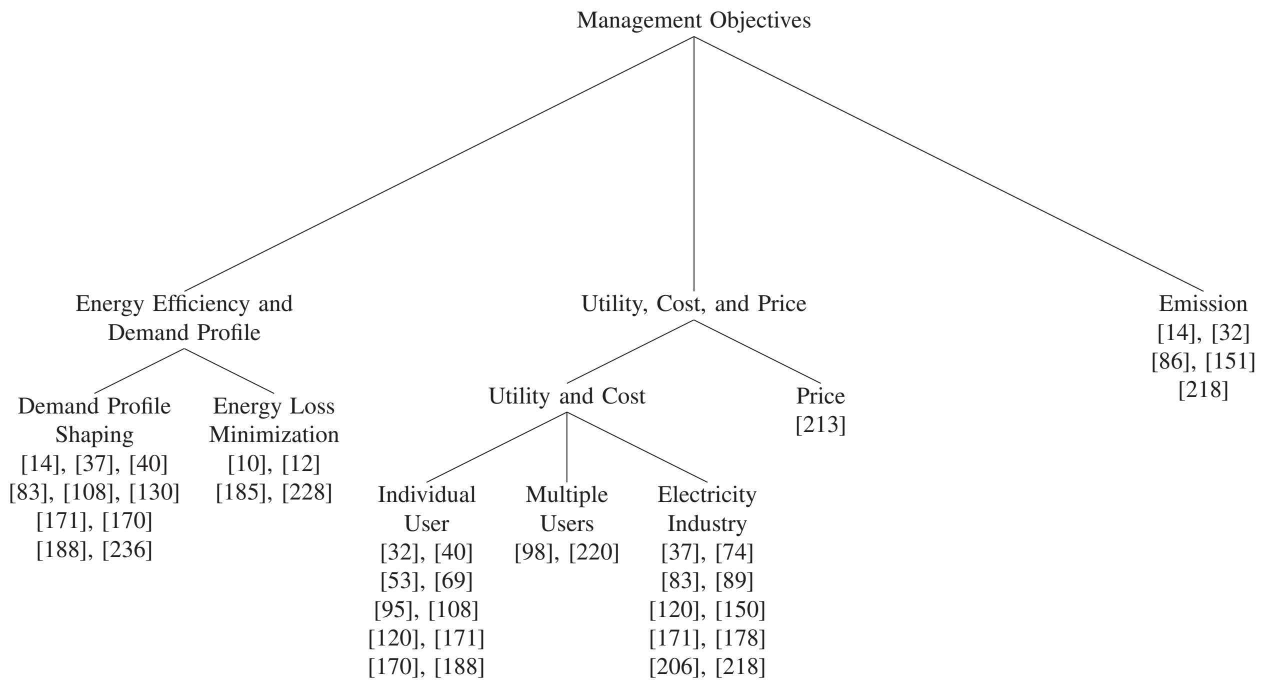

Fig. 14. Classification of Management Objectives

works for smart management mainly focus on the following three objectives:

1) Energy efficiency and demand profile improvement;
2) Utility and cost optimization, and price stabilization;
3) Emission control.

Fig. 14 shows a detailed classification of the research works related to these management objectives.

The research on energy efficiency and demand profile mainly focuses on two topics. The ***first*** one can be categorized as *demand profile shaping*. It can help match the demand to the available supply. The usual way to shape demand profile is shifting, scheduling, or reducing demand in order to reshape a demand profile full of peaks to a nicely smoothed demand profile, or reduce the peak-to-average ratio or peak demand of the total energy demand [14], [37], [40], [83], [108], [130], [170], [171], [188], [236]. As discussed before, since electrical generation and transmission systems are generally sized to correspond to peak demand, lowering peak demand and smoothing demand profile reduces overall plant and capital cost requirements, and also increases the system reliability. Next we briefly describe these research works.

Bakker *et al.* [14] designed a three step control and optimization strategy and focused on the control algorithms used to reshape the energy demand profile of a large group of buildings and their requirements. Caron and Kesidis [37] proposed a dynamic pricing scheme incentivizing consumers to achieve an aggregate load profile suitable for utilities, and studied how close they can get to an ideal flat profile. Chen *et al.* [40] studied two abstract market models for designing demand response to match power supply and shape power demand. They characterized the resulting equilibria in competitive as well as oligopolistic markets, and proposed distributed demand response algorithms to achieve the equilibria. Ibars *et al.* [108] aimed to smooth the electric demand curve and avoid overloading both the generation and distribution capacity of the grid, by using a network congestion game, where each user allocates demand as a response to other users' actions. Kishore and Snyder [130] first presented an optimization model for determining the timing of appliance operation to take advantage of lower electricity rates during off-peak periods. They then proposed a distributed scheduling mechanism to reduce peak demand within a neighborhood of homes. They finally introduced a more powerful energy management optimization model, based on dynamic programming, which accounts for electricity capacity constraints. Mohsenian-Rad and Leon-Garcia [170] proposed an optimal and automatic residential energy consumption scheduling framework, which attempts to achieve a desired trade-off between minimizing the electricity payment and minimizing the waiting time for the operation of each appliance. Mohsenian-Rad *et al.* [171] discovered that by adopting pricing tariffs which differentiate the energy usage in time and level, the global optimal performance is achieved at a Nash equilibrium of the formulated energy consumption scheduling game. O'Neill *et al.* [188] proposed an online learning algorithm to reduce residential energy costs and smooth energy usage. Taneja *et al.* [236] introduced a generalized measure of dispatchability of energy (called slack), identified two classes of dispatchable energy loads, and created models for these loads to match their consumption to the generation of energy sources. Ghosh *et al.* [83] designed an optimal incentive mechanism offered to energy customers. According to their mechanism, customers who are more willing to reduce their aggregate demand over the entire horizon, which consists of multiple periods, rather than simply shifting their load to off-peak periods, tend to receive higher incentives, and vice versa.

The ***second*** topic of energy efficiency and demand profile is minimizing energy loss. However, using distributed energy generation in SG makes this problem more complicated. In order to minimize the system energy loss, Ochoa and Harrison

[185] proposed to determine the optimal accommodation of distributed renewable energy generation for minimizing energy loss by using an optimal multi-period alternating current power flow. Atwa *et al.* [12] aimed to minimize energy loss through the optimal mix of statistically-modeled renewable sources. Aquino-Lugo and Overbye [10] presented a decentralized optimization algorithm to minimize power losses in the distribution grids.

We have reviewed the works on energy efficiency and demand profile improvement in the above. Improving utility, increasing profit, and reducing cost are also important management objectives. Researchers realize these objectives in various levels and from various perspectives, such as individual user cost/bill or profit [32], [40], [53], [69], [95], [120], [170], [171], [188], single energy bill or aggregate utility of a group of users [98], [220], cost or utility of electricity industry and system [37], [74], [83], [89], [120], [150], [171], [178], [206], [218]. Stabilization of prices is also a research topic in SG, since relaying the real-time wholesale market prices to the end consumers creates a closed loop feedback system which could be unstable or lack robustness, leading to price volatility. Roozbehani *et al.* [213] therefore developed a mathematical model for characterization of the dynamic evolution of supply, demand, and market clearing (locational marginal) prices under real-time pricing, and presented a stabilizing pricing algorithm.

Emission control, another important management objective in the electric power industry, has a significant influence on environment protection. However, note that minimizing generation cost or maximizing utility/profit is not directly equivalent to minimizing emission by utilizing renewable energy as much as possible. This is because, generally speaking, the cost of power generation from renewable energy source is not always the lowest. Therefore, as suggested by Gormus *et al.* [86], environmental impact of energy produced from fossil fuels should be factored into the demand scheduling algorithm as a cost parameter which may result in more peak loads to be moved to the periods where renewable sources have a higher percentage in the generation mix. However, individual users should be willing to accept their appliances to be scheduled according to the requirements of low carbon scheduling. In addition, many researchers have also investigated how to optimize emission reduction. Saber and Venayagamoorthy [218] studied how to take advantage of both plug-in hybrid electric vehicles and renewable resources to reduce emission. Bakker *et al.* [14] presented a three step control strategy to optimize the overall energy efficiency and increase generation from renewable resources with the ultimate goal to reduce the CO_2 emission caused by electricity generation. Bu *et al.* [32] modeled the stochastic power demand loads as a Markov-modulated Poisson process, and formulated the unit commitment scheduling problem of power generation systems as a partially observable Markov decision process multi-armed bandit problem. By adjusting the pollutant emission costs, the CO_2 emissions can be reduced. Liu and Xu [151] performed a mathematical analysis for the effects of wind power on emission control, and developed a load dispatch model to minimize the emission.

Considering the importance of microgrids and G2V/V2G, we particularly list the works related to them.

Microgrids: Guan *et al.* [89] applied microgrid technology to minimize the overall cost of electricity and natural gas for a building operation while satisfying the energy balance and complicated operating constraints of individual energy supply equipment and devices. The results showed that through integrated scheduling and control of various energy supply sources of the building, significant energy cost saving can be achieved. Vandoorn *et al.* [249] presented a method for active load control in islanded microgrids, which is triggered by the microgrid voltage level. This is enabled by using the voltage-droop control strategy and its specific properties. It is shown that the presented demand dispatch strategy leads to reduction of line losses and that with the combination of the active power control and the presented active load control, the renewable energy can be exploited optimally. A review of challenges to power management in microgrids can be found in [52].

G2V/V2G: As stated in Section IV-D, in G2V, high penetration levels of uncoordinated electric vehicle (EV) charging will significantly reduce power system performance and efficiency, and even cause overloading. Coordinated charging has hence been proposed to mitigate these negative impacts using stochastic programming [48], [49], quadratic optimization [93], particle swarm optimization [218], and dynamic programming [95]. Recall that particle swarm optimization can solve complex constrained optimization problems quickly, with accuracy and without any dimensional limitation and physical computer memory limit. In the context of coordinated EV charging, Sortomme *et al.* [228] studied the relationship between feeder losses, load factor, and load variance. They showed the benefits of reduced computation time and problem complexity, when we use load variance or load factor as the objective function rather than system losses. Another interesting work is done by Pan *et al.* in [192]. Instead of attempting to find an optimized power dispatching approach, they explored how to aptly place EV infrastructures like battery exchange stations so that they can support both the transportation system and the power grid.

In V2G, we often discharge the battery to deliver the power to the grid and then recharge it later when the price is low. Therefore, a key question is how to determine the appropriate charge and discharge times throughout the day, taking into account the requirements of both vehicle owners and utility. Hutson *et al.* [107] studied this problem and used binary particle swarm optimization to look for optimal solutions that maximize profits to vehicle owners while satisfying system and vehicle owners' constraints. In addition, Lund and Kempton [159] analyzed the positive influence of V2G on integration of renewable energy into the electricity sectors. Since today's abundant renewable energy resources have fluctuating output, to increase the fraction of electricity from them, we must learn to maintain a balance between demand and supply. V2G technology can provide storage, matching the time of generation to time of load. They found that adding V2G to these national energy systems allows integration of much higher levels of wind electricity without excess electric production, and also greatly reduces national CO_2 emissions.

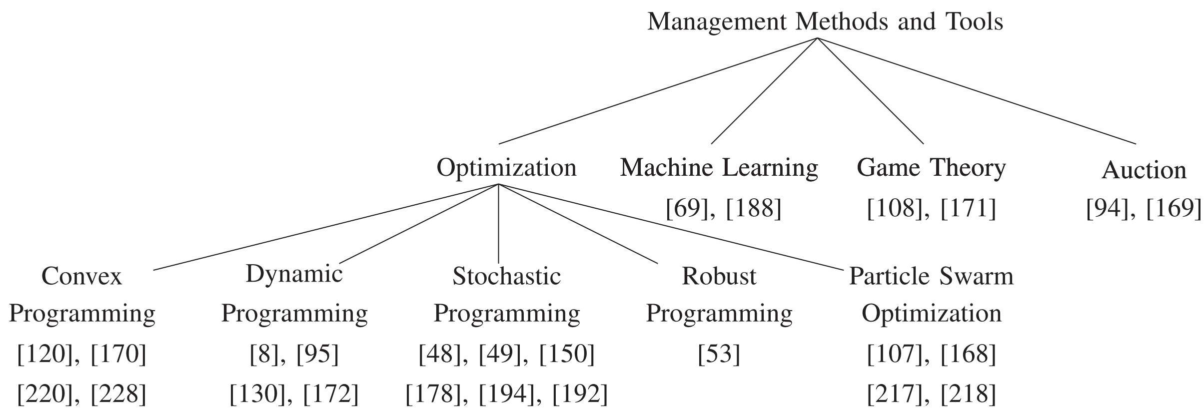

Fig. 15. Classification of Management Methods and Tools

B. Management Methods and Tools

In order to solve management objectives, researchers have adopted various methods and tools. Thus far, researchers mainly use optimization, machine learning, game theory, and auction as tools to solve various management problems. Fig. 15 shows a classification of the related works.

For optimization approaches, the commonly used mathematical tools are convex programming [120], [170], [220], [228] and dynamic programming [8], [95], [130], [172]. Since the renewable energy supply is often a time-varying process, other optimization techniques such as stochastic programming [48], [49], [150], [178], [192], [194] and robust programming [53] are also widely used. In addition, since the particle swarm optimization can solve complex constrained optimization problems quickly, with accuracy and without any dimensional limitation and physical computer memory limit, it is also a widely used optimization tool [107], [168], [217], [218].

Machine learning focuses on the design and development of algorithms that allow control systems to evolve behaviors based on empirical data, such as from sensor or phasor measurement unit (PMU) data. O'Neill *et al.* [188] used online learning application to implicitly estimate the impact of future energy prices and consumer decisions on long term costs, and thus schedule residential device usage. Fang *et al.* [69] used online machine learning to analyze the renewable energy resource use strategy in islanded microgrids. More specifically, a customer tries to decide among multiple renewable energy sources which should be used to maximize profit. Although the power pattern of the renewable energy source is not known in advance, they proved that when the time horizon is sufficiently large, on average the upper bound on the gap between the expected profit obtained at each time slot by using the optimal renewable energy source and that by following their strategies is arbitrarily small. Considering that a large number of smart meters, sensors, and PMUs will be deployed, we believe that machine learning will play an important role in analysis and processing of user data and grid states.

Game theory is also a strong analysis tool for SG management. One reason is that we cannot always expect and require all the users to be cooperative. Game theory can help us design effective schemes to cope with this case. For example, Ibars *et al.* [108] proposed a distributed solution based on a network congestion game to guarantee that the optimal local solution of each selfish consumer is also the solution of a global objective. In [171], by adopting pricing tariffs that differentiate the energy usage in time and usage level, the global optimal performance is achieved at the Nash equilibrium of the formulated energy consumption scheduling game. Another reason why game theory is desirable is that the emerging SG will lead to the emergence of a large number of markets, which will be akin to multi-player games. For example, the consumers within a microgrid can create a market for trading energy. Game theory can help us analyze the resulting market. For example, Chen *et al.* [40] characterized the resulting equilibria in competitive as well as oligopolistic markets, and proposed distributed demand response algorithms to achieve the equilibria.

Auction may also be popular in the emerging SG. Distributed energy generation and microgrid will be widely used in SG. As mentioned above, the consumers within a microgrid can create a market for trading energy. Bidding and auction can be used for energy sale within a local microgrid market. Auction is not limited to the microgrid market. The authors of [94], [169] proposed demand reduction bid, a kind of demand response programs. Recall that demand response can be used to reduce the system peak load. At the peak load period, customers send demand reduction bids to the utility with the available demand reduction capacity and the price asked for. This program encourages customers to provide load reductions at prices for which they are willing to curtail.

C. Summary and Future Research

Within the framework of SG, many management goals, which are difficult and even infeasible to realize in conventional power grids, become easy and possible.

As reviewed in this survey, we found that most of the works on the smart management aim to improve energy efficiency, shape demand profile, increase utility, and reduce costs and emissions based on the advanced SG smart infrastructure. We believe that this advanced infrastructure will lead to an explosion of functionalities, and that more and more new management services and applications will emerge. We present two possible services in the following.

1) **The integration of pervasive computing and Smart Grid**: Pervasive computing is a post-desktop model in which information processing has been thoroughly integrated into everyday objects and activities. Using the information provided by pervasive computing, SG is able to serve users more effectively and smartly, and eventually revolutionize the consumers' lives. Let us consider a simple example. In summer, the average high temperature in Phoenix (Arizona, USA) area can be over $100°F$ ($37.8°C$) and has spiked over $120°F$ ($48.9°C$). People hope that when they get home, the temperature at home is within $60-80°F$. Therefore, the smart meter connected to the air conditioner can periodically inquire the position of the house owner by sending the inquiry to the owner's smart phone which can obtain the owner's position via GPS. If the smart meter finds the owner coming back home, it will decide to turn on the air conditioner in advance so that when the owner gets home, the temperature is within the comfortable zone.

2) **Smart Grid Store**: Like "Apple's Application Store"[9], many management applications and services are available online. Users can choose their expected services and download them to the local system (e.g. the smart meter). For example, a user, who needs a management program supporting the smart control of air conditioner mentioned above, can buy such a program from the Smart Grid Store online and download it. This Smart Grid Store provides an integrated platform, which can drive the third party to develop new management programs and meantime help users easily customize their management services.

Although a smart management system in SG is promising and encouraging, we still face many challenges. We summarize the important challenges and the possible research directions worth exploring in the following.

1) **Regulating emerging markets:** As mentioned before, microgrids could lead to the emergence of new markets among users within a microgrid for trading energy. Due to the lack of supervision of conventional utilities, it is a challenge to regulate such new markets.

For example, in an auction market where the consumers within a microgrid trade energy, how to guarantee truthful auction is a challenge, since some users could make untruthful bids to cheat the seller in order to obtain the benefit which they cannot get in truthful bidding. Note that truthful auction has been studied for several years. One of the most well-known auction schemes is the Vickrey-Clarke-Groves (VCG) scheme [47], [88], [253], which is a type of sealed-bid auction where multiple items are up for bid, and each bidder submits a different value for each item. This system charges each individual the harm they cause to other bidders, and ensures that the optimal strategy for a bidder is to bid the true valuations of the objects. The truthful auction problem in SG may be solved along this line.

2) **Effectiveness of the distributed management system:** The SG is expected to utilize distributed management systems more often, since distributed generation and plug-and-play components will be widely used to form autonomous and distributed subgrids (e.g. microgrids). However, generally speaking, more amount of timely information means smarter management decisions in the management process. Therefore, considering the limitation on accessible information, distributed management systems usually cannot compute a globally optimal decision. We thus need to consider how to determine the optimal size of a subgrid controlled by a distributed management system and how to obtain necessary timely information, so that the local decision is good enough.

3) **Impact of ad-hoc organization of SG:** In an SG many parts (such as solar panels) are deployed in a distributed manner, and are even required to work as plug-and-play components. More flexibility from the users' perspective also leads to more difficulty in system design and management. This actually opens up many possible research topics.

For example, we need to study the self-configuration of the power grid, and further how to manage the power dispatching in such a self-configured system. Let us consider a more specific example. In a power system containing many functioning microgrids, when some components stop functioning in one microgrid, it could be interesting to study how to optimally allocate some resources (e.g. distributed energy generators) from other microgrids to this one to improve the overall performance of the whole power system.

4) **Impact of utilization of fluctuant and intermittent renewables:** The utilization of the renewable resources, such as wind and solar, also makes management more difficult due to their fluctuant and intermittent nature. The management system should maintain reliability and satisfy operational requirements, meanwhile taking into account the uncertainty and variability of energy sources.

In order to solve the optimization problems related to such renewables, we suggest that stochastic programming and robust programming [53] play more important roles as mathematical tools, since they can model optimization problems that involve uncertainty. As discussed in Section IV-E, Markov process and online machine learning technology may also be applicable for the analysis of renewable source performance. Based on the prediction of renewable source performance, we can try to achieve our management objectives.

VIII. Smart Protection System

The smart protection system in SG must address not only inadvertent compromises of the grid infrastructure due to user errors, equipment failures, and natural disasters, but also deliberate cyber attacks, such as from disgruntled employees, industrial spies, and terrorists.

In this section, we explore the works targeted the smart protection system in SG. We first review the works related to system reliability analysis and failure protection mechanisms, and then the security and privacy issues in SG.

A. System Reliability and Failure Protection

Reliability is the ability of a component or system to perform required functions under stated conditions for a stated period of time. System reliability is an important topic in power grid research and design. In the U.S., the annual cost of outages in 2002 was estimated to be in the order of $79B, while the total electricity retail revenue was $249B [173].

Furthermore, cascading blackouts could happen. For example, in the infamous 2003 East Coast blackout, 50 million people in the U.S. and Canada lost power for up to several days [182]. An initial review of methods for cascading failure analysis in power grid systems can be found in [15]. The future SG is expected to provide more reliable system operation and smarter failure protection mechanism.

1) System Reliability : It is expected that distributed generation (DG) will be widely used in SG. While using some fluctuant and intermittent renewables may compromise the stability of the grid [61], [132], the authors of [43], [173] stated that innovative architectures and designs can offer great promise to connect DGs into the grid without sacrificing reliability.

Chen *et al.* [43] proposed to take advantage of new architectures such as microgrid to simplify the impact of DG on the grid. Intuitively, as loads are being served locally within a microgrid, less power flows within the entire grid infrastructure. Thus, the reliability and stability of the SG can be enhanced. They found a very encouraging result that local power generation, even when only introducing a small number of local generators into the grid, can reduce the likelihood of cascading failures dramatically. Moslehi and Kumar [173] observed that an ideal mix of the SG resources (e.g. distributed renewable sources, demand response, and storage) leads to a flatter net demand that eventually further improves reliability. However, realizing this requires a systematic approach – developing a common vision for cohesive gridwide integration of necessary information technologies. Thus, they proposed an architectural framework to serve as a concrete representation of a common vision.

Furthermore, the reliability and stability of an SG also depends on the reliability of the measurement system which is used to monitor the reliability and stability of the SG. Recently, the wide-area measurement system (WAMS) based on phasor measurement units (PMUs) is becoming an important component for the monitoring, control, and protection functions in SG. In order to analyze the reliability of WAMS, Wang *et al.* [255] presented a quantified reliability evaluation method by combining Markov modeling and state enumeration techniques. This method can be used for evaluating the reliability of the backbone communication network in WAMS and the overall WAMS from a hardware reliability viewpoint.

Another research topic is using simulation for system reliability analysis. The more accurately a simulation platform can emulate the behavior and performance of an SG architecture, the better we will understand its advantages and potential shortcomings. However, the question is how to build up a simulation system which is accurate, flexible, adaptable, and scalable enough. Bou Ghosn *et al.* [25] utilized an incremental method, beginning with simulating a local microgrid, but with a scalable design that can grow hierarchically into a more complete model. Such a simulator can help us understand SG issues and identify ways to improve the electrical grid. Godfrey *et al.* [85] proposed to model both the communication network and the power system in SG using simulation. This model provides means to examine the effect of communication failures as a function of the radio transmission power level.

2) Failure Protection Mechanism: In this subsection, we first review two topics related to failure protection mechanism. First, failure prediction and prevention play important roles in the smart protection system since they attempt to prevent failures from happening. Second, once the system does fail, failure identification, diagnosis, and recovery are required to make the system recover from the failure and work normally as soon as possible. Fig. 16 shows a classification of the works related to these two topics. In addition, since the microgrid is regarded as one of the most important new components in the SG vision, we review the works focused on the microgrid protection.

Failure Prediction and Prevention: For an SG, one effective approach to preventing failures from happening is predicting the weak points or the region of stability existence in its energy subsystem. Chertkov *et al.* [44] developed an approach to efficiently identify the most probable failure modes in static load distribution for a given power network. They found that if the normal operational mode of the grid is sufficiently healthy, the failure modes are sufficiently sparse, i.e., the failures are caused by load fluctuations at only a few buses. Their technique can help discover weak links which are saturated at the failure modes, and can also identify generators working at the capacity and those under the capacity, thus providing predictive capability for improving the reliability of any power system. Vaiman *et al.* [248] proposed to utilize PMU data to compute the region of stability existence and operational margins. An automated process continuously monitors voltage constraints, thermal limits, and steady-state stability simultaneously. This approach can be used to improve the reliability of the transmission grid and to prevent major blackouts.

Failure Identification, Diagnosis, and Recovery: Once a failure occurs, the first step must be quickly locating and identifying the failure to avoid cascading events.

Due to the wide deployment of PMUs in SG, the authors of [237], [238], [272] proposed to take advantage of the phasor information for line outage detection and network parameter error identification. Tate and Overbye [237] developed an algorithm which uses known system topology information, together with PMU phasor angle measurements, to detect system line outages. In addition to determining the outaged line, their algorithm also provides an estimate of the pre-outage flow on the outaged line. Later, Tate and Overbye [238] studied how double line outages can be detected using a combination of pre-outage topology information and real-time phase angle measurements that are obtained from PMUs. Zhu and Abur [272] showed that the identification of certain parameter errors based on conventional measurements, no matter how redundant they are, may not always be possible. They hence described the need for phasor measurements to overcome this limitation.

Other works on failure identification and diagnosis include [34], [35], [101], [216]. Sometimes we need to select proper features to identify the root cause. Cai *et al.* [34] reviewed two popular feature selection methods: 1) hypothesis test, 2) stepwise regression, and introduced another two: 3) stepwise selection by Akaike's Information Criterion, and 4) LASSO/ALASSO. Those algorithms are used to help engineers to find out the information that may be buried under

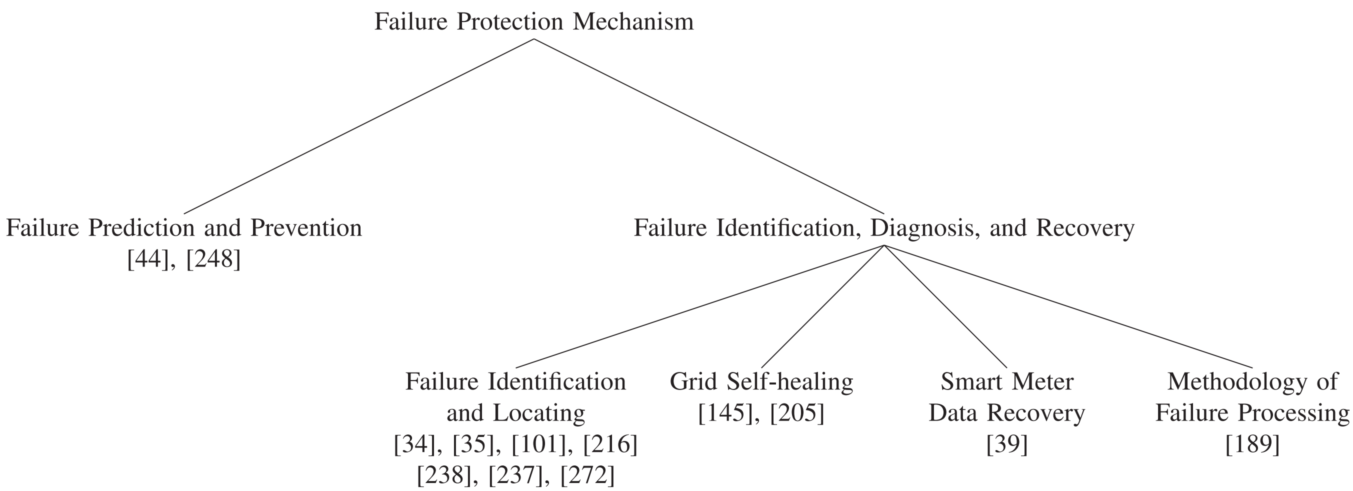

Fig. 16. Classification of Failure Protection Mechanisms

the massive data. Considering that many events in power systems are stochastic, He and Zhang [101] proposed to use probabilistic graphical models for modeling the spatially correlated data from PMUs, and to use statistical hypothesis testing for the task of fault diagnosis. Calderaro *et al.* [35] carefully designed a Petri Net to capture the modeling details of the protection system of the distribution grid, and presented a method based on this Petri Net to detect and identify the failures in data transmission and faults in the distribution grid. Note that the Petri net is one of several mathematical modeling languages for the description of distributed systems. Russell and Benner [216] presented some examples of the types of incipient failures that can be detected from substation electrical waveforms, and described the significant data and analysis requirements to enable detection and classification.

The ability to "self-heal" in the event of failure is expected to be an important characteristic of SG according to the standards [177] from the National Institute of Standards and Technology (NIST). An effective approach is to divide the power grid into small, autonomous islands (e.g. microgrids) which can work well during normal operations and also continue working during outages [205]. By appropriately controlling the system reconfiguration, the impact of disturbances or failures can be restricted within the islands or can be isolated. Cascading events and further system failures can hence be avoided. Therefore the overall efficiency of system restoration can be improved [145].

Failures could also occur on smart meters so that load data could contain corrupted or missing data. Processing or even recovering such data is important since it contains vital information for day-to-day operations and system analysis. Chen *et al.* [39] hence presented B-Spline smoothing and Kernel smoothing based techniques to cope with this issue and automatically cleanse corrupted and missing data.

In addition, for the methodology of making decision on how to process a failure, Overman and Sackman [189] suggested that the decision-making ability should be distributed to the substation and/or field devices; or at the minimum, to preload these distributed devices with sufficient information such that they can take corresponding automatic actions in the event of a system failure without having to wait for instructions from the central controller. They found that when coupled with a distributed rather than hierarchical communications architecture, preloading substation and field devices with a set of next-actions-to-be-taken instructions can significantly increase grid reliability while simultaneously reducing real-time impact from loss of reliable control.

Microgrid Protection: Protection of microgrids during normal or island operations is also an important research topic since microgrids will be widely used in SG. Note that protection of a microgrid is strongly related to its control and operation issues [133]. For example, traditional protection for distribution grids is designed for high fault-current levels in radial networks. However, during an islanding operation of the microgrid, high fault-currents from the utility grid are not present. Moreover, most of the DG units which will be connected to the low voltage microgrid will be converted/interfaced with limited fault-current feeding capabilities. This means that the traditional fuse protection of low voltage network is no longer applicable for microgrid, and that new protection methods must be developed. Feero *et al.* [72] also examined several protection problems that must be dealt with to successfully operate a microgrid when the utility is experiencing abnormal conditions, and pointed out that there are two distinct sets of problems to solve. The first is how to determine when an islanded microgrid should be formed in the face of abnormal conditions that the utility can experience. The second is how to provide segments of the microgrid with sufficient coordinated fault protection while operating as an island separated from the utility.

These new issues drive the research on new protection methods. Various methods for microgrid protection have been proposed in [4], [31], [62], [133], [179], [219], [229], [246]. Al-Nasseri and Redfern [4] described a relay that uses disturbances in the three phase voltages to provide reliable and fast detection of different types of faults within the microgrid. Brucoli and Green [31] investigated the fault behavior of inverter-supplied microgrids. They showed that the response of the system in the event of a fault is strongly dependent on the inverter control which actively limits the available fault current. Therefore, the choice of an alternative protection scheme for an islanded microgrid is strongly dependent on

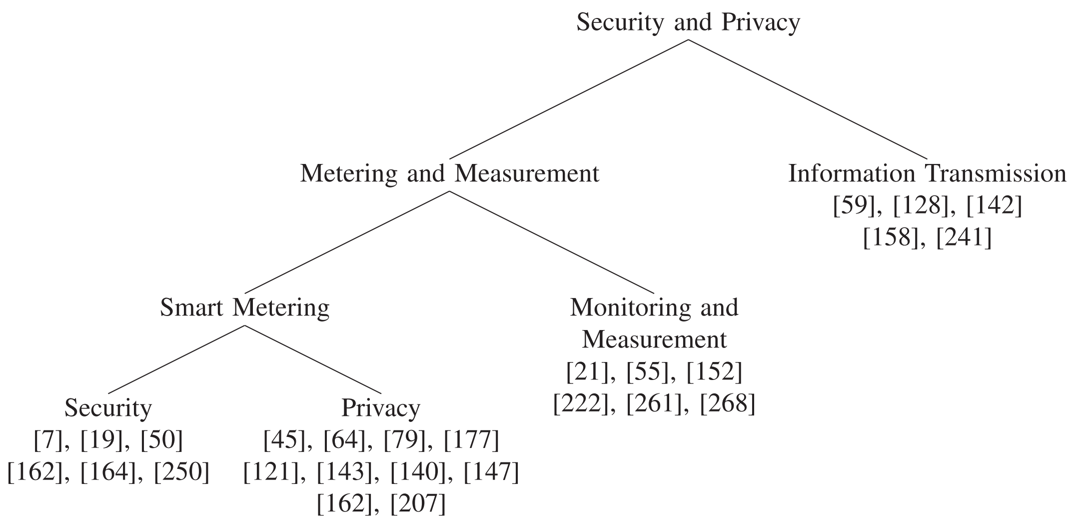

Fig. 17. Classification of the Works on Security and Privacy for SG

the type of control implemented. Driesen *et al.* [62] discussed protection issues concerning DG. Their simulations concern the effect of local induction generators on protection selectivity in a system with parallel distribution feeders. Nikkhajoei and Lasseter [179] indicated that the philosophy for microgrid protection is to have the same protection strategies for both islanded and grid-connected operations, and that it is important that the protection functions have plug-and-play functionality. Laaksonen [133] presented the protection issues of low-voltage microgrids and developed extensions to the low-voltage microgrid protection concept based on simulations with PSCAD simulation software [201]. Tumilty *et al.* [246] aimed at developing practical protection, control, and automation schemes for microgrids, and outlined several schemes covering both urban and rural applications. Sortomme *et al.* [229] proposed a protection scheme using digital relays with a communication network for the protection of the microgrid system, explored the increased reliability of adding an additional line to form a loop structure, and demonstrated a novel method for modeling high impedance faults to show how the protection scheme can protect against them. Salomonsson *et al.* [219] proposed a low-voltage DC microgrid protection system design. They presented the operating principles and technical data of low-voltage DC protection devices, both available and in the research stage. They also discussed different fault-detection and grounding methods.

B. Security and Privacy

Security is a never-ending game of wits, pitting attackers versus asset owners. SG security is no exception to this paradigm. Cyber security is regarded as one of the biggest challenges in SG [17], [166], [177]. Vulnerabilities may allow an attacker to penetrate a system, obtain user privacy, gain access to control software, and alter load conditions to destabilize the grid in unpredictable ways [166]. Fig. 17 shows a classification of the works on security and privacy for SG. We must note that the advanced infrastructure used in SG on one hand empowers us to realize more powerful mechanisms to defend against attacks and handle failures, but on the other hand opens up many new vulnerabilities. Thus in the following, we also discuss many new security and privacy issues due to the deployment of smart meters, sensors, and PMUs, together with some solutions.

1) Information Metering and Measurement: **Security in Smart Metering:** One of the security issues comes from the newly deployed smart meters. Smart meters are extremely attractive targets for malicious hackers, since vulnerabilities can easily be monetized [162]. Hackers who compromise a smart meter can immediately manipulate their energy costs or fabricate generated energy meter readings to make money. A common consumer fraud in traditional power grid is that customers turn a traditional physical meter upside down in the electrical socket to cause the internal usage counters to run backward. Due to the use of smart meter, this attack can even be done with remote computers.

Moreover, widespread use of smart meters may provide a potentially large number of opportunities for adversaries. For example, injecting misinformation could mislead the electric utility into making incorrect decisions about local or regional usage and capacity. Let us consider a simple but probably effective Denial-of-Service (DoS) attack. An adversary forges the demand request of a smart meter, and keeps requesting a large amount of energy. Within the framework of SG, it is possible that the electric utility disconnects all the appliances connected to this meter so that all the power services for this user are denied.

Widespread deployment of smart meters not only leads to a potentially large number of opportunities for adversaries, but also opens up a door to the cyber attacks which could result in broad effects and even large-scale disasters. Let us consider an example given by Anderson and Fuloria [7]. An ideal attack on a target country is to interrupt its citizens' electricity supply. Until now, the only plausible way to do that involves attacks on critical generation, transmission, and distribution assets, which are increasingly well defended. However, the emergence of smart meters changes this game. The nightmare scenario is that a country installs tens of millions of smart meters, controlled by a few central controllers. The attacker can compromise these controllers and send the combination of commands that will cause meters to interrupt the supply. Such attack could cause disastrous results.

In order to improve the security of smart metering systems, researchers have investigated many possible attacks and proposed some solutions. Cleveland [50] discussed the security requirements (confidentiality, integrity, availability, and accountability) and related threats to the main components of an advanced metering infrastructure (AMI). McLaughlin *et al.* [164] studied an adversary's means of defrauding the electrical grid by manipulating AMI systems, and validated the viability of these attacks by performing penetration testing on commodity devices. They concluded that not only is theft still possible in AMI systems, but that current AMI devices introduce a myriad of new vectors for achieving it. To prevent the adversary from forging the smart meter reading and guarantee the reading accuracy, Varodayan and Gao [250] proposed a secure method for power suppliers to echo the energy readings they receive from smart meters back to the customers so that users can verify the integrity of the smart meter. Furthermore, their mechanism can guarantee information-theoretic confidentiality, therefore solving the potential confidentiality leak introduced by the redundant measurement. Berthier *et al.* [19] explored the practical needs for monitoring and intrusion detection through a thorough analysis of the different threats targeting an AMI. They indicated that specification-based detection technology has the potential to meet the industry-strength requirements and constraints of an AMI. However, such technology incurs a high development cost.

Privacy in Smart Metering: Smart meters also have unintended consequences for customer privacy. NIST pointed out that "the major benefit provided by the SG, i.e. the ability to get richer data to and from customer meters and other electric devices, is also its Achilles' heel from a privacy viewpoint" [121], [177]. The obvious privacy concern is that the energy use information stored at the meter acts as an information-rich side channel, and can be repurposed by interested parties to reveal personal information such as individual's habits, behaviors, activities, preferences, and even beliefs [45], [147], [162]. A small-scale monitoring experiment on a private residence conducted in [147] showed that personal information can be estimated with high accuracy, even with relatively unsophisticated hardware and algorithms.

In order to address the privacy issues of smart meters, some approaches have been proposed. Li *et al.* [140] proposed a distributed incremental data aggregation approach, in which data aggregation is performed at all smart meters. Homomorphic encryption is used to secure the data en route. Hence, intermediate meters do not see any intermediate or final result. Li *et al.* [143] proposed to compress meter readings and use random sequences in the compressed sensing to enhance the privacy and integrity of the meter readings. Rial and Danezis [207] proposed a privacy-preserving protocol for billing and for performing general calculations on fine grained meter readings. The Zero-knowledge proofs are used to ensure that the fee is correct without disclosing any consumption data. Costas and Kalogridis [64] addressed the privacy problem by anonymizing smart metering data so that information gleaned from it cannot be easily associated with an identified person. Garcia and Jacobs [79] suggested that the current smart metering structure should be rethought in order to replace a unilateral trust assumption with a more multilateral architecture in which meters have a trusted component and enjoy a certain level of autonomy. Kalogridis *et al.* [121] introduced a load signature moderation system that protects smart metering data privacy. They discussed a model in which the amount of utility energy required may (partially) hide the consumer's demand, by configuring a power router to determine the power provided or required by a rechargeable battery. Such a system allows users to control (to a certain degree) their energy usage and their home energy privacy.

Security in Monitoring and Measurement: Wide deployment of monitoring and measurement devices (e.g. sensors and PMUs) could also lead to system vulnerabilities. The effective operation of SG depends on the widely-deployed accurate measurement devices. These measurements are typically transmitted to a control center, such as Supervisory Control and Data Acquisition (SCADA) Systems [176]. State estimators in the control center estimate the power grid state through analysis of measurement data and power system models. Therefore, it is very important to guarantee the integrity of the data.

A typical attack to compromise data integrity is the *stealth attack* (also called *false-data injection attack*), which was first studied by Liu *et al.* in [152]. It was shown that an attacker can manipulate the state estimate without triggering bad-data alarms in the control center. Xie *et al.* [261] also showed that with the knowledge of the system configuration, such attacks will circumvent the bad-data measurement detections in present SCADA systems, and may lead to profitable financial misconduct. In order to estimate how difficult it is to perform a successful false-data injection attack against particular measurements, Sandberg *et al.* [222] defined security indices to quantify the least effort needed to achieve attack goals while avoiding bad-data alarms in the power network control center. Yuan *et al.* [268] fully developed the concept of load redistribution attacks, a special type of false data injection attacks, and analyzed their damage to power system operation in different time steps with different attacking resource limitations.

To prevent such attacks, researchers have proposed various approaches. Recall that the control center uses state estimators to estimate the power grid state. In [21], it was shown how one can completely protect a state estimator from these unobservable attacks by encrypting a sufficient number of measurement devices. Dán and Sandberg [55] extended the works in [21], [222] and proposed two algorithms to place encrypted devices in the system to maximize their utility in terms of increased system security.

2) Information Transmission: It is well-known that the communication technologies we are using are often not secure enough themselves. It is expected that most of the security and privacy issues existing in the general communication networks (e.g. Internet and wireless networks) could also exist in SG.

Particularly, we need to focus more on wireless communication technologies since wireless networks are expected to be the more prevalent networks in SG. For example, wireless mesh networks (WMNs) are considered very reliable because they provide redundant communication paths, but WMNs are vulnerable to attacks by intelligent adversaries. ZigBee is a low-cost, low-power, wireless networking standard, based on the IEEE 802.15.4 standard. However, there are known vulnerabilities associated with IEEE 802.15.4 implementations [59].

Malicious attacks on information transmission in SG can be categorized into the following three major types based on their goals [158].

1) *Network availability*: Malicious attacks targeting network availability can be considered as DoS attacks. They attempt to delay, block, or even corrupt information transmission in order to make network resources unavailable to nodes that need to exchange information in SG. As pointed out by NIST [241], the design of information transmission networks that are robust to attacks targeting network availability is the top priority, since network unavailability may result in the loss of real-time monitoring of critical power infrastructures and global power system disasters.
2) *Data integrity*: Data integrity attacks attempt to deliberately modify or corrupt information shared within the SG and may be extremely damaging in the SG.
3) *Information privacy*: Information privacy attacks attempt to eavesdrop on communications in SG to acquire desired information, such as a customer's account number and electricity usage. An initial work was done by Li *et al.* [142], who studied a fundamental limit, i.e., how much channel capacity is needed to guarantee the secured communications in SG, from the information theory perspective, and investigated the case of single meter and Gaussian noise communication channel with an eavesdropper.

In order to improve the security and privacy of information transmission, researchers have proposed various solutions. Lu *et al.* [158] suggested that the design of countermeasures to attacks targeting data integrity and information privacy should consider authentication protocol design and intrusion detection. Furthermore, Khurana *et al.* [128] proposed a set of design principles and discussed engineering practices which can help ensure the correctness and effectiveness of standards for authentication in SG protocols. These design principles include explicit names, unique encoding, explicit trust assumptions, use of timestamps, protocol boundaries, release of secrets, and explicit security parameters.

C. Summary and Future Research

In this section, we have reviewed the works on the smart protection system in SG. Although realization of reliable system operation, resistance to attacks and failures, and preservation of privacy are the principle characteristics in the SG vision, realizing these objectives poses many challenges. We summarize the important challenges and the possible research directions worth exploring in the following.

1) **Interoperability between cryptographic systems:** Since many different communication protocols and technologies will be used in SG, and each of them may have their own cryptography requirements and security needs, realizing interoperability between cryptographic systems is not a trivial problem. Before cryptography can be used, we need a method of securely issuing and exchanging cryptographic keys. One possible solution is to design, as suggested in [17], a public key infrastructure approach, which can mimic the layered approach used in communication models. A complete solution based on this initial idea is needed.

2) **Conflict between privacy preservation and information accessibility:** How to balance privacy preservation and information accessibility is not an easy task. Consider, for example, a group of users. On one hand, the more information about demand patterns these users are willing to disclose, the smarter decisions a management system can make for optimizing profits. However, more accessible information usually means more privacy leaks, which may easily disclose user profiles and behaviors. We suggest defining several privacy preservation levels similar to those in access control, each of which describes a tolerable amount of information leak. In each level, based on the accessible information, we can define the management objectives. For example, one privacy policy may allow full information exchange within a group of users. Therefore, this group of users can optimize their profits using their shared information. Other mechanisms using advanced encryption techniques may also be applicable.

3) **Impact of increased system complexity and expanded communication paths:** The advanced infrastructure used in SG is a double-edged sword. On one hand, it lays the foundation for the future advanced grid which can serve us better. On the other hand, increased system complexity and expanded communication paths can easily lead to an increase in vulnerability to cyber attacks and system failures. Note that a fully implemented SG may consist of tens of millions of nodes. This system scale makes it difficult to anticipate how attacks may be manifested by an unpredictable and intelligent adversary, and what failures could happen due to many dependent or independent unpredictable factors [59].

One possible research direction to solve this challenge is to divide the whole system into many autonomous sub-grids so that the system complexity can be decreased dramatically. Therefore, the impact of system failures and attacks can be restricted to a limited level as much as possible. This is essentially similar to the concept of microgrid. We must note that "autonomy" does not mean absolutely no connection among these sub-grids and electric utilities. The result of the existence of such connections is that failures or attacks cannot be completely isolated. Thus a complete solution needs to consider both autonomy and interconnectivity.

4) **Impact of increasing energy consumption and asset utilization:** The modern grid is working at the "edge" of its reliable operation in more locations and more often because of increasing energy consumption and especially the methodology of increasing asset utilization (as much as possible) using modern tools [173]. This inevitably increases system reliability risk.

In order to improve system reliability, we first need to develop effective approaches to compute the margins in advance for reliable operation of the system. Second, we need real time monitoring methods to dynamically observe the margins. In addition, as stated before, maximizing the asset utilization could reduce the margins and hence increase the risk of system failure. We have to balance the utilization maximization and the risk increase.

5) **Complicated decision making process:** In order to process failures in SG, we usually have to solve much more complex decision problems, but within shorter time [173]. Considering that a commercial SG may have tens of millions of nodes, realizing this is challenging.

A possible solution is trying to use more distributed decision making systems. That is to say, a large number of failure controllers could be placed in the SG. Each of them takes care of several devices and makes decisions locally. This can decrease the complexity of the decision making process and thus reduce the failure response time. However, a locally optimal decision is not always globally optimal. We need to consider how to balance the response time and the effectiveness of the local decision.

IX. Conclusions and Lessons

Due to the potential importance of SG, this survey comprehensively explores the technologies used in SG. We have surveyed the major SG projects/programs/trials and three major technical systems in SG: the smart infrastructure system, the smart management system, and the smart protection system. We have outlined challenges and future research directions worth exploring for each of these three systems.

We further divided the smart infrastructure into three subsystems: the smart energy subsystem, the smart information subsystem, and the smart communication subsystem. For the smart energy subsystem, we have reviewed the works on power generation, transmission, and distribution. We have also described two important new grid paradigms: microgrid and G2V/V2G. For the smart information subsystem, we have reviewed the works on information metering, measurement, and management. For the smart communication subsystem, we have reviewed the wireless and wired communication technologies, and the end-to-end communication management. In brief, in the transition from the conventional power grid to the SG, we will replace a physical infrastructure with a digital one. The needs and changes present the power industry with one of the biggest challenges it has ever faced [116].

For the smart management system, most of the existing works aim to improve energy efficiency, demand profile, utility, cost, and emission, based on the smart infrastructure by using optimization, machine learning, and game theory. We believe that within the advanced infrastructure framework of SG, more and more new management services and applications would emerge and eventually revolutionize consumers' daily lives.

For the smart protection system, we have reviewed the works related to system reliability, failure protection mechanism, security and privacy in SG. However, we must note that the advanced infrastructure used in SG on one hand empowers us to realize more powerful mechanisms to defend against attacks and handle failures, but on the other hand, opens up many new vulnerabilities. More thorough research on the smart protection system is desirable.

From the existing efforts on SG, we have also learned some useful lessons. In the following, we list these lessons from four perspectives: practical deployments and projects, infrastructure, management system, and protection system.

First, the practical deployments and projects of SG should be well-analyzed before the initiative begins. For example, Xcel Energy's SmartGridCity project [260] aimed at turning Boulder, Colorado into an ultimate SG hub. However, when the project was almost finished in 2010, only 43% of Boulder residents had installed smart meters and the cost of the project ballooned to $42.1 million from $15.3 million. Note that this number does not count the cost of running and maintaining the grid. One possible reason why the result was not satisfactory is that Xcel failed to perform a thorough cost-benefit analysis before the initiative begins. Therefore, although SG itself is an encouraging and promising technology, we still need to carefully design blueprints of SG projects. In other words, new and advanced technologies do not necessarily and directly lead to a profitable and bright future. We need advanced and mature project initiation, planning, execution, and controlling to ensure that the practical projects of SG can be completed satisfactorily.

Second, the current projects and programs are mainly led by electric utilities or related organizations (refer to Table IV). They probably may not have enough experience on the design and deployment of complicated communication and information systems. However, SG is a complex system of systems, resulting in complicated interactions among energy, information, and communication subsystems. The evolution of the SG infrastructure may ask for more experienced information and communication technology sectors to be involved. For example, electric utility may still lead the evolution of the grid while getting other sectors involved by outsourcing or collaboration.

Third, the term *smart* in "Smart Grid" implies that the grid has the intelligence to realize advanced management objectives and functionalities. However, thus far, as stated in Section VII, most of such objectives are related to energy efficiency improvement, supply and demand balance, emission control, operation cost reduction, and utility maximization. The experience in other sectors, especially consumer electronics, tells us that only the technologies leading to customer-oriented functionality will eventually motivate customers to accept and use them. SG is no exception. For example, one of the important management objectives in SG is reducing CO_2 emission. However, this does not necessarily imply that the customers are willing to upgrade their devices to support the new feature. Therefore, in addition to designing various management objectives and functionalities, the electric power industry needs to think about how to motivate customers to buy into these new ideas.

Fourth, for the protection part, we have the following two lessons. The **first** one is that we need to investigate the behaviors of electric utilities. Although SG is expected to provide advanced protection mechanisms, in real life the electric utilities desire to provide services to minimize costs or maximize profits. Therefore, they may tend to neglect security and privacy, and long-term system reliability in the face of a threat not well understood [59]. This poses some potential challenges for other system designers. For example, we may ask "*Should we still fully trust the electric utility when we* *design our functions in the domain of this electric utility?*" It is likely that the electric utility itself is trustworthy, but it has no capacity of providing fully trusted services. As mentioned in Section V-C, in order to save cost, electric utilities may outsource the information management to a third party (e.g. a cloud provider). As a result, electric utilities may lose, to some extent, the control of ensuring the information confidentiality and integrity. The **second** lesson is that when we introduce new technologies into SG, we should also assess the possible risk introduced. For example, as stated in Section VIII, using the smart metering architecture itself introduces many new security and privacy issues. Therefore, we need to do a thorough assessment on the new technologies.

In summary, there is no doubt that the emergence of SG will lead to a more environmentally sound future, better power supply services, and eventually revolutionize our daily lives. However, we still have a long way to go before this vision comes true. We need to explore not only how to improve this powerful hammer (SG), but also the nails (various functionalities) it can be used on.

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Appendix A
Abbreviations

See Table III (right).

TABLE III
ABBREVIATIONS

3G or 4G	3rd or 4th generation mobile telecommunications
AC	Alternating current
AP	Access point
DC	Direct current
AMI	Advanced metering infrastructure
AMR	Automatic meter reading
DER	Distributed energy resource
DG	Distributed generation
DOE	Department of energy
DoS	Denial-of-service
EV	Electric vehicles
FNET	Frequency monitoring network
G2V	Grid-to-vehicle
GPS	Global positioning system
GSM	Global system for mobile communications
IEEE	Institute of electrical and electronics engineers
IETF	Internet engineering task force
IP	Internet protocol
NIST	National institute of standards and technology
PHEV	Plug-in hybrid electric vehicle
PLC	Powerline communications
PMU	Phasor measurement unit
QoS	Quality of service
RF	Radio frequency
SCADA	Supervisory control and data acquisition
SEP	Smart energy profile
SG	Smart grid
SMS	Short message service
TCP	Transmission control protocol
V2G	Vehicle-to-grid
VCG	Vickrey-Clarke-Groves
VPP	Virtual power plant
WCDMA	Wideband code division multiple access
CDMA-2000	Code division multiple access 2000
UML	Unified modeling language
WAMS	Wide-area measurement system
WMN	Wireless mesh network
WSN	Wireless sensor network
XML	Extensible markup language

Appendix B
Smart Grid Projects/Programs/Trials

See Table IV next page.

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TABLE IV
A SUMMARY OF MAJOR PROJECTS/PROGRAMS/TRIALS

	Project/Program Name	Organization	*Country	Period	Brief Description of Project/Program/Trial	Project/Program /Trial Category
1	Acea Distribuzione Smart Metering in Rome [226]	Acea Distribuzione	IT	From 2004	The implementation of the integrated advanced metering management system began in 2004 with the objective of improving energy efficiency in Italy's capital. The system includes high accuracy bi-directional meters and smart grid applications such as network operation control, and the ability to monitor low and medium voltage line status automatically.	Smart meter and AMI
2	American Transmission Company's Phasor Measurement Unit Project [5]	American Transmission Company	US	2010-2012	It aims at building a fiber optics communications network for high-speed communications to maximize the full capability of phasor measurement networks across American Transmission Company's transmission system.	Transmission grid
3	Austin Energy Smart Grid [13]	Austin Energy	US	From 2003	Smart Grid 1.0 deployment started in 2003. It is the first fully operational SG deployment in the U.S. Smart Grid 2.0 deployment started in 2008. It offers improved customer services, including: 1) by phone or online real-time meter reads, 2) web-based management of smart consumer appliances, and 3) remote service turn-on and shut-off.	Integrated system
4	CERTS Microgrid Test Bed Demonstration [134], [138]	American Electric Power	US	From 2006	It aims at enhancing the ease of integrating small energy sources into a microgrid.	Integrated system and microgrid
5	DLC+VIT4IP [84]	Kema Nederland BV	DE, AT, UK, NL, IT, BE, IL	2010-2013	It aims at developing, verifying, and testing a high-speed narrow-band power line communications infrastructure using the Internet Protocol (IP) which is capable of supporting existing and extending new and multiple communication applications.	Communication and information systems
6	EU-DEEP[84]	GDF Suez	FR, GR, UK, DE, BE, ES, SE, PL, LV, AT, HU, IT, FI, CY, CZ, TR	2004-2009	It brings together eight European energy utilities and aims at removing most of the technical and non-technical barriers that prevent a massive deployment of distributed energy resources in Europe.	Integrated system and distributed resources
7	Fenix [84]	Iberdrola Distribución	ES, UK, Sl, AT, DE, NL, FR, RO	2005-2009	It aims at boosting distributed energy resources by maximizing their contribution to the electric power system, through aggregation into large scale virtual power plants and decentralized management.	Integrated system and virtual power plants
8	Grid4EU[84]	ERDF	DE, SE, ES, IT, CZ, FR	2011-2015	It is led by a group of European distribution system operators and aims at testing in real size some innovative system concepts and technologies in order to highlight and help to remove some of the barriers to the SG deployment (technical, economic, societal, environmental or regulatory).	Integrated system
9	INOVGRID [84]	EDP Distribucao SA	PT	2007-2011	It aims at replacing the current low voltage meters with electronic devices called Energy Boxes, using Automated Meter Management standards.	Integrated system and home application
10	IntelliGrid[30], [112]	Electric Power Research Institute	US	From 2001	It aims at creating a new electric power delivery infrastructure that integrates advances in communications, computing, and electronics to meet the energy needs of the future. At present, the IntelliGrid portfolio is composed of five main projects: IntelliGrid architecture, fast simulation and modeling, communications for distributed energy resources, consumer portal, and advanced monitoring systems.	Other
11	Large-scale demonstration of charging of electric vehicles [84]	ChoosEV A/S	DK	2011-2013	Its main investigation is whether it is possible to move the charging of electric vehicles to a more environmental friendly time and whether the electric vehicle owner is interested in it.	Smart meter and AMI, integrated system, and electric vehicle

*Country Codes: AT-Austria, BE-Belgium, CA-Canada, CN-China, CY-Cyprus, CZ-Czech Republic, DE-Germany, DK-Denmark, FI-Finland, FR-France, GR-Greece, ES-Spain, HU-Hungary, IL-Israel, IT-Italy, LV-Latvia, MK-Macedonia, NL-Netherlands, RO-Romania, PL-Poland, PT-Portugal, SE-Sweden, Sl-Slovenia, TR-Turkey, UK-United Kingdom, US-United States

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TABLE IV
A SUMMARY OF MAJOR PROJECTS/PROGRAMS/TRIALS (CONTINUED)

	Project/Program Name	Organization	*Country	Period	Brief Description of Project/Program/Trial	Project/Program /Trial Category
12	Model City Manheim [84]	MW Energie	DE	2008-2012	It concentrates on an urban conurbation in which distributed renewable energy resources are used to a large extent. Within the framework of the E-Energy project, a representative large-scale trial is being conducted both in Manheim and in Dresden to demonstrate that the project can be applied and translated to other regions.	Integrated system
13	More Microgrids [84]	ICCS/National Technical University of Athens	ES, GR, PT, NL, IT, DK, MK, DE	2006-2009	It aims at: 1) implementing sophisticated control techniques for distributed generators; 2) integrating micro-grids into operation and development of the power system; 3) conducting field trials to test control strategies on actual microgrids; and 4) quantifying microgrids effects on power system operation and planning.	Integrated system, smart meter and AMI, microgrid, distribution grid, and home application
14	Pacific Gas and Electric Company's SmartMeter Program [190]	Pacific Gas and Electric Company	US	From 2006	It is part of a statewide effort driven by the California Public Utilities Commission to upgrade California's energy infrastructure with automated metering technology. This technology will enable new programs that help California energy customers use less energy and save money.	Smart meter and AMI
15	Pacific Northwest Smart Grid Demonstration Project [191]	Bonneville Power Administration	US	2010-2014	It aims at 1) validating new smart grid technologies and business models; 2) providing two-way communication between distributed generation, storage, and demand assets and the existing grid infrastructure; 3) quantifying smart grid costs and benefits, and 4) advancing standards for interoperability and cyber security approaches.	Integrated system
16	SmartGridCity, Boulder, Colo. [260]	Xcel Energy	US	2008-2010	SmartGridCity is a technology pilot that explores smart-grid tools in a real-world setting. The goal of this pilot is to help determine: 1)Which energy management and conservation tools customers want and prefer; 2) Which technologies are the most effective at improving power delivery; 3) How best to incorporate SG technology into the business operations to improve efficiency, reduce carbon emissions and modernize the energy delivery system; 4) How to roll out the most promising SG components on a wider scale. Xcel Energy has installed approximately 23,000 smart meters in Boulder as part of a new era in electricity grid management.	Integrated system, smart meter and AMI
17	Smart Grid Demonstration Project in Sino-Singapore Tianjin Eco-city [225]	Tianjin Electric Power Company	CN	2010-2011	The project aims at building a smart power supply network with 220kV and 110kV transmission grid, 10-35kV distribution lines, and 380V/220V low voltage distribution grid.	Integrated systems

*Country Codes: AT-Austria, BE-Belgium, CA-Canada, CN-China, CY-Cyprus, CZ-Czech Republic, DE-Germany, DK-Denmark, FI-Finland, FR-France, GR-Greece, ES-Spain, HU-Hungary, IL-Israel, IT-Italy, LV-Latvia, MK-Macedonia, NL-Netherlands, RO-Romania, PL-Poland, PT-Portugal, SE-Sweden, Sl-Slovenia, TR-Turkey, UK-United Kingdom, US-United States

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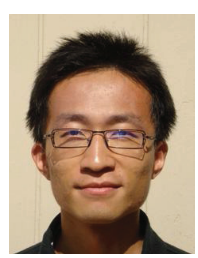

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