A Holistic View on Developing Smart Grids for a Low-Carbon Future

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Abstract This chapter provides a holistic overview of the development of smart grids as an essential element for a low-carbon future. It examines how four key aspects, namely technology, economics, regulation/policy, and social acceptance, are complementary and therefore need to be considered concurrently for the deployment of smart grids. This chapter emphasizes that there is no one-size-fit-all solution, and the choice of solutions differs across countries and localities. A good understanding of local features such as historical, cultural, resources, market, and regulatory factors that coexist with strong and consistent commitment, careful road mapping, learning through trials as well as supporting innovation and research are required for the effective transition toward different smart grid systems in a low-carbon world.

1 Introduction

Power grids are designed to interconnect generation and load entities for the purpose of delivering electricity in a safe, economical, reliable, and socially acceptable manner. Engineering marvels have made today's power grids one of the most complex and valuable systems humans have ever built [18]. Our industrialization, technological advancements, social well-being, and high living standards are based on the electricity delivered through the power grids, without which we would not have developed so rapidly in the past century.

Disclaimer: This chapter and other materials mentioned herein reflect my own views and do not necessarily reflect the views of CLP Research Institute or any other organization with which I am affiliated.

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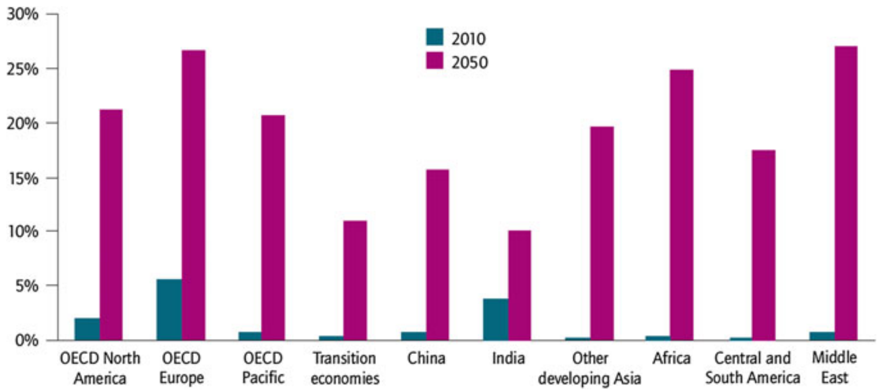

Fig. 1 Portion of variable generation of electricity by region (BLUE Map Scenario) [10]

However, with rapid development and a heavy reliance on fossil fuels to generate electricity globally, greenhouse gas emissions have also brought on new challenges for the global community, namely climate change and global warming. Social norms are favoring the adoption of more environmentally friendly and sustainable development practices to be adopted. Volatile fuel prices and resource constrains have also prompted many countries to place energy security high on their national agendas. For instance, Germany's "Energiewende" (roughly translated as "Energy Transition") favors more renewables instead of the conventional coal or nuclear facilities, which has driven the rapid development of wind and solar generation. Within the last decade, traditional generation mix and associated practices have been rapidly evolving. Figure 1 shows the potential increase of variable generation of the world by 2050, according to IEA's estimates [10].

Meanwhile, the need to upgrade and reinforce the grid is also necessary. Most power grids were built over 50–60 years ago and are aging with different degrees of deterioration. With the continuous needs of meeting load growth, equipment retirement, network reinforcements, and the ever-changing market conditions, the power industry finds itself facing a dilemma. Should the industry continue to invest in conventional means, which only offers the status quo at best, or leap to a more efficient, smarter, interactive, and flexible grid for a low-carbon future?

With maturing Information and Communications Technology (ICT) and their wide applications and deployment in different sectors, a technological pull also provides the industry with different tools and applications to enable the making of a more advanced power grid or as it is commonly known a "smart grid."

Global smart grid developments vary widely in terms of scope and pace of development. In fact, even the definition of smart grid may differ from place to place. In most developed countries, smart grid developments focus on renewables, smart meters (SM), and demand response (DR). The main drivers are on renewables integration, energy efficiency, and provision of more choices to consumers. On the other hand, in emerging economies like China, smart grid developments are focusing on building a "strong and smart" grid. The main driver is to build a reliable and strong transmission and distribution system to meet rapid demand growth. Mega-projects like HVDC and EHV lines stretching thousands of kilometers are being built to bring bulk power from remote sites to major load centers. Digital substation and distribution automation (DA), coupled with different smart meter deployment schemes, are also being trialed in major cities to increase reliability or simply to gain the development experience.

This chapter suggests that a holistic view encompassing four key aspects of smart grid development should be examined concurrently. These aspects include technology, economics, regulation/policy, and social acceptance. As different communities or nations have their own sets of existing conditions, their needs, aspirations, resources, implementation, and results could be all different. Like any other grand problems confronting the global community, each community has its own unique characteristics as well as intricate relationships with each other. The choice of solution would therefore differ, but it is important to understand the inherent and related issues in a holistic manner to constantly refine them. It is hoped that this chapter will help facilitate meaningful discussions and further research and development and ultimately make deployment of smart grids a universal reality—a necessity for this and future generations to build a low-carbon world.

2 Capabilities of Smart Grids and Implications

The notion of a "smart grid" should not be misconstrued to say that the existing power grids are dumb or unsophisticated. Instead, we should appreciate and anticipate what will be required of future grids. In essence, a smart grid is the conventional grid equipped with extensive information-based and technology-based equipment and systems to do or support most, if not all, of the following:

- Integrate a larger share of renewable energy (RE);
- Enable customers to participate in supplying and balancing the grid;
- Accept new load entities such as electric vehicles (EV) and smart appliances;
- Interconnect with different distributed energy resources (DER) and micro-grids;
- Enable market-based power transactions or new business models;
- Recover robustly and more reliably after extreme disturbances;
- Improve grid efficiency and reduce transmission losses; and
- Do the above while upholding or exceeding existing reliability and safety standards, with a sound economic base under the allowable regulatory framework and social acceptance.

With full deployment, smart grids could enable us to reduce carbon dioxide emissions significantly. For instance, it was estimated the potential for carbon dioxide (CO2) reduction in US alone could range from 4 to 27 % based on

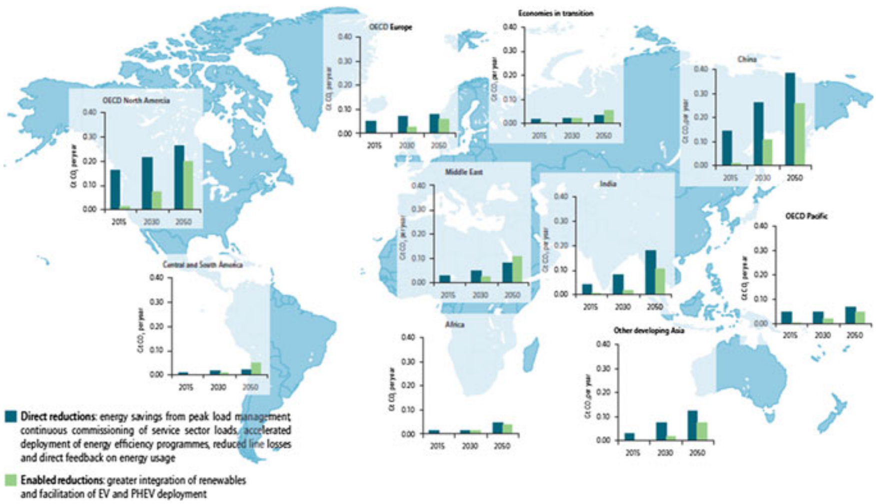

Fig. 2 Regional CO2 emissions reduction through smart grid deployment [10]

different studies [23]. Figure 2 shows an estimate of regional CO2 emissions reduction through the deployment of smart grids according to [10].

However, like all infrastructure establishments, any fundamental change of this magnitude would involve many aspects. Based on the main smart grid capabilities, Table 1 highlights the key implications with respect to four major aspects, namely technical, economic, regulatory, and societal. The following sections will elaborate on each of the key aspects.

3 Key Technologies and Their Current Stage of Development

If one were to take a quick look over the development pace of the ICT infrastructure buildup in the last decade, the growth is nothing but astounding. For instance, fiber-optic cables (the backbone of today's communication networks) have grown from 95 billion km in 2000 to 180 billion km in 2011 [11]. Mobile cellular subscribers have increased almost nine times to 6.3 billion in 2012 since 2000 [12]. Meanwhile, global Internet users grew from 0.361 billion (5.8 % of world population) to more than 2.75 billion (38.8 % of world population) in 2013 [13]. Most smart grid technologies are also built on this ubiquitous and extensive communication technology and infrastructure. However, beyond the ICT, what are the key technologies that are required in order to fulfill the prescribed objectives of a smart grid? This, of course, depends on the local environment [6, 7, 15, 22]. Instead of being pulled by any political agenda, fashionable rhetoric or technology

Table 1 Overview of smart grid capabilities and implications

Smart grid capabilities	Technical	Economic	Regulatory/Policy	Societal
Integration of renewables	Frequency control; dispatch coordination; system and weather forecasting; resource quality and availability; grid codes; loop flows; power and voltage controls; and backup facility controls	Levelized cost of energy for RE; cost of development; and cost of backup facilities	National policy; RE content and target; feed-in tariff; and government incentives	Willingness to purse a higher RE contents; affordability of the local communities; NIMBY resentment; social welfare redistribution; and poor subsidizing the rich
Customers engagement (smart meters and AMI)	Forecasting; response time; reliability; coordination; and cooperation	Investments; ownership; price of "megawatt"; and elasticity of demand	Approval of smart meters and AMI investments and cost recovery method; ownership of metering data; and privacy	Public acceptance of smart meters; perceived health and privacy issues
Distributed energy resources	Sizing; dispatching coordination; power flow controls; voltage controls; maturity of energy storage devices; grid codes; interconnection; and coordination	Cost and availability of alternative fuels; PV systems and storage devices; Stranded grid assets; and innovative business models	Energy and environmental policies, energy security, roles of grid backup, emissions monitoring and control policies	Public sentiment and acceptance to opt for DER (especially after major interruptions experienced)
Electric vehicles supports (e.g., charging and V2G)	Connection and interface standards; mobile load shifts; grid reinforcements to sustain charging peaks and locations; storage devices; and vehicle to grid	Local tariffs; generation mix; cost of EVs; and incentive for charging	Incentives to push charging stations and EV purchases; RE developments	Acceptance and popularity of EV or plug-ins
Distribution automation	Equipment standards; protection philosophy, scheme, and coordination	Asset management practice; investment deferral; and costs of loss of load or interruptions	Policies to deal with cost recovery; RE integration policy	Public awareness and education of the needs and benefits of DA

lobbyists, it is useful to first examine the nature of different "smart grid" technologies and understand their stage of development and deployment today.

3.1 Smart Meters and Automated Metering Infrastructure

Today, hundreds of millions of SM have been deployed globally. ENEL of Italy was a first mover on SM, and over 30 million, SM have already been installed. The fastest growth today is in China. According to Navigant Research [19], there were 139 million SM installed in 2012 and this figure will likely grow to 377 million by 2020. SM are electronic meters which are more intelligent and versatile than the conventional electromagnetic meter. They offer a wide range of functions including the abilities to capture and store detailed consumption data, communicate by wire or wireless means, remotely connect and disconnect, enable net metering, support dynamic pricing or prepaid, and monitor power quality and outage conditions. Although not all the above-mentioned functionalities are present in these SM deployments, almost all are capable of supporting automatic meter reading, dynamic pricing scheme, and detailed consumption data recording.

Automated metering infrastructure (AMI) refers to the bidirectional communication system linking hundreds and thousands of SMs (the customers) with the backend systems (the utilities/distributors). This is usually accomplished by linking the SMs with collectors and concentrators using one or more of mesh networks, power line carrier, optical fiber, Wi-fi, or Wimax technologies. AMI can carry out multiple functions such as automatic meter reading; meter data management system (e.g., integrity check and lost data retrieval); interfacing with customer supports, billing, and outage management systems; and supporting in-home energy displays and/or Web-based customers' consumption portal.

With SMs and AMI, the detailed usage information, bidirectional communication, and near-real-time access of load entities' condition open up new opportunities for both consumers and utilities [10]. With the versatility and convenience of these technologies, cyber security and privacy issues are also present. The new infrastructure therefore also needs to have high security features built into the design so that customer's privacy is reasonably protected and supply reliability is ensured against any cyber attacks.

3.2 Demand Response and Automated Demand Response

DR refers to the active customer engagement requested by the grid operator to reduce demand when there is insufficient generation or transmission capacity to supply all load entities under normal or abnormal conditions (e.g., severe weather or loss of supply). The customers are generally rewarded by compensation or entitlement to special tariff schemes. DR has been demonstrated to be quite successful in USA. The recruitment of participants and management of DR executions are generally performed semiautomatically with lead time in terms of days and hours ahead. Automated demand response (ADR) incorporates special hardware to control major appliances such as air conditioners and hot water heaters to reduce demand directly upon request from the utility. The lead time is reduced to almost real time and is more certain to the operators. In theory, having the means like DR and ADR to control the demand side is desirable as it enhances the flexibility of the network. In practice, the implementation also depends on the nature of the customer fabric and their corresponding effects on the system when DR/ADR is called upon. The level of compensation also depends on the elasticity of demand, tariffs, program flexibility, and general acceptance to the notion of participating in grid control.

3.3 Phase Monitoring Unit and Wide Area Monitoring System

PMU is a high-precision sensor designed to capture subsecond-level information of the voltage and current conditions on the grid. They can be deployed in key or strategic locations (e.g., interconnection points or major substations) of the grid to form a WAMS. PMUs are synchronized to a common and precise clock such that they can monitor the power flows and voltage profiles together at a much higher sampling frequency compared to conventional means. As a result, PMUs and WAMS offer system operators in a control region (as well as across different control regions) the ability to react in a timely manner to avoid or mitigate the damage caused by any disturbances happening far away. It should be noted that PMUs and WAMS are most beneficial to long-distance bulk power transfers and large networks stretching across a wide area. The integration and usage of them are only gradually being introduced to the industry in the last decade, so many are yet to be convinced of its effectiveness in improving the reliability supply.

3.4 Power Electronics, HVDC, and FACTS Devices

Power electronics have been used for grid applications since the 1960s. Many of the inverter and converter stations in HVDC lines or back-to-back HVDC systems were built on the thyristor-based technology [1]. HVDC lines stretching hundreds and thousands of kilometers can now bring in remote hydro power in bulk and lower costs. The same facilities can also be used to harness mega-size wind and solar facilities. This technology is mature and stable after years of development and deployment experience. Today, thyristors are being gradually replaced by a more efficient and powerful technology using integrated gate bipolar transistors

(IGBT). The main difference is that IGBT can be freely switched on and off, while thyristors can only be switched on. This allows faster and more complicated switching schemes to be implemented (e.g., multi-level modular converter). FACTS[1] devices such as STATCOM (or called SVG in China) or SVC are used to alter the natural flow of AC power such that the voltage profile can be maintained and/or real power transfer capability increased. In short, the rapid deployment of power electronic equipment in the grid today is offering more flexibility and security to grid operations. The benefit is wide as the technology can be applied to both bulk power flow controls and on smaller scales, using distributed and variable interconnections with micro-grids and distributed energy resources.

3.5 Distribution Automation

Technologies used in DA are quite mature. To a large extent, similar monitoring and control features used in SCADA and EMS[2] systems for generation and transmission systems are now downloaded to the distribution level. Through the extensive deployment of Remote terminal unit (RTUs) in substations or supply feeders, DA will normally cover the following functions [21]:

- Monitoring and control of distribution circuits and voltage profile;
- Outage location and automated restoration;
- Semi- or automatic reconfiguration;
- Voltage and reactive power controls (via transformer tap changing or capacitor bank switching);
- Load flow calculation and contingency analysis; and
- Equipment health monitoring.

Together with SMs and AMI, DA can significantly enhance service reliability and robustness.

3.6 Energy Storage

To date, energy storage remains the holy grail for the power industry. However, the future looks more and more encouraging due to the rapid concurrent development of various storage technologies, renewables, and EV. With energy storage, we can harness the full potential of uncertain and intermittent RE to give a more

[1] *FACTS* Flexible AC transmission system; *STATCOM* Static Synchronous Compensator; *SVG* Static Var Generator.

[2] SCADA—Supervisory Control and Data Acquisition System; EMS—Energy Management System.

controllable interface with the grid, hence providing a better utilization of low-carbon energy. Traditionally, pump hydro was the reliable and most widely used utility-scale means of energy storage around the world. Part of the reason may be because of the storage means used—water is relatively safe to store in bulk and stable enough without the needs for expensive monitoring or maintenance setups. Sodium sulfur (NaS) or Lithium–ion (Li ion)-based battery systems are both commercially available today, and trials are taking place around the world to test their applicability for different uses. Although their unit costs are still high, the deployment rate and applications are growing, particularly in strengthening the supply consistency of renewables. Figure 3 shows an overview of different storage technologies and their stage of development.

3.7 Micro-grids

Micro-grids are self-contained local electrical networks which have one or more generation units feeding the local loads through a small network. The network usually is low-to-medium voltage (1,000 V or below) with limited nodes connecting DER like solar PV, wind turbines, combined heat and power (CHP), fuel cells, and energy storage devices. They typically deal with loads like community buildings, households, and EVs. Figure 4 shows a schematic comparison between today's distribution grid and a micro-grid. In theory, with the distributed generation and sophisticated control and coordination, a micro-grid would be more resilient to disturbances and capable of operating even if the connection with the main grid is disconnected.

3.8 New Paradigms, Systems, and Technologies for a Flexible Grid

Multiple factors are driving the shift toward a low-carbon future, and power grids have to be more flexible [10] to accommodate higher share of renewables (e.g., >30 %), more AC/DC system interactions, more emission-constrained dispatching in accordance with market activities (power markets and/or carbon markets), more demanding controls over the interconnections, and sophisticated coordination of distributed systems (e.g., micro-grids). It is impossible to list all the new paradigms and associated technological needs in this context as some of them have yet to be discovered. However, it is worthwhile to note that different combinations of the above-mentioned technologies, which increase the grid observability and controllability, are just the basic building blocks. They have to be linked by a robust, reliable, and ubiquitous communication framework and overlaid with a suite of elaborated ICT-based monitoring and control applications.

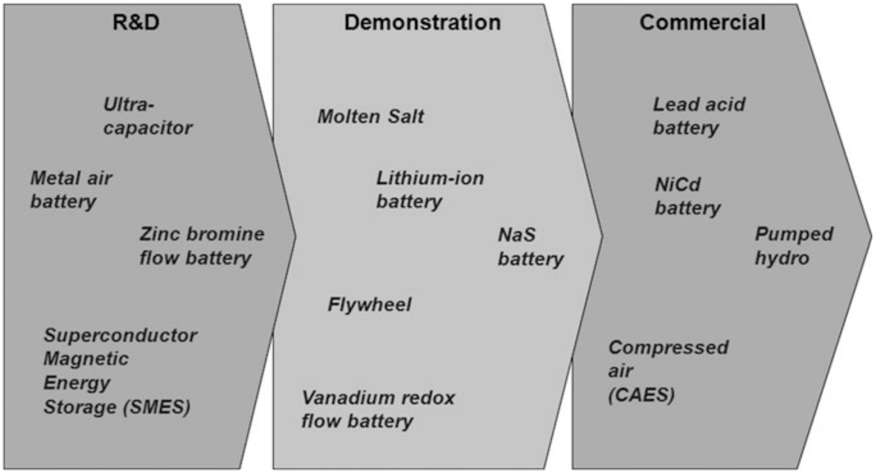

Fig. 3 Storage technologies and stage of development

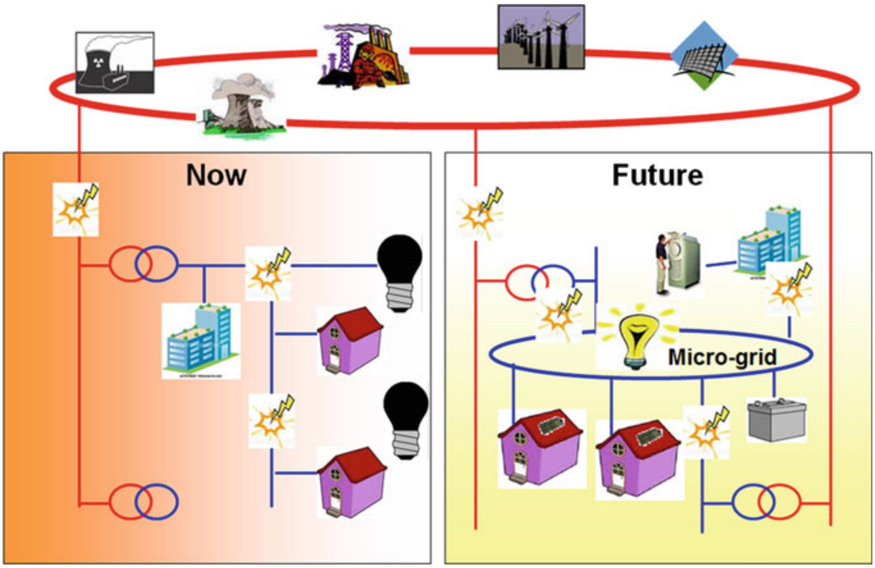

Fig. 4 Comparison of conventional grids with micro-grids

3.9 Enabling Customer Interactions and Dynamic Pricing Scheme

Today, the most popular value chain of a smart grid is composed of SM–AMI–Metering Data Repository System–Enterprise Application Systems. This new value chain provides multiple functions to stakeholders including meter reading, energy audits, customer interactions, net metering of distributed renewables, dynamic pricing support and auditing, outage monitoring, remote connection, DR, direct load control, and detailed billing information.

3.10 Providing Flexibility and Intelligence to Grid Operations

Grid operators and system planners both understand very well that the power grid is a highly complex machine with many different characteristics and unique practices derived from historical, market, and technical developments. With new technologies, innovative models and algorithms are needed to make the grid more flexible, robust, and reliable. For instance,

- Intelligent tools using remote sensing images to deduce accurate wind and solar generation, optimized with coordinated interconnection control and generation dispatch;
- Decentralized control incorporating DR, DER, and micro-grids instead of the conventional hierarchical approach;
- Data mining on usage data to derive new business opportunities and applications [5];
- Equipment health monitoring diagnostics and monitoring.

4 Economic Values, Benefits, and Market Forces

A power grid is implicitly a natural monopoly because it requires huge investment and long lead time to build and is also costly to maintain. The barrier to entry is so high that grid companies are usually owned by governments, local communities, large corporations, or highly regulated grid operators. To better understand what the different values and/or economic justifications of upgrading to a smart grid are, one must look at it from three different levels, i.e., transmission, distribution, and metering.

4.1 Transmission

Smart grid investments on the transmission level are usually driven by conventional needs such as

- Increasing monitoring and control capabilities through PMUs and WAMS for large-scale networks;
- Harnessing remote energy resources (e.g., hydro) using long-distance EHV lines and/or HVDC systems;
- Reinforcing the networks to increase transfer capacity using STATCOM (SVG) or FACTS devices;
- Upgrading aging infrastructure with new facilities (e.g., reconductoring and voltage upgrading) or intelligent software (e.g., dynamic line rating); and
- Resource sharing by building interconnections among neighbors (e.g., back-to-back HVDC tie lines).

The economic benefits would include revenue generation from the import/export of energy, reserve sharing, investment deferral, system reliability, and security improvements (avoiding blackouts or interruptions).

4.2 Distribution

Traditionally, investments in distribution networks are built on increasing service reliability measured by reliability indices such as SAIFI, SAIDI in the USA, and CML and CI in the UK [2, 24]. These indices are used to quantify the reliability needed in order to justify investment. The costs to meet the prescribed level of reliability will then be compared to the cost of interruption/unreliability. This conventional practice is usually guided by regulation in most developed countries.

With increasing numbers of DER such as solar PVs, CHP and fuel cells are gradually being added to the distribution grid on the customer's side. Business values for the distribution grid reinforcements and changes become murkier and more challenging to justify because the new technologies also bring in new players and business paradigm shifts. Management of the distribution networks becomes much more complex. For instance, the return on investment (ROI) for network reinforcements and DA may be diluted, while some new players may benefit more than others without bearing any costs or risks.

More distributed generation would also mean less revenue to the grid company, but the existing feeders and interconnectors remain as assets of the utility. The costs to maintain these assets are unlikely to shrink in the future, but the number of customers may vary. Some of these grid assets may then become a sunk cost as well. As such, innovation and new paradigms to build the business case for distribution-level investments and cost recovery are urgently needed as distribution generation grows [16].

However, charging stations for EVs and the associated infrastructure reinforcements may have a clearer picture with a win–win–win business case. For instance, if the generation mix is reasonably low carbon such as powered by renewables, nuclear, or natural gas and the distribution grid is strong, the added new EV loads could increase the revenue for the utilities. They would reduce roadside pollution and provide a lower-cost transportation means to consumers. Unfortunately, development and popularity of EVs is only taking off slowly globally [14].

4.3 Metering

As previously mentioned, the first mover on utility-scale deployment of SM is ENEL of Italy. ENEL installed 30+ millions SM costing €2.1 billion in 2001. However, the annual benefits through revenue protection, dynamic pricing, and remote connection management were up to €500 million annually. In other words, the payback period was only 5 years [4].

Electricity meters are the cash registers for a power utility company. The evolution from electromagnetic meters to electronic matters is in fact imminent under today's pace of technological progress. Depending on individual utilities, the business case to bring in SM and AMI needs to incorporate existing and future policies on dynamic pricing, renewables targets, net metering, DR, and energy storage facilities (including EVs).

As the industry moves toward widespread deployment of SM and AMI, the utility and consumers are also offered new opportunities such as the provision of energy audits, Internet access, or related applications (e.g., home security monitoring). The key values would include cost savings in automatic meter reading, usage optimization through DR and dynamic pricing, prepaid services, remote disconnect, energy theft reduction, and outage management. These capabilities could add new revenue-generating services for utilities that were not possible or available in the past. However, it should be noted that the deployment of SM is a long-term and capital intensive investment. Without a clear commitment and mandate from the regulatory bodies and policy support, the business case of full deployment (trials are different) will take time to build. Stakeholder education and engagement as well as public supports are key to a successful deployment [8, 9].

5 Regulation and Policies

The planning and operation of power grids are heavily regulated by local, if not national-level authorities. This section first focuses on the primary objectives and current practices that guide electric utilities today in general, followed by the growing challenges in regulation and policy. We then review some global experiences for reference.

5.1 Different Industry Structure

Globally, electric utilities operate in different forms of organizational structure; hence, the regulation and policies applied to them may vary. For simplicity, the following briefly describes the major structures:

- Vertically integrated, investor-owned utilities (IOUs) that own and operate generation, transmission, and distribution and are regulated by the local government;
- Independent system operators (ISOs) are usually set up in a deregulated environment. Their responsibility is to look after the delivery system, while the generation and distribution functions are given to separate business entities. Competitive markets on the wholesale and/or retail levels are set up to interact with the ISO. While the these GENCO and DISCO are more or less market driven, the ISO is always regulated by the local government; and
- Publicly owned utilities (POUs) like the State Grid in China, TVA in US, or BC Hydro in Canada are generally exempt from regulation as they are expected to have the consumer's best interests in mind and hence will offer the best tariff and services to the public.

5.2 Common Regulation Objectives

Today, depending on historical, geographical, and political reasons, heterogenic (e.g., USA), semiheterogenic (e.g., China), and homogenic (e.g., Japan) mixes of IOUs, ISOs, and POUs are present. Despite their differences, a set of common overseeing objectives for the regulators/governments include the following:

- Customer values and rate calculation rules
- Investment cost recovery principle
- Socioeconomic developments
- Efficiency incentives and measures
- Reliability standards
- Environmental considerations
- Other policies (e.g., pollution controls)

5.3 New Objectives and Regulation

With the aspiration of building and deploying smart grids to achieve a low-carbon future, regulators are confronted with some new challenges [16, 17, 25]:

- Technologies are changing the roles of generators and loads;
- Incentives to promote renewables also imply higher rates combined with conventional generation;

- DR may contradict traditional rate structure;
- New entities such as distributed generation, storage devices, and EV are changing the role of the grid and hence their values;
- New players may discourage traditional investment decisions due to higher risks of reasonable rate of return; and
- Evolving and constantly changing public opinions.

As such, government and regulators have to incorporate new objectives and design appropriate measures to nurture a healthy development of the power grids. These objectives may include a combination of the following, depending on their suitability of meeting local needs:

- National policy and/or international commitments on climate, pollution control, etc;
- Target of generation mix for a low-carbon future, including RE target;
- Demand-side management and energy efficiency policies;
- Service reliability standards for distributed and centralized generation;
- Grid charge calculation methodology;
- Guidelines to set up smart grid trials and corresponding evaluation framework;
- Incentives or subsidies for distributed generation, storage, and EV development;
- Electricity market design, monitoring, assessment rules, and dynamic pricing policy;
- Cost recovery principle and means (e.g., for stranded costs);
- Smart grid standards: equipment interoperability for SM, AMI, digital substations, etc;
- Utility's own performance measures: grid efficiency and performance metrics;
- Cyber security requirements: data security and intrusion prevention;
- Privacy protection policy;
- Supports for innovation and R&D;
- Stakeholders' education and coordination; and
- Workforce training policy and programs.

According to a recent report [17], global smart grid development projects have different focuses. In North America, the main objectives are on peak load reduction and dynamic pricing schemes, automatic metering reading, revenue protection, and outage management. In Europe, the focus is more on efficiency improvement through distributed resources and emission reduction means. In Asia Pacific, the objectives vary from country to country. For instance, building a strong transmission grid and automating distribution has been and will remain a strong driver to the rapidly growing infrastructure buildup in China. Australia, however, is closer to the American approach with more emphasis on load management.

Regulator's tasks are increasingly difficult today as new generation and load entities are rapidly entering the arena driven by rapid technological advancements and new business paradigms. Aspirations, decisions, and commitments of the government policymakers and/or the regulators have a long and crucial impact to individual smart grid developments universally. As such, demonstration projects are important. It is imperative for local regulators to provide sufficient funding and flexibility to allow utilities and different stakeholders to conduct demonstration projects such that the policymakers can identify the key aspects to concentrate, mistakes to avoid, skills to acquire, and the pace to undertake.

6 Societal Benefits, Impacts, and Acceptance

Last but not least, the social aspects of what smart grids will bring must be understood and properly addressed for any developments to take place. As different communities have their own unique history, culture, and economic, political, and regulatory environment, their corresponding social issues are different. These are some of the key considerations:

6.1 Economic Growth, Competitiveness, and Jobs

Smart grid development could bring employment to local communities on infrastructure construction, technology development and exports, energy independence, and new markets for products and services. By reducing costs on conventional fuels and dependency, economic developments could increase national competitiveness and economic growth [20].

6.2 Emissions and Pollutant Reductions

Smart grids increase the capability to absorb more renewables, demand-side management, and storage devices. In others words, the dependency on existing fuels such as coal or gas can be reduced and hence less emissions and pollution. As such, the health impacts to local communities and the nation at large could be long term and significant.

6.3 Customer Engagements

Despite what technologies may offer, the new paradigm of offering active participation (e.g., DR, ADR) and financial incentives to load entities to participate in balancing the grid operation requires a committed mass. The aspiration to use energy wisely for a better world, the willingness to relinquish traditional convenience and opt for a better "common good" habitually and continuously, may not be universally accepted nor easily achieved overnight.

6.4 Reactions to the New Prosumers

As more DERs are allowed and developed, the new prosumers' paradigm will undoubtedly go through stages of progressive evolution. It is quite obvious that the more privileged or large load entities will most likely be able to afford the changes and hence enjoy the benefits ahead of others. The subsequent impacts in terms of potential tariff increase, different service reliability, social fairness, and perceived winners may render an unfair judgment of smart grid developments.

6.5 Value of Reliability

System reliability is a complicated notion which encompasses two key aspects, i.e., adequacy and security [2]. Adequacy is a probabilistic measure to gauge the level of resources and redundancy a system should have to ensure the expected load is met. Security, on the other hand, is a deterministic measure to gauge a system's ability to response and recover from a prescribed list of contingencies. Smart grids can offer new or additional reliability benefits through technologies such as DR, DER, and micro-grids. To date, such cost and benefits are most appealing to the niche market such as the military, heavy and big industries, and data centers because interruption or "blackout" is not an option for them. However, the task of convincing policy-makers and the general public on the value of reliability (or the cost of unreliability) is a challenge sometimes because it is difficult to prove or it may be taken for granted. The value of reliability has to be an integral part of the low-carbon future and hence must be understood and accepted by most if not all stakeholders.

6.6 Privacy

Smart meter deployments in the USA have taught us a valuable lesson when the media and some customers question or even totally reject SM as they feel their most sacred guarded place, namely their home, has been intruded. The reality of many security breaches, personal privacy, and financial losses certainly does not help. As such, cyber security of SM and AMI has become one of the biggest concerns as well as requiring substantially expensive development [3]. The value of using the collected data in helping the community to a more efficient and intelligent use of resources must be explained to the stakeholders (from regulator to customers) along with addressing privacy issues. More importantly, choices (including opting out) should be present simultaneously.

6.7 EV Adaption Rate

The adaptation of EVs in different communities varies, which will also affect the pace of smart grid development. Private vehicles in today's societies are no longer just a transportation means, but also a symbol of social status. Unfortunately, the choice of EVs on the market today is still limited. In the meantime, other hybrids (e.g., diesel electric or gasoline electric) or even diesel-based or CNG-based competition exists. How the consumers and local communities open up to the use of EVs will not only take time to come up to speed, but also depends on EV markets globally.

Ironically, social norm changes help fuel the development of renewables, smart grids, sustainable practices, and the notion of a low-carbon futuristic aspiration. However, it is also the general public that represents one of the biggest hurdles. Public inertia is slow to adapt some behavioral changes and paradigm shifts brought on by smart grids. Education would help, but the cultural background, openness, and flexibility of the local communities will also affect the course of local smart grid development.

7 Neither a Silver Bullet Nor One Size Fits All

The conventional grid is designed based on a well-defined set of end points so that the corresponding power flows are generally well understood. The distance, capacity, and associated protection systems of individual connecting lines/cables are also carefully designed and utilized based on prescribed generation and load profiles. The implicit responsibilities of the grid are to interconnect the power systems in a reliable, safe, and sustainable way in an economic manner. With the arrival of more renewables, customer interactions, DER, and increasing mobile loads (e.g., EVs), the grid needs new technologies, regulatory changes as well as a sound business model to ensure its implicit responsibilities and performance remain unchanged. The challenges and the scope of involvement are huge.

Undoubtedly, smart grid development will be evolutionary instead of revolutionary. It will not be one size fits all either. To ascertain a stable and healthy smart grid development for a low-carbon future, different communities will have their own way and choices [16, 25]. The following is only one of many views on how key processes should be included:

7.1 Take Inventory

Review historical and existing conditions including natural resources available, fuel sources, grid structure and extent, geography, regulatory structure, generation mix, interconnections, national policy, political infrastructure, long-term contracts, and social fabric.

7.2 Set Targets

Establish a targeted generation mix, renewables ratio, energy efficiency performance, reliability standards, interconnection commitments, reserves, minimum level of conventional plants needed, climate policy, and pollution control targets.

7.3 Assemble a Road Map

Envision and design a road map with intermediate targets to allow adjustments of development pace and possible technology changes.

7.4 Stage for Flexibility

Staging can help mitigate risks or burdens in financial commitments, complexity of transitioning from legacy systems, technology obsolescence, policy changes, and/or societal reactions.

7.5 Trial Different Options

Identify clear trial objectives and select appropriate assessment methodology. The objectives may include testing the capabilities of selected technologies or the reactions of customers subjected to different schemes. Trial design and execution should be tailored to fit individual communities' needs and encompassing conditions. Learning from other utilities' experiences and sharing one's own findings could accelerate learning.

7.6 Standardize Equipment and Practices

Use of open architecture can ensure interoperability and expedite implementation with less "special" or "exceptional" cases. Following international standards is an option, but using national standards is also acceptable as far as consistency, scalability, equipment interoperability, and cyber security requirements are also met.

7.7 Retrain Workforce

New skills and experiences in operating and planning DER, SM, DR, EV, etc. are needed to enable the existing workforce to manage and deal with the massive implementation and subsequent demand.

7.8 Educate the Public

Educating all levels of the community in terms of the needs and benefits of building a low-carbon future is important. Stakeholder's engagement and public campaigns to promote how smart grids can facilitate a low-carbon future not only strengthen the commitment, but also help stimulate innovation and accelerate the adoption rate.

7.9 Review and Adjust Periodically

Regular reviews and assessments are necessary to ensure the trials or implementation processes are on track and if any adjustments are needed. However, frequent major changes could be detrimental so firm guidelines and strong commitment to reach the goal post are important.

7.10 Research and Development

Technology plays a key role in smart grid developments. Many technologies and associated practices are new in commercial and large-scale applications. R&D is important to help identify risks, pitfalls, and opportunities of new business opportunities.

8 Research Needs

With the gradual shift of our generation mix to favor more renewables and distributed energy resources, the grid naturally needs to adjust not just for the physics and engineering needs, but also the changing business environment. New opportunities and challenges are arising. In particular, the development of distributed renewables, storage devices, CHP, DR, and micro-grids will affect conventional utility operation paradigms to different degrees in different communities.

A healthy research and development program is considered important in this crossroad of the industry. Some of research directions may include the following:

- Economic values of DER for different technologies, markets and regulatory structure;
- Renewable resource assessment, monitoring, and utilization;
- Integration of renewables, DSM, and micro-grid;
- Cost allocation model of smart grid taking into consideration various stakeholders, e.g., prosumers;
- Value of reliability under extreme contingencies or severe weather conditions; and
- Power electronics applications in micro-grids, storage, and bulk power transfer.

9 Conclusion

A low-carbon world is a necessity not only to mitigate climate change, but also to achieve a more sustainable future for our own and future generation. Transformation toward a low-carbon world will need to incorporate more renewables, distributed energy resources, efficient delivery systems, and intelligent use of energy. A smart grid powered by advanced technologies, coupled with sufficient economic conditions and regulatory environment, is an inevitable and crucial component interconnecting the new forms of generation and load entities as well as making the existing infrastructure work more intelligently and efficiently.

Globally, smart grids will have different flavors because of different local needs, available resources, historic and social backgrounds, economies, and regulatory frameworks. Grid changes in terms of more customer engagements, wider integration of renewables, and DER (including storage) will be the main thrust in developed countries such as the USA, EU, and Japan. On the other hand, grid changes in bulk power transmission system developments, network reinforcements, and DA will be the main focus in developing countries and emerging economies such as China, India, and Brazil. In due course, both main streams will converge in terms of technologies which are built on the ubiquitous and versatile Internet, sensors, sophisticated controls, wireless communications, data analytics, and smart decision tools.

However, technology will only be one of the fundamentals for smart grid development and deployment. Healthy economics and appropriate regulatory push-and-pull elements are considered crucial, and they need to be in-synch with technological advances to make any smart grid deployment usable, beneficial, and acceptable to the local communities. Policies to incentivize more renewable contents in the generation profile must also provide sufficient support to reinforce (and smarten up) the associated network to handle intermittency and complex flows of electricity. Policies to encourage trialing/implementing new technologies to allow optimization of grid operations through efficiency improvement, outage management, and asset life extension are welcome. Smart meter deployment must also consider a win–win business model for both utility and customers.

For individual communities, policymakers must set out an inspirational and yet practical vision toward a low-carbon future. A road map and periodic reviews of it will help, but a strong commitment from policymakers and the public is equally important. To decarbonize the electric power generation and increase efficiency and customer engagement, we must also include the efforts and costs of smartening/reinforcing the grid to meet the needs of new players and new challenges. These challenges are not just technical, but also can be economic, social, and environmental. The processes and endeavors are unique to each community. They are neither trivial nor short-lived. Smart grids are the conventional power grids being remade. Long-term commitments toward a low-carbon future, robust technologies, sound business models, and consistent and timely regulatory changes will provide the wind. The industry in turn will set the sail by making our grids stronger, smarter, and more flexible such that we and our future generation can confidently depend on.

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