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A survey on the development status and challenges of smart grids in main driver countries

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ABSTRACT

Smart grids are among the most significant evolutionary developments in energy management systems because they enable integrated systems, including decentralized energy systems, the use of large-scale renewable energy and major improvements in demand-side-management. Research on smart grid development has been carried out worldwide for more than ten years, and there are already successful cases and rich experiences in this field. This paper compares the development backgrounds and infrastructure statuses of smart grids in various countries. It also presents an overview of the smart grid development situation within these countries. Moreover, it discusses the research results and lessons learned from smart grid projects in different countries and summarizes their achievements and challenges. Although every country has its own electricity market modes and basic energy situation, our findings can provide a map for national policy makers and power companies to guide the development of smart grids.

1. Introduction

The growing problems of conventional energy shortages and environmental pollution have become the largest challenges facing the sustainable development of human society. Climate change impacts, rising energy costs, and renewed concerns over nuclear risks have heightened the urgency for the transition from a conventional energy structure to a low-carbon future [1,2]. To solve such problems, energy-efficient technologies, renewable energy technologies, new transportation technologies and other low-carbon technologies must be rapidly developed and deployed at large scales [3]. Moreover, a variety of such types of technologies have focused on renewable energy generation and end-user perspectives, resulting in dramatic changes in the generating side and consumer side of traditional power grids. Moreover, new challenges have been presented in the development and safe operation of electricity transmission and distribution networks [4–6]. With this background, SGs have emerged at a historic moment and have been widely recognized worldwide.

This paper compares the development backgrounds and infrastructure statuses of various countries. It presents an overview of SG development by discussing the research results produced by SG projects in various countries while summarizing their achievements and challenges. In this paper, we intend to create a roadmap for national policymakers and power companies that can guide the development of SGs. We will first present the background and definitions of SGs in Section 2. Next, basic information about SGs will be introduced in Section 3. The development status and achievements of SGs will then be extensively evaluated in Section 4. Subsequently, we will discuss challenges and barriers related to SGs for each country, and future trends and tendencies will also be noted. Finally, the conclusions will be provided in Section 6.

2. Background and definitions of SGs

□The growing problems of conventional energy shortages and environmental pollution have become the most significant challenges facing the sustainable development of human society. According to a report by the World Resources Institute, from 1990 to 2014, worldwide greenhouse gas emissions (GHG) by sector continued to increase beyond the problems that have already been noted over the last two decades. Moreover, the GHG released during energy production accounts for the majority of total GHG emissions. In the International Energy Outlook 2016 (IEO2016) Reference case, world energy-related CO2 emissions will increase from 32.3 billion metric tons in 2012 to 35.6 billion metric tons in 2020 and to 43.2 billion metric tons in 2040. Awareness of the environmental impact and the carbon footprint of all energy sectors continues to increase [7].

In conjunction with this phenomenon, decarbonization has been proposed by many researchers and unions. Two elements are highlighted as important for decarbonization: improved energy efficiency

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and increased shares of renewable energy. Efficient energy usage at all stages of the energy chain from production to final consumption is meaningful for the reduction of GHG and therefore the mitigation of climate change. In addition, conventional energy shortages and serious environmental pollution problems have compelled many countries to develop environmentally friendly renewable energy so that they can reduce their dependence on conventional energy resources, realize reductions in environmental pollution caused by the increasing energy demand, and ensure sustainable social and economic development. However, compared to conventional energy sources, many renewable energy sources exhibit randomness and intermittency. A large amount of renewable energy generation in a power system, whether in large-scale centralized systems or small-scale distributed systems, can adversely impact the safety and reliability of traditional power systems. Therefore, sophisticated control systems are needed to facilitate the connection of sources to the highly controllable grid [8]. In such cases, SGs play a pivotal role in renewable-based low-carbon energy systems while providing an essential platform to enable renewable energy generation in the central grid [54,55].

SGs are therefore essential to realizing decarbonization in the energy sector. In addition, the call for nuclear-free production in the energy sector has appeared many times in recent years owing to the vulnerabilities and insecurities of nuclear power, although nuclear resources are environmentally friendly. In other words, the emissions of GHG from the energy sector can be eliminated with technologies that are now available or foreseeable [9]. This can be realized while creating a much more effective energy system than before. The conventional electricity grid has no potential to provide enough services to address energy needs and the integration of RE at the scale required to meet the clean energy demand for the future [10]. Therefore, the introduction of SGs is essential to reduce GHGs.

The development of SGs has attracted considerable interest from fields as diverse as economics, sociology and electrical engineering [11]. G.M. Shafiullah investigated the current major research programs in Europe, America and Australia for smart grids from the technological perspective, focusing on the deployment integration of renewable energy sources [12]. Clastres provided a preliminary overview of possible solutions to encourage the emergence of new smart grid technologies [13]. Uchechi Obinna explored the roles and perceptions of different stakeholders involved in the development and implementation of smart grid pilot projects in the Netherlands and proposed more active involvement of end users during the SG development progress [14]. Mah et al. examined the motivations, processes and outcomes of the development of smart grids in South Korea through the perspectives of governance and innovation systems [15]. Mohamed E.EI-Hawary introduced SGs and described their technical, environmental and socioeconomic, and other non-tangible benefits to society [16]. Zio and Aven considered the future world of smart grids from a different perspective of uncertainties and the related risks and vulnerabilities [17]. Although studies on SGs have been conducted from the perspectives of technologies, stakeholders, pilot projects, processes and outcomes, and risks and vulnerabilities, most work focused only on one aspect of SGs. Moreover, the countries selected for analysis were primarily OECD countries. This paper provides a comprehensive and systematic survey of most of the topics related to SGs, and both OECD countries and non-OECD countries are considered.

The improvement and performance of new power networks continue what network operators have been doing for several decades, with each region having its own approach and focus. Fig. 1 presents the main drivers of SG development [18]. Here, we select one or two typical objects from each driving sector as representatives to investigate the development status of SGs. The United States and the European Union are the main OECD countries, Japan was selected from OECD Asian countries, and China represents Emerging countries. Since 2009, these countries have developed their own SG roadmaps and have started research and pilot projects in accordance with their own situations and requirements [19–21]. Following a series of attempts and explorations, SG development has entered a critical period. Most pilot projects in the United States and Europe have been completed with the support of government funds. These pioneers should describe mature technologies, present a reasonable market mechanism and business model, establish a generally approved standard system so that these activities can attract investment in SGs and encourage common users to actively participate in the subsequent construction of SGs, and remove the barriers to the widespread use of SGs. By the end of 2015, Japan finished four domestic demonstration projects in Keihanna Science City, Yokohama City, Kitakyushu City and Toyota City as planned [35]. The experience of their utilization of renewable energy and energy management systems and other advanced technologies is worthy of a detailed summary. Even in China, a large number of research and pilot projects have been deployed on schedule, and some mature technologies have already entered the extension phase. Consequently, the exchange and cooperation between countries is very important at such a crucial time. Sharing lessons learned, strengthening technical cooperation, and formulating international standards together toward achieving the goal of SG development represent effective ways of avoiding technical risks and reducing the early-stage investment requirements. These actions also represent a rational choice for major countries in the context of economic globalization.

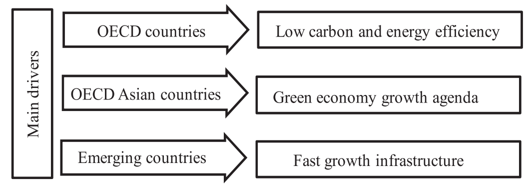


Fig. 1. Main drivers of SG development [7].

A uniform definition of SGs has yet to be formed at the international scale. In the United States, SGs emphasize the reliability, safety and operational efficiency of power systems through the strong support of digital and other advanced technologies. In addition, the United States is also devoted to the reduction of the power supply costs created by an aging power infrastructure [22]. Europe's innovative SG scheme attempts to reconcile two approaches of renewable energy development, namely, large-scale centralized approaches and small-scale, local and decentralized approaches, to realize a transition toward a fully low-carbon electricity system [23] while attempting to realize energy trading between European countries. To promote such objectives, the European Commission also monitored SG projects, proposed guidelines for the cost-benefit analysis of SG projects and smart meter deployment, investigated the complexity features of smart energy grids, and evaluated the social dimensions of SG projects [24–29]. In Japan, because its energy self-sufficiency is a mere 4% [30], the focus of SG plans is to build renewable-friendly power grids. Moreover, the Great East Japan Earthquake that struck on March 11, 2011, and the subsequent nuclear power plant accident have prompted the Japanese government to adopt reforms targeted at the power system; here, SGs provide stable power supplies and optimize overall grid operations from power generation to the end user [31,32]. Moreover, Japan has developed SGs to achieve the CO2 emission reductions stipulated in the Kyoto Protocol. In China, high electricity consumption and multiple electricity load structures have appeared with the rapid development of the economy and increasingly large populations, which result in a high demand for a Strong SG [33]. China prefers to renovate traditional power systems with modern information technology while establishing a highly automated and widely distributed network for energy exchange to solve its energy balance problem [34].

SG definitions represent the development needs of national or regional electricity. They are merely a different way of articulating the development of electricity systems [42]. However, conceptual consistency among various working groups is necessary to perform analyses

Table 1
Definitions of SGs.

Organizations		Definition
International Electrotechnical Commission (IEC)		An electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers and those that do both—to efficiently deliver sustainable, economical and secure electricity supplies [37].
USA	National Institute of Standards and Technology (NIST)	A modernized grid that enables bidirectional flows of energy and uses two-way communication and control capabilities that will lead to an array of new functionalities and applications [38].
	Institute of Electrical and Electronic Engineers (IEEE)	A large 'System of Systems', in which each functional domain consists of three layers: (i) the power and energy layer, (ii) the communication layer, and (iii) the IT/computer layer. Layers (ii) and (iii) above are the enabling infrastructure that makes the existing power and energy infrastructure 'smarter' [38].
EU	European Commission (EC)	Energy networks that can automatically monitor energy flows and adjust to changes in the energy supply and demand accordingly, reach consumers and suppliers by providing information on real-time consumption, and better integrate renewable energy [39,59].
	European Regulators' Group for Electricity and Gas (ERGEG)	An electricity network that can efficiently integrate the behavior and actions of all users connected to it—including generators, consumers and those that do both—to ensure an economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety [40].
Japan	Japan Smart Community Alliance (JSCA)	A system that can promote the greater use of renewable and unused energy and local generation of heat energy for local consumption and contribute to the improvement of energy self-sufficiency rates and reduction of CO2 emissions. Provides a stable power supply and optimize overall grid operations from power generation to the end user [41].
China	State Grid Corporation of China (SGCC)	An integration of renewable energy, new materials, advanced equipment, information technology, control technology and energy storage technology, which can realize digital management, intelligent decision making and interactive transactions of electricity generation, transmission, deployment, usage and storage [33].

and create high-quality standards [43]. Table 1 shows the selection of SG definitions. Although six different definitions of SGs exist, they are reasonably consistent. In brief, the principal parameters of SGs can be summarized as follows [42,44]: (1) Digitization, two-way communication and automatic monitoring; (2) Accommodating all generation and storage options: integrating renewable and energy storage in the electricity network; (3) Self-healing from power disturbance events with necessary maintenance of self-adaptive networks; (4) Enabling the creation of new products, services and markets; (5) Demand response and energy management system for lowering peak demand and overall load; (6) Enabling active participation of end users and provide more user options; and (7) Optimizing assets and operating efficiently and resiliently.

3. Basic information of SGs

3.1. Characteristics of SGs

The basic characteristics of SGs are summarized in Table 2, in which compatibility, flexibility and high efficiency are the basic characteristics of SGs. Serviceability and safety are auxiliary characteristics of SGs, and interoperability represents the backbone. Fig. 2 shows the interoperability layer of SGs.

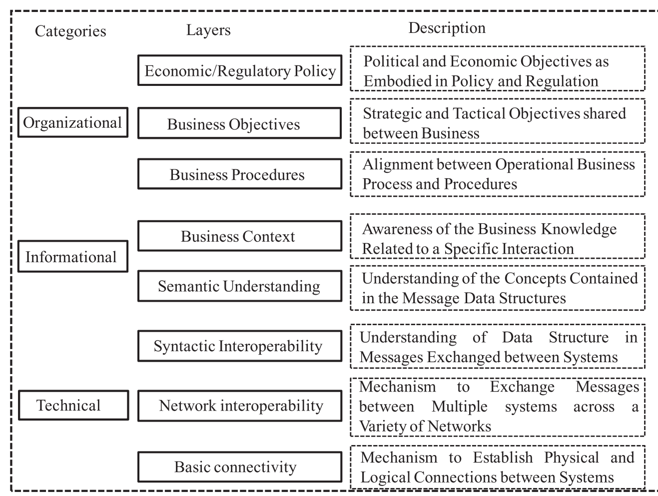


Fig. 2. The interoperability layer of SGs [61].

3.2. Technological systems of SGs

SGs play an important role in current and future grid construction [62]. Moreover, the critical issues concerning smart grids can mainly be defined as technologies (including equipment, skills, systems, services, infrastructure, software and components) that are currently available or are expected to become available in the near future [63,64]. According to previous studies and many academic surveys concerning SGs [65–70], the relevant technologies can be mainly divided into technologies for the transmission system, technologies for the distribution system, and technologies for the demand side. In addition, these technologies can be classified by function as follows: ① monitoring and control technologies for power transmission and distribution systems, ② energy management technologies for the demand side, ③ possible advanced technologies to enable the effective operation of systems, and ④ advanced interface technologies. Additional details are depicted in Fig. 3.

Table 2
Key characteristics of SGs.
Source: [19,60]

Characteristics	Contents
Compatibility	Accommodates all generation options; Deployment includes the integration of various types of distributed resources (renewable energy, small-scale combined, power and energy storage, etc.)
Flexibility	Flexible power resources; enables informed participation by customers (Demand response); New controllable loads (electric vehicles);
High efficiency	Digital information and advanced technologies; dynamic optimization of power resource allocation; enhanced system operating efficiency
Serviceability	Enables new products, services and markets; provides the necessary power quality for a range of needs; integration of smart appliances and consumer devices
Safety	Self-healing ability; resiliency to disturbances, attacks and natural disasters
Interoperability	Deployment of smart metering; control and visualization technologies; information communication technologies

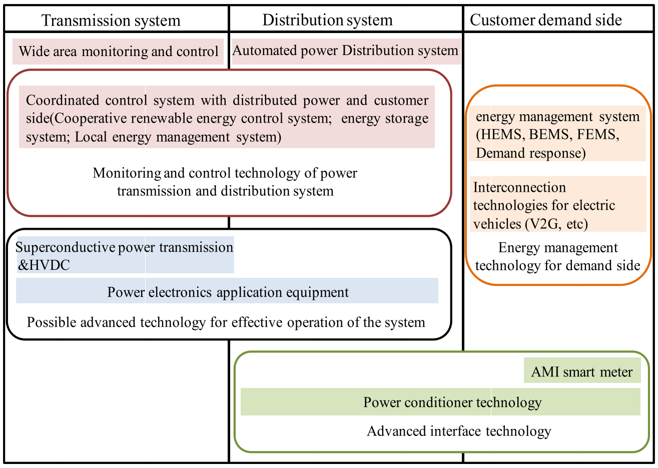


Fig. 3. SG technologies [42].

4. Development status and achievements of SGs

4.1. Infrastructure of SGs

Because the internal environment and the basic conditions of existing grids are different in each selected country, their development priorities and routes for SGs must be different. Five essential aspects were analyzed to compare the infrastructures of SGs for various countries.

Concerning the organizational and incentive perspective, America and Europe follow the most similar modes. Both have government-dominated systems, making SG development a national development strategy through legislation. Moreover, the government provides special funds to support research and demonstration projects. Japan uses a special operation mode wherein government, industry and academic institutions jointly promote SGs. The government (METI) provides policy supervision and creates a favorable business environment; industry (NEDO) and academic institutions lead research and demonstration projects [56,71]. In China, SGs were included in the national development strategy and in the 12th Five-Year Plan. The government supports the research work in the form of national science and technology projects. The demonstration and construction of SGs has been led by the grid company [57].

Concerning supervision and tariffs, America and Europe have strong regulations and market mechanisms: they have applied a terminal price; have experience implementing real-time pricing (RTP), critical peak pricing (CPP), peak time rebate (PTR) and time-of-use (TOU) prices [58]; and have facilitated the implementation of automated demand response and distributed energy. Japan has only introduced various types of TOU price systems. Some regional pilot programs have implemented CPP prices. China continues to employ time-invariant electricity pricing, although some regional pilot programs have introduced TOU pricing. Clearly, there is a large gap between China and the other two countries and Europe in terms of electricity tariff mechanisms.

In terms of customer features, China exhibits significant differences from other countries. In America, Europe and Japan, residents consume a higher proportion of electricity, generally approximately 30%. However, in China, industry consumes a higher proportion of electricity. Residential electricity consumption accounts for a relatively small proportion, generally approximately 15.1% in 2014.

Concerning energy structure, America and Europe have a uniform distribution and rational structure. In Japan, most of the energy resources rely on imports from abroad, which creates a large demand for the utilization of renewable energy. In addition, renewable energy in these two countries and Europe is provided to the grid mainly in a distributed manner. In addition, all these countries utilize fuel- and gas-fired generators. Unlike in America, Europe, and Japan, the energy and load distribution of China is unbalanced; electricity must be transmitted over long distances, ranging from 1000 and 3000 km and must be provided with a wide-range configuration due to power resources (mostly located in northern and western China) being far from power demand centers (usually located in central and eastern China). Renewable energy, such as wind power, is provided to the grid mainly in concentrated forms. The power grid is dominated by thermal power plants instead of gas, oil and other plants, which can achieve higher efficiencies.

Concerning management, the management of SGs in America and Europe is decentralized. Moreover, the formulation of widely recognized standards is a time-consuming process because there are many stakeholders and suppliers involved in the electricity system. In Japan, there are only 10 electricity companies divided up by area, and grid ownership and management is relatively decentralized. The government directs energy consumption, and power companies must implement corresponding policies. Compared to power grids in America, Europe, and Japan, China's power grid has a relatively concentrated ownership and control structure, which favors unified planning and scheduling.

4.2. Policy support

In Europe and the above three countries, there are numerous SG stakeholders due their wide variety of functions and applications [52]. Both power company providers and common stakeholders are integral aspects of SGs. Therefore, how to form a balance under such complex situations is essential to the continued development of SGs. Here, policy plays an important guiding role in this process. Clear policy can be used to establish a good external development environment for SGs while facilitating the coordination and cooperation of all parties involved in SGs.

SGs are extremely complex systems with many components, including generation, transmission, substation, distribution, consumption, power dispatch, and information platforms. Any policy related to these areas can be further related to SGs [46]. Table 3 summarizes the policy support for SGs among the three selected countries and Europe. It is evident that America, Japan, Europe, and China published several regulations to support the development of SGs in the early stages.

SG policies in America and Europe are mainly established by states. In America and Europe, the construction of SGs is organized and guided by legislative actions, and the government releases policy framework reports. Among them, the United States has focused on formulating policy related to the upfront investment in an attempt to motivate private investment and stimulate the long-term involvement of all stakeholders to promote the development of SGs. Europe, as an active promoter in the reform of world energy generation, has concentrated their SG policies on low-carbon programs. Energy supply security is their objective. Japan has focused on the deployment of renewable energy in an attempt to improve their energy self-sufficiency while affirming the importance of SGs in its new energy structures. The government of China, as representative of emerging countries, has issued a series of support policies for renewable energy development and energy savings. Since 2010, the implementation of SGs has been promoted as a national strategy.

4.3. Investment

Investment is the economic foundation for the development of SGs. Generally, the landscape of SGs is highly dynamic and rapidly changing, and emerging economies are major players in SG investment [86]. Table 4 shows the investment situation of SGs in various countries.

Clearly, America, Europe and China have invested substantial funds in the development of SGs. In contrast to those countries and Europe, Japan invested only $849 million to develop its SG in 2009. Prior to the

Table 3
Policy support for SGs.
Source: [72–85]

Countries	Time issued	Policy Support	Main Contents
America	2007	EISA [72]	Commitment to allocate state-owned special funds; Support NIST to compile standards system for SGs; Coordination of nationwide SG standardization
	2009	ARRA [73]	Commission Department of Energy grants totaling $4.5 billion of government funds; Motivate domestic private investment into SGs; Support the research and demonstration of SGs
Europe	2008	EEPP [74]	Indicate that green technology plays a key role in the economic recovery plan; Stipulate considerable portion of funds should be used for electricity interconnection and Offshore wind projects
	2009	Third Legislation for Further Liberalization of the Electricity and Gas Markets [75]	States to further liberalize the electricity markets to facilitate greater supplier competition and consumer choice
	2010	European Council summits [76]	Encourage the investigation of energy infrastructure, research and innovation projects; Guarantee the security of EU energy supply system; address climate change
	2012	Energy Efficiency Directive 2012/27/EU, the European Commission [35]	Clear focus on achieving the overall energy efficiency target of reducing primary energy consumption by 20% by 2020.
	2014	Regulation [EU] No 333/2014 and No 517/2014 on Carbon dioxide emissions [36]	Establishes updated policies and strengthens the existing climate policies.
Japan	2009	Policy Package to Address the Economic Crisis [77]	Advocate the development of solar power generation, energy-saving appliances and low-fuel-consumption cars; Attempt to realize an installed solar power generation capacity of 28 million kW by 2020
	2010	Report of the next-generation power transmission and distribution network [78]	Emphasis on the stability of power systems; Set encouragement strategies for improving distribution systems and developing battery technologies; Guarantee a power supply during system accidents;
	2010	New Strategic Energy Plan [79]	Establish 3E energy viewpoint (energy security; environment; economic efficiency); Promote the development of SGs
	2014	Fourth Basic Energy Plan [80]	Concentrates on the policy objectives of energy reliability, security, affordability, efficiency, and reduced emissions.
China	2006	Renewable energy pricing and cost-sharing (pilot management scheme) [81]	Stipulate two types of pricing mechanisms: government-directed pricing and government-guided pricing.
	2006	Management measures on auxiliary service in power system 2006 [82]	States that power plants will provide two kinds of ancillary services: basic ancillary services and paid ancillary services
	2010	Renewable energy law [83]	Stipulate full protective purchase of renewable electricity.
	2012	Twelfth Five-Year Plan related to major science and technology industrialization projects of Smart Grid [84]	Present the development ideas and principles of SG; Establish general development objectives; Perform nine key tasks
	2013	Financial subsidy for distributed PV project [85]	Give subsidies for distributed PV based on resource conditions related to distributed energy in SGs

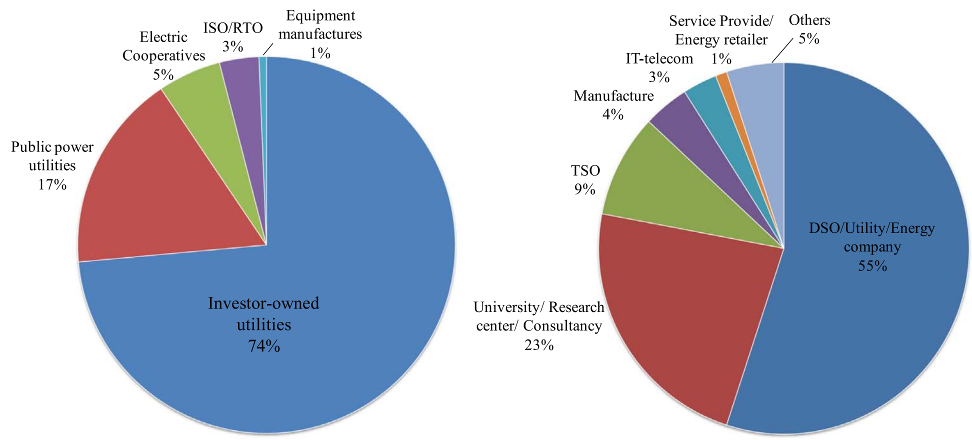
Fukushima nuclear crisis, the energy supply structure of Japan was stable and secure. At that time, some people even believed that a SG did not need to be developed. Therefore, in terms of past funding for SGs, the investment by Japan has not been as strong as that of other countries. However, the promotion of efficiency and reliability of energy over the last several years has ultimately forced all utilities to make plans for the development of SGs. The investment in SGs in Japan will increase from approximately $1 billion in 2011 to $7.4 billion in 2016 [87].

Europe has invested the most money ($261 billion) in the development of SGs. Europe also forecasts that it will increase its investment in SG development to $79 billion by 2020 [88]. Table 4 shows that America will increase investment to $338 to $476 billion in its SG implementation. The costs allocated to transmission and substations are between 19% and 24% of the total cost, the costs allocated to distribution are between 69% and 71%, and the costs allocated to consumer systems are between 7% and 10% [89]. In China, SGCC is solely responsible for the development of nationwide SGs. A total of $101 billion will be provided to support future SG development [90]. Compared to Europe, America and China will provide greater funding for the future study of SGs. Concerning smart meter deployment, America and Europe have already deployed a large number of smart meters; in contrast, China remains in the planning stage. In Japan, 10 major utilities have planned to begin widespread smart meter rollouts between 2016 and 2024, by which time an expected 82 million units will be in place for residential and low-use customers [95].

Concerning funding allocation, we only analyze America and Europe because Japan and China have relatively simple stakeholder systems for SGs. Funding in America is mainly provided by SGIG (Smart grid Investment Grant). Fig. 4(a) illustrates SGIG funds by type

Table 4
Investments in SGs.
Source: [87–94]

Countries	Forecast SG investments	Funding for SG development	Smart meters deployments & plans (number)
America	$338 to 476 billion by 2030 [89]	$7 billion in 2009 [91]	8 million in 2011; 60 million by 2020 [92]
Europe	$79 billion by 2020 [88]	$261 billion	45 million already installed; 240 million by 2020 [88]
Japan	$7.4 billion by 2016 [87]	$ 849 million in 2009 [91]	82 million by 2023 [93]
China	$101 billion [90]	$ 7.3 billion in 2009 [91]	360 million by 2030 [94]



(a) SGIG funds by type of recipient [96]

(b) Distribution of EC funding across leading organizations [97, 98]

Fig. 4. Investment allocation in America and Europe [96–98].

of recipient. Clearly, investor-owned utilities account for the largest proportion, followed by public power utilities. Fig. 4(b) shows the distribution of European funding across leading organizations. In contrast to America, DSO/Utility/Energy companies spent the greatest proportion of the funds, reaching 55%, followed by University/ Research center/Consultancy.

4.4. Projects and achievements

Over the past decade, various countries have strengthened their SG research with increasing demonstrations and policies. The current situation of SG projects plays an important role in terms of formulating a clear future direction for SGs. Table 5 shows the categories for the classification of SG projects in the above three countries and Europe. The table shows that the pilot projects in America, Europe and Japan concentrate on the deployment of advanced and digital electricity systems (introducing smart meters, etc.) while focusing on the application of renewable energy and distributed generation. In addition, America, Europe, and Japan also attempt to provide a greater number of new services to customers such as smart houses and storage batteries. However, China continues to focus on developing its electricity infrastructure and ensuring a “unified, strong and smart grid network”.

Fig. 5 presents the proportion of project numbers by technology application in America and Europe. The figure shows that both America and Europe have attached great importance to the study of smart network management, aggregation of DR and VPP and smart consumers and smart house technologies. In addition, Europe prefers to research the integration of DER and electric vehicle technologies, and America prefers to study smart meters.

Table 6 shows the detailed demonstration project situation of SGs in Japan. In four demonstration areas, Japan has studied technologies

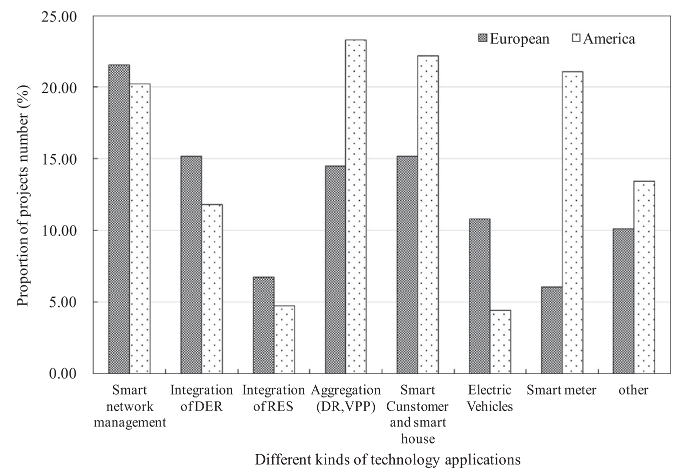


Fig. 5. Proportion of the projects by technological application [101,102].

related to SGs, including energy use visualization, home appliance control, demand response, family electric vehicles (EVs) and optimization of power storage systems [53], while attempting to achieve optimal energy utilization through an energy management system (EMS). The implementation of the four demonstration projects not only represents technical tests but also helps create new business models toward providing new services.

The SGCC also strongly promotes the development of SG projects in China. The SGCC organized 26 provincial branches to conduct SG pilot projects, arranging in total 303 projects across 32 categories, and completed 269 projects across 29 categories. Moreover, the SGCC constructed distribution automation systems in 64 central urban spaces, which enhanced the intelligence of the distribution network. In addition, it also built 360 electric vehicle charging stations and put

Table 5
Categories for the classification of SG projects in various countries and the European Union.
Source: [23,99,100]

America	European Union	Japan	China
Advanced Metering Infrastructure	Smart Network Management	Renewable energy generation	Generation
Electric Transmission Systems	Integration of DER		Transmission
Electric Distribution Systems	Integration of large scale RES	Renewable energy utilization	Transformation
Integrated and crosscutting Systems	Aggregation (Demand Response, VPP)		Distribution
Customer Systems	Smart Customer and Smart Home	Electricity network	Utilization
Storage Demonstration	Electric Vehicles applications	Customer systems	Dispatch
Equipment Manufacturing	Other (please specify)	Transportation	

Table 6
Demonstration projects for SGs in Japan.
Source: [100]

		Yokohama	Toyota	Kyoto	Kitakyushu
Renewable energy generation	Solar power generation	•			•
	Wind power generation				•
	Cogeneration				•
Renewable energy utilization	Solar heat	•			
	Biomass			•	•
	Waste energy (Rubbish , water reclamation , sewage sludge)	•		•	•
	By-product energy	•			•
	Regional air conditioning	•			
Electricity network	Superconducting and transmission network	•			•
	Storage batteries	•	•	•	•
Customer systems	CEMS· HEMS· BEMS· FEMS	•	•	•	•
	Demand response (DR)	•	•	•	•
	Two-way communication	•	•	•	•
	Smart house / building / industry	•	•	•	•
	Storage battery	•	•	•	•
Transportation	EV· PHV	•	•	•	
	EV charging infrastructure	•	•	•	•
	Advancement of the transportation system	•	•	•	•
Consult	Comprehensive Solution	•			
University	Industry-university cooperation	•	•	•	•

them into operation in 26 provinces, thereby stimulating the rapid development of industries related to electric vehicles.

4.5. Standardization

Regarding the existing international SG standards, the common recommended core standard is IEC TC 57. According to the number of recommendations, we select four standards from TC 57 that cover the matters of greatest importance according to most experts. One IEEE standard is also considered; however, it does not have much impact on the worldwide scale [52]. The standardization of SGs in various countries is shown in Table 7. Clearly, America and Europe play leading roles in international standardization efforts due to their rich experience and mature SG development system, whereas Japan and China play a supporting role as a result of their SG development statuses.

NIST and SGIP are responsible for the standardization work for SGs in America. Under the guidance of EISA 2007, NIST developed the SG standards system in 2009 and published the "Framework and roadmap for smart grid interoperability standards," version 1.0 and version 2.0 [103,104]. In addition, to facilitate America SG standardization and attract stakeholders to participate in the standardization efforts, NIST subsequently established SGIP. With the impetus and guidance of SGIP, America has completed a series of SG standards revision works and have formulated a standard library (Category of Standards, CoS) [105]. Although these standards have not yet been widely recognized, the SGIP's work has been highly valued by the Federal Energy Regulatory committee (FERC). These standards have also laid a firm foundation for the internationalization of the America SG standards. The Joint Working Group (CEN, CENELE, ETSI) is responsible for the development of the SG standardization roadmap of Europe [106]. That group transformed into a permanent organization, namely, the Smart Grid Coordination Group (SGCG), which continues to be responsible for coordinating and guiding the European SG standardization efforts. The key points of European SG standardization can be categorized into two aspects: setting European standards for electric vehicles and electric meters and making recommendations to international standardization organizations [107]. The SG standardization effort of Japan was led by the Japanese Industrial Standards Committee (JISC), which mainly focused on the standardization of the related technology in favor of cooperation among various companies [108]. SGCC was responsible for China's SG standardization. In 2010, SGCC published the “Framework and roadmap for strong and smart grid standards” [109] and released a series of detailed SG standards that represent an important component of SG international standardization.

5. Discussion

5.1. Barriers and challenges

In America, there are four main problems facing SG development. First, although the government has fully affirmed the progress of SG development, industry and the public remain skeptical. Industry and the public believe that the development status of the current SG remains slow and that SGs have not achieved what the government promised the public. These promises include realizing two-way communication between users and grids, allowing users to manage their own energy production and consumption and providing more employment opportunities for the community. Second, there is a substantial problem in how power and utility companies communicate with users who have already installed smart meters. Because America simultaneously promoted new technologies and introduced new electricity tariffs, consumers have a poor understanding of the results of pilot projects. Moreover, high quality and how to interact with customers and persuade them to recognize the value and real benefits of SGs have become important subjects in the continued development of the SG. Third, with encouragement in the form of financial support provided by the government, SG research and demonstration efforts have seen smooth progress; however, the investment enthusiasm by power companies and other private businesses is not high, which affects the future development of SGs to a certain extent. Fourth, America must strongly invest in SGs to meet the policy requirements for the full deployment of the SG by 2030. However, in the present circumstances, it is difficult for America to continue to invest in SGs. Actually, the power asset ownership and management of many American power companies are relatively decentralized, and investments in electrical equipment are very high and have long life cycles. This results in each

Table 7
Standardization of SGs in various countries.
Source: [74–76,78–82]

Countries	Leading organization	Time issued	Main SG Standards	Main contents
IEC TC 57 (International Electrotechnical		2003	IEC 60870 [46]	Defines systems used for controlling electric power transmission grids and other geographically widespread control systems.
Commission Technical Committee 57)		2006	IEC 62351 [47]	Focuses on power system management and associated information exchange—data and communication security.
		2007	IEC 61970 [45]	Addresses the application program interfaces for energy management systems (EMS)
		2009	IEC 62357 [48]	Focuses on power system control and associated communications—object model, service facilities and protocol architecture with references.
IEEE (Institute of Electrical and Electronic Engineers)		2009	Draft Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System [51]	Focuses on smart grid interoperability consisting of consistent terminology, characteristics, functional descriptions, evaluation criteria and appropriate development activities.
America	NIST (National Institute of Standards and Technology)	January 2010	Framework and roadmap for smart grid interoperability standards Release 1.0 [103]	Identifies 19 standards that require priority revision; establishes SGIP to attract various stakeholders to participate in the standardization efforts.
		February 2012	Framework and roadmap for smart grid interoperability standards Release 2.0 [104]	
	SGIP (Smart Grid Interoperability Panel)	–	CoS (Catalog of Standards) [105]	Continued research on conceptual architectural framework and SG interoperability panel (SGIP); focuses on the standards identified for implementation and cybersecurity strategy; discusses framework for SG interoperability testing and certification.
Europe	Joint Working Group (CEN/CENELE/ETSI)	2009	Mandate CEN/CENELEC M/441 [49]	Focal topics of standardization including terminology, systems aspects, data communication reference architecture and data communication interfaces with the focus on sectional standards including DMS, SCADA, data models, and ERP interfaces.
		October 2010	Report on standards for smart grids V1.0 [110]	Provides a conceptual model and reference architectural principles; establishes the framework of the SG architecture model (SGAM); sets the Europe standards for electric vehicles and electric meters; makes recommendations to the IEC and other international standardization organizations.
		June 2011	Final report of the CEN/CENELE/ETSI Joint Working Group on Standards for Smart Grids [111]	
	SGCG (Smart Grid Coordination Group)	October 2012	First, Set of Standards Version1.1 [107]	
Japan	JISC (Japanese Industrial Standards Committee)	December 2012	Twenty important items for international standardization of SGs [108]	A total of 8 review groups select 20 important items for the international standardization of SGs, including energy management and demand response systems, distribution automation systems, smart meter systems, and technologies related to electric vehicles.
	METI (Ministry of Economy, Trade and Industry)	February 2012	Recommend HEMS and ECHONET lite [108]	METI encourages the application of HEMS and ECHONET, realizing collaboration among different companies.
		2010	Japans Roadmap to International Standardization for Smart Grid and Collaborations with other Countries [50]	
China	SGCC (Smart Gird Corporation of China)	August 2010	Framework and roadmap for strong and smart grid standards [109]	Establishes an SG standard system based on integrated planning, generation, transmission, substations, distributions, communication and 2 other professional branches involving 26 technical areas and consisting of 92 standard series; compiles 220 enterprise SG standards and 841 national and industry standards.

power company having to perform a cost-effectiveness analysis before making investment decisions. Therefore, subsequent follow-up funding is difficult to obtain.

In Europe, the situation is similar to that in America: the most significant bottleneck in the development of SGs is follow-up funding problems; this issue is even more serious than it is in America. According to estimates by Pike research, the investments in SGs of EU countries will reach 79 billion Euros by 2020. Moreover, due to the impact of the European credit crisis, the speed of and capital investment in Europe SG development continue to face uncertainty. Moreover, the interoperability of Europe SGs is not high. As new applications of SGs are realized, the roles and responsibilities of various stakeholders remain uncertain. A clear cost-benefit-sharing mechanism also remains unclear.

Japan's SG pilot project realized many achievements and essentially met its original targets. However, scaling-up small-scale pilot projects into large-scale practical applications remains a substantial problem. In addition, although Japan's SG-related technologies, especially battery technology, are world class, America continues to have the power to establish basic SG international standards. Actively participating in and promoting the development of international standards remains a significant challenge to Japan.

In China, the most significant obstacle encountered in SG development is the lack of a clear national policy and roadmap. Although a series of documents have been issued to facilitate the implementation of SGs, planning and related standards that guide specific actions have not been introduced, making various SG stakeholders feel anxious and confused. In addition, China continues to need to break through technical barriers. Chinese power companies view developing renewable energy resources as an opportunity but face many challenges in certain technical aspects. The traditional Chinese grid is powered by thermal power plants and hydropower plants, and the design of the grid network is expected to remain stable for a long time. However, with the introduction of wind, solar and other clean energy generation types, grid technologies have begun to exhibit various issues. Addressing the transition between the old and new grid represents a substantial challenge to China's SG development.

5.2. Future trends and tendencies

The United States and Europe still need to establish and improve relevant laws and regulations for the long-term development of SGs in terms of managing the risks and benefits from the perspective of policy. They must do this while developing technical standards that can be accepted by industry and achieving the integration of different equipment manufactured by different companies. This would encourage the active participation of various private enterprises and power companies while attracting subsequent investment. In addition, strengthening communication with users is also very important and can help SG developers understand the lack of SG process. The development of SGs in Japan should continue to strengthen the links and interaction between the three institutions (government, industry and academic institution) and attempt to create a new method that can help promote SGs while providing new services in line with the needs of users. This would enhance their understanding of SGs, encourage and stimulate the active participation of local residents and local businesses, and finally push the widespread development of SGs. What is more, Japan should continue to concentrate on international cooperation related to SGs, seeking to use its technological advantage to obtain the right to influence international standard-setting. The Chinese government should focus on implementing a reform of the power grid, therein actively improving the infrastructure of the power industry so that it can be coordinated with the development of SGs. In addition, the Chinese government should give strong support to SGs through policy and continue to improve the relevant standards and provide favorable conditions for the development of SGs.

SG is still a relatively new concept despite its great accomplishments. To realize the scale-up and industrialization of smart grids, significant further effort is still required. According to the above analysis, SG development can be improved in three respects. The first is the end user side. Enhancing the feedback of end users is essential to the process of developing SGs. This factor has the most effective and direct influence on the successful implementation of SGs. The related technology must be constantly upgraded to meet the changes in users' motivation. Only in this way can end users adapt the technology according to their own needs and expectations. Human habits must also be seriously investigated to improve the efficiency and flexibility of energy management systems. In addition, users' knowledge of SGs plays an important role during the promotion of SGs. With better understanding of SGs, end users can take an active part in SG development. For example, improved understanding can help them correctly install and properly configure the smart devices while improving the awareness of energy management. The second is the technology side. Simple technology should be explored to coordinate with the consumers; more products and services should be provided to meet the requirements of different stakeholders. The challenge of developing good technology is not only realizing the data communication but also the ability to enable various roles to have the opportunity for continual involvement in the adaptation and customization process of SG. The last is the policy side. SGs involve a series of new technologies that have great potential in future power grid development. To build a secure, economic, clean, transparent and compatible power grid in the future, we should take measures to propel the development of smart grids [44]. In a word, SGs represent not only energy system innovation but also institutional innovation. The healthy development of SGs is closely related to clear policy support and unified technical regulations under the background of power marketization. A generally approved standard system is also a key factor for orderly development of SGs owing to the complexity of SGs, which involve many industries and technical areas.

6. Conclusion

SGs are considered as being subject to an evolving ecosystem, the development of new technologies, the adjustment of policies and market mechanisms, and the formation of standards, all of which have a large impact on SG development. This paper presented the development status of SGs in America and Europe, Japan and China, which represent OECD countries, OECD Asian countries and emerging countries, respectively. Based on their development statuses, this paper analyzed SG development barriers and challenges, noting that America and Europe have the most similar development mode for SGs and have already entered into a mature period. The focus of their recent work is on the application of intelligent technologies, addressing challenges produced by renewable power integration in the case of possible mitigation investments. Moreover, this paper found that the Japanese model of SG development is a government-led, community-oriented, business-driven approach that focuses on technological innovation. In addition, Japan provides experience in terms of creating a business model for SGs. This paper also demonstrated that China has the most unique SG development structure of all the countries studied. The management of SGs in China is highly centralized, and China has made encouraging progress in ultra-high-voltage transmission systems.

Although each country has made many achievements in the development of SGs, our review also reveals that a common problem that they face is a lack of clear standards for SGs. For example, the lack of a clear cost-benefit-sharing mechanism makes subsequent investments difficult, and the lack of worldwide technical standards restricts the integration of different equipment manufactured by different companies, both of which hinder the continued development of SGs. Therefore, the three countries and Europe should strengthen their standardization development while sharing experience and putting substantial effort behind forming international standards for SGs. In addition to the policy and standard side, this paper also provided useful recommendations from the end user side and technology side, finding that the problem of low participation of end users during the development of SGs exists in every country. This paper proposed exploring human habits and feedback from end users to improve the efficiency of SGs; the enhancement of users' knowledge of SGs is also helpful. Co-shaping technology with end users and creating simple SG products and services provide another effective way to well develop SGs.

Consequently, in the context of economic globalization, the rational choices for the major countries toward developing their SGs are to exchange and cooperate with other countries, develop more mature technologies, present a reasonable market mechanism and business model, establish a generally approved standards system, and remove barriers to the widespread use of SGs. In this way, SGs will achieve good development prospects and contribute significantly to renewable energy development.

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