

# 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 CO<sub>2</sub> 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.El-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

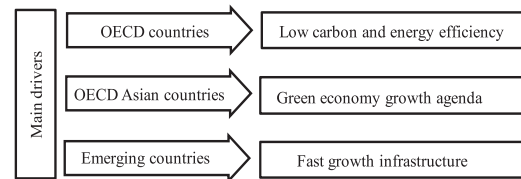


Fig. 1. Main drivers of SG development [7].

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 co-operation, 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.

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 CO<sub>2</sub> 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

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