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Smart Grid Architecture Overview

The electric power system is the largest and best engineering invention and achievement in human history. However, this grid paradigm faces serious challenges with regard to the increasing demand for electricity, the expanding penetration of intermittent renewable energies, and the need to respond to emerging needs such as wide usage of electric vehicles. The newly faced and expected challenges and expectations from the grid are forcing drivers to transform the current power system into a smarter grid. Smart grid (SG) is a new paradigm shift that combines the electricity, information, and communication infrastructures to create a more reliable, stable, accessible, flexible, clean, and efficient electric energy system. The SG comprises two main parts, SG infrastructure, and smart applications and operation. SG infrastructure entails a smart power system, information technology (IT), and communication system, while SG applications and operation are categorized into fundamental and emerging areas. The fundamental ones refer to energy management strategies, reliability models, security, privacy, and demand-side management (DSM). Emerging applications include the wide deployment of electric vehicles and mobile charging and storage stations. All this indicates that SGs are characterized by automated energy generation, delivery, monitoring, and consumption with stakeholders from smart utilities, markets, and customers.

Initially in this chapter, the principles of current electrical power systems will be briefly discussed. After that, the implications of the transformation trend toward SG architecture will be investigated. Following this, SGs are addressed in greater depth, covering fundamentally diverse concepts and classifications. Lastly, some SG architectures will be highlighted and the future challenges and directions will be addressed.

1.1 Introduction

Today, power grids are being challenged to meet the ever-growing energy demands of the twenty-first century. Energy usage is projected to rise by 50% by 2050, according to the Energy Information Administration [1]. Today's grid is an aging infrastructure, combined with the growth of distributed energy resources (DERs), it is therefore more prone to outages and disturbances leading to poor reliability and power quality. These factors present a

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significant challenge for distributed renewable energy integration to the grid with unidirectional power flow [2]. The current grid is characterized by one-directional electricity flow, lack of information exchange, centralized bulk generation, lack of flexibility to directly trade in electricity markets, inefficient monitoring and control of the power distribution networks, lack of flexibility and accessibility to new innovative solutions such as flexible loads, accommodating large scale of fluctuating energy resources, electric vehicles wide usage, etc. The SG is designed to tackle all these challenges by integrating and smartly utilizing the electricity, information, and communication infrastructures.

The SG is the solution to overcome the aforementioned challenges while also responding to the current and future humanity energy expectations. SG's implementation will not only have environmental benefits through high penetration of renewable sources, but will also have significant regional, national, and global impacts related to achieving a more reliable, efficient, and economic energy system. The SG paradigm integrates a variety of modern advanced technologies such as smart sensors and measurements, advanced communication and information, edge computing and control. This paradigm allows a flexible and reliable electricity system with bi-directional power and information flows [3]. The structures of the SG anticipate and respond to electric system disturbances, optimize asset utilization, and operate efficiently. SG houses all generation and storage options, which hinders the dependency on peak demand back-up power stations – thus, cutting significant costs related to the generation, transmission, and distribution. Furthermore, SG enables active participation of customers, new products, services, and markets – thus can support the uptake of new industries. SG functions resiliently against attacks and natural disasters, delivers power quality for the digital economy- thus, creating new jobs and regenerating the economy at a time of financial crisis. The SG is a power network that contains distributed nodes, which operate under the pervasive control of smart subsystems, so-called smart microgrids. A microgrid is a small-scale version of the electric grid, however possessing distributed generation and potentially energy storage (ES). Microgrids can operate in a grid-connected mode, islanded mode, or in both modes which improve the grid's reliability, controllability, and efficiency. Widespread installations of microgrids enable a faster transformation to the SG paradigm from the current grid infrastructure [4].

1.2 Fundamentals of a Current Electric Power System

The two main characteristics of conventional electrical power systems are: centralized energy generation and unidirectional power delivery systems. This means that electric power is first produced by bulk power generation and then transmitted across the electricity grid to the distribution layer, and finally to the end users. The flow of electricity in the grid is from top (high-voltage network) to bottom (low-voltage network). Figure 1.1 shows the three main stages of generation, transmission, and distribution [5]. Those grid elements are briefly explained in the next sub-sections.

1.2.1 Electrical Power Generation

Traditional power plants burn the fossil fuel to generate electricity therefore they contribute in significant amount of greenhouse gas emission to the environment. The crucial need

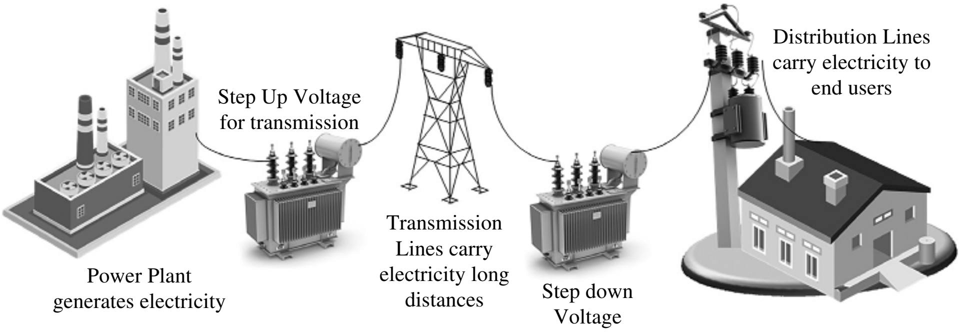

Figure 1.1 The fundamentals of electric power system. Adapted from Ref Num [5].

to adopt power-generation approaches that have fewer environmental impacts is an essential requirement for modern power grids, which means moving toward more renewable energy systems. Among renewable energies, sunlight (photovoltaics) is converted into electricity, wind kinetic energy is converted into electricity, water gravitational and kinetic energy is converted to electricity (hydro) [6]. Continuous technology development is used to convert renewable energies into electricity at increased efficiency and lower cost. Therefore, it is essential for the current power grid to efficiently accommodate a constant increase of fluctuating renewable energy sources.

1.2.2 Electric Power Transmission

The transmission system has the highest voltage rating and is used to transmit the energy from the bulk generation plant to the distribution networks through interconnecting substations. The transmission system may include overhead lines, underground and under water cables. This transmission system could be high voltage alternating current (HVAC) or high voltage direct current (HVDC). Traditionally, an HVAC system is mostly used, however, the HVDC is rapidly gaining popularity due to reduced losses and cost particularly over large distances. The electric power could also be transported and distributed via underground cables. Construction of an underground transmission system normally costs 4 to 10 times that of an equal distance overhead line [7]. The overall amount of power and distance that the power needs to be transported, overdetermine the essential design of the transmission and distribution systems. Hence, the greater the distance and the more power to be transferred, the higher the rated voltage is, and the higher the cost of the system will be as shown in Figure 1.2 [8]. This shows that distributed renewable energy generation allows for the reduction of the cost not only of the central power generation plants, but also of the transmission and distribution infrastructures. This is one of the drivers for the SG energy paradigm.

1.2.3 Electric Power Distribution

The distribution network is the last stage in electric power delivery responsible for carrying electricity from the transmission and sub-transmission systems to end users. There are four main arrangements used in electric power distribution: radial, parallel feeders, ring main, and interconnected (mesh) systems as shown in Figure 1.3 [9]. Distribution networks

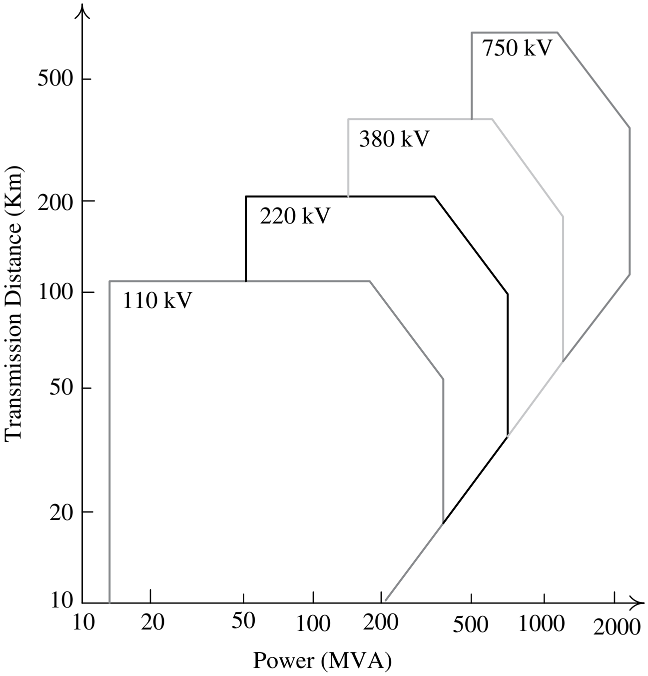

Figure 1.2 Selection of rated voltage for three-phase AC transmission line. Ref [8]. Reproduced with permission from John Wiley & Sons.

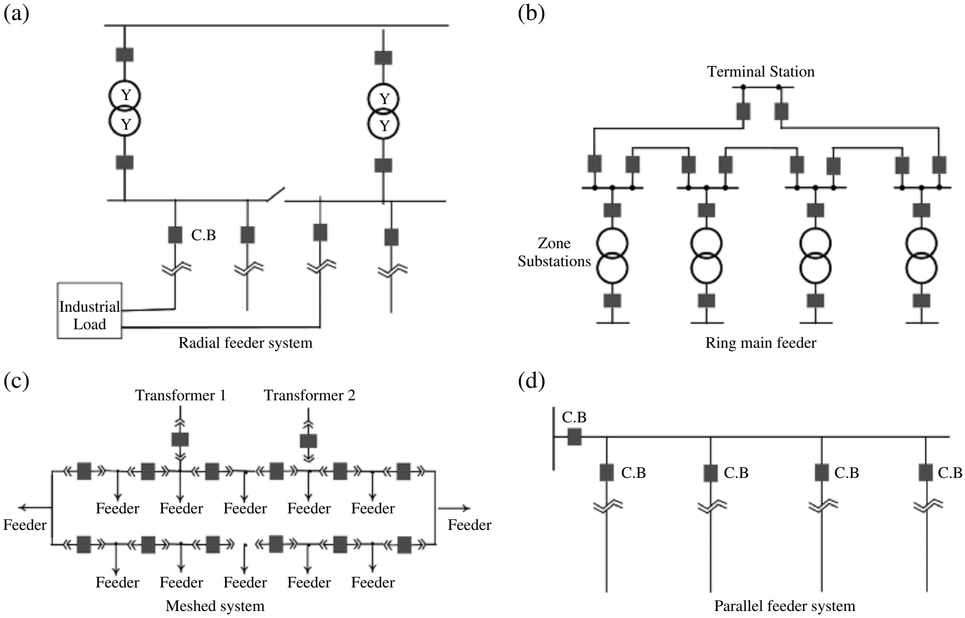

Figure 1.3 Main types used in electric power distribution, (a) Redial feeder system. (b) Ring main feeder. (c) Meshed system. (d) Parallel feeder system. Adapted from Ref Num [9].

typically have a radial topology "star network," with merely a single power flow path between the distribution substation and a certain load (unidirectional power flow). Distribution networks rarely implement a ring or loop topology, with two power flow paths between the distribution substation and the load [10]. Moving toward renewable energy systems and introducing distributed generators (DGs) enforces the use of bidirectional power flows which causes many challenges for traditional distribution systems. A transformation to the SG paradigm includes smart elements to allow for bidirectional power flow and ES technologies. ES systems may include pumped hydro, compressed air, electrochemical batteries, flow batteries, compressed air, superconducting magnetic ES, supercapacitors, and flywheels.

1.3 Limitations of the Traditional Power Grid

The first AC generating system was built more than 130 years ago as a centralized and unidirectional system [11]. The traditional power network consists of various elements such as conductors, transformers, switches, relays, etc. for safely delivering electricity to end consumers. The traditional power grid is a centralized control and management system that uses a supervisory control and data acquisition (SCADA) as shown in Figure 1.4.

Developing real-time control, supervision, and monitoring systems with a smart protection system is essential to optimize the production and consumption of electricity, to improve the overall efficiency, and to ensure the grid's reliability. The challenge is that several new generation sources must randomly connect and disconnect seamlessly with the distribution grid. Moreover, controlling a large number of different sources with different characteristics is of the utmost importance due to the possibility of conflicting requirements and limited communication resources [12]. Those are essential challenges for transforming the current grid into an SG. Other challenges before implementing the SG could be as follows:

1.3.1 Lack of Circuit Capacity and Aging Assets

In many locations worldwide, the power system has extended widely since the 1950s and the distribution and transmission equipment are now beyond the expected lifetime and require replacement. The capital costs of like-for-like change are very high. A typical large-scale utility may require hundreds of billions of dollars to fully modernize the whole grid's infrastructure, which is an overrated cost and should decrease gradually over time. The practical solution is to transform this overstrained infrastructure into an SG, which may even take 20 years or more.

1.3.2 Operation Constraints

Every power system should operate within predefined voltage and frequency limits. The capacity of traditional distribution circuits is restricted by power limits and the changes in voltage and frequency that exist between maximum and minimum loads. Different actions should be taken to vary the output of generations according to the demand, as well as to reconfigure and optimize the network to prevent system collapse. Increasing the output of

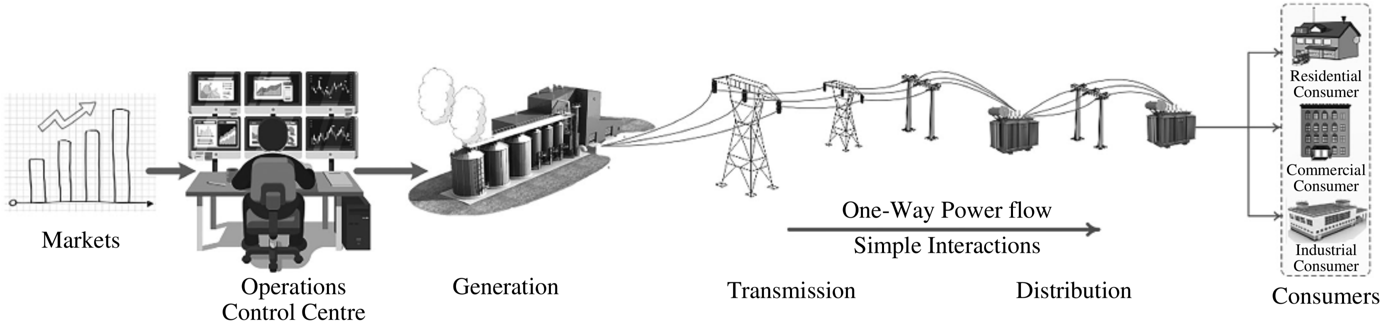

Figure 1.4 Traditional power grid.

generation as per demand at different points in the network is an acceptable solution in case the overloads are small and infrequent [13]. If constraints continue to exist, other solutions should be considered such as advancing the capacity of current power lines, including new lines, or producing separate electricity "highways" to avoid the affected parts, which is still of high cost. SG paradigm can achieve the energy management in a cheaper way by engaging end users in managing their consumption levels which protects the grid without the need to add new expensive infrastructure.

1.3.3 Self-Healing Grid

Nowadays, society needs a growing reliable electricity supply as crucial loads are increasingly connected. The conventional approach is to add more redundant systems, at a considerable environmental impact and capital cost. No action has been needed to maintain supply after a fault other than disconnecting the faulty circuit. The SG paradigm allows for distributed renewable energy generation and intelligent post-fault reconfiguration and self-healing for sustained electricity supply at significantly reduced cost [14]. Better utilization of assets can be achieved with SG at fewer redundant circuits, lower cost, and higher efficiency.

1.3.4 Respond to National Initiatives

Many agencies and policy makers are promoting SG initiatives as cost-effective solutions for modernizing their power systems while activating the deployment of low-carbon energy resources. Advancements of the SG can be noticed in a number of countries. Governments are aware that the SG principle is able to mitigate various blackouts and contingencies at lower cost. Many of SG technologies are already deployed, whereas others are in the demonstration and planning phases. Lastly, the increasing concerns over the natural disasters and terrorist attacks in many countries have motivated the governments to call for a more resilient grid that is less dependent on centralized power stations. SG solutions respond to those challenges and expectations.

1.4 Smart Grid Definition

The Department of Energy (DOE) defines the SG as "the electricity delivery system, from point of generation to point of consumption, integrated with communications and information technology for enhanced grid operations, customer services, and environmental benefits" [15]. The SG implements electricity, information, and communication infrastructures to generate power more efficiently and reliably, and as cleanly and safely as possible for preserving the environment [16]. The European Technology Platform defined the SGs as "an electricity network that can intelligently integrate the actions of all users connected to it generators, consumers, to efficiently deliver sustainable, economic and secure electricity supply" [17]. From the previous definitions, it is evident that the SG is an electrical grid that entails a variety of smart technologies, operations, and measurements such as smart meters, smart appliances, renewable energy resources, electric vehicle, flexible loads, smart

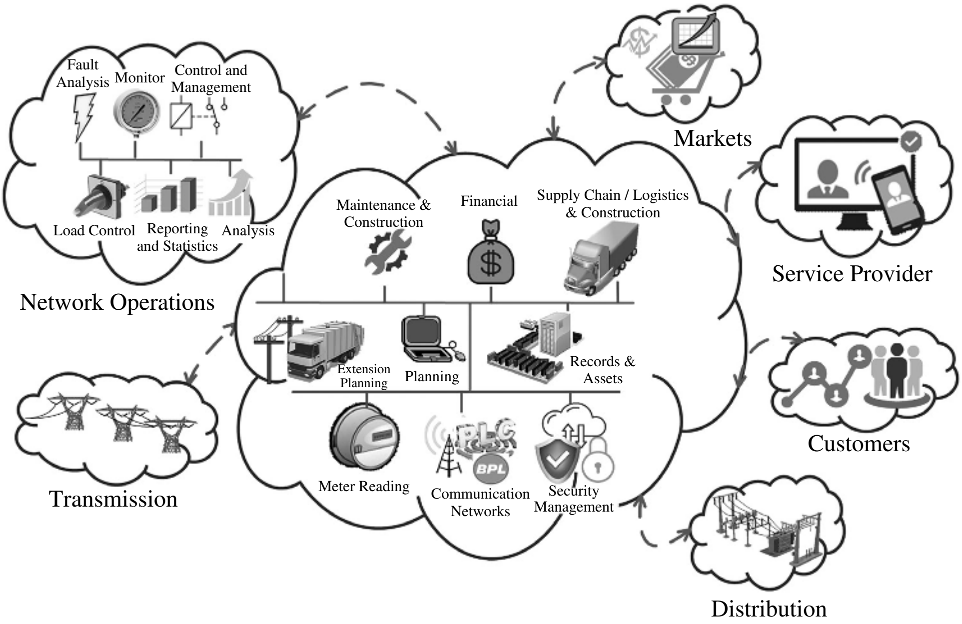

Figure 1.5 The conceptual model of SG framework. Ref [18]. Reproduced with permission from Walter de Gruyter GmbH.

markers, various energy-efficient programs, and smart end users. The SG includes the benefits of advanced communications and information technologies that provide real-time information which can intelligently and cost-effectively integrate the behaviors and actions of all users connected to it, i.e. generators, operators and consumers. This will ensure reliable, efficient, and economically viable solutions for the continuous delivery of clean and affordable energy. One important difference between present grids and the SG is the two-way exchange of power and information within the grid. The conceptual model of a SG is shown in Figure 1.5 [18]. SG implements innovative products and services along with intelligent monitoring, control, communication, and processing to:

- Improve facilitation between the grid elements of all sizes.
- Permit customers to play an important role in improving the operation of the system.
- Offer customers more information and options to participate in the energy market.
- Significantly decrease the environmental impact of electricity generation.
- Improve the electric system efficiency, reliability, quality, and security.
- Improve service quality and reduce electricity cost.

1.5 Smart Grid Elements

The SG architecture consists of three main systems: power, communication, and information. Proper architecture is necessary to ensure SG functionality. The design and analysis of future SGs require fundamental insight into the impact of power network topology and integrated network control with Big Data utilization. Furthermore, it is essential to have an insight into the complex interaction between the physical layer and cyber layer that includes the supporting communication, information, and computational systems. SG architecture can be represented as a layered structure including the following five main layers as shown in Figure 1.6: System architecture, Distribution Control, Applications, Standards, and Cybersecurity measures.

The grid modernization is expected to make the grid more flexible, accessible, and manageable with interconnected networks consisting of a number of smaller-sized subsystems integrated with a large number of renewable energy sources. Making the grid more accessible is possible by having grid resources available and considering the access to the loads. The SG serves the needs of multiple stakeholders in the electricity industry. Devices and systems developed individually by different vendors and for different electric utilities are employed by various customers, so they must work together in harmony; these systems must achieve interoperability requirement. The upcoming technology in the SG interoperability framework is the real-time dynamic control and management systems. The components of SG are the combination of intelligent appliances and equipment that play an important role in the production, delivery, and consumption of electricity. SG elements can be grouped into seven key technology areas [19]. These areas are distributed generation, electric storage system, smart meters, advanced control, integrated communications, sensing and measurement, improved interfaces, and decision support using customer engagement and demand response (DR) as shown in Figure 1.7.

1.5.1 Distributed Generation

DER are defined as small-scale decentralized power generation sites as shown in Figure 1.8 [20]. The systems with DER are modular, and flexible usually located in the vicinity of the load. DER systems utilize renewable energy sources such as small hydro, biomass, biogas, solar,

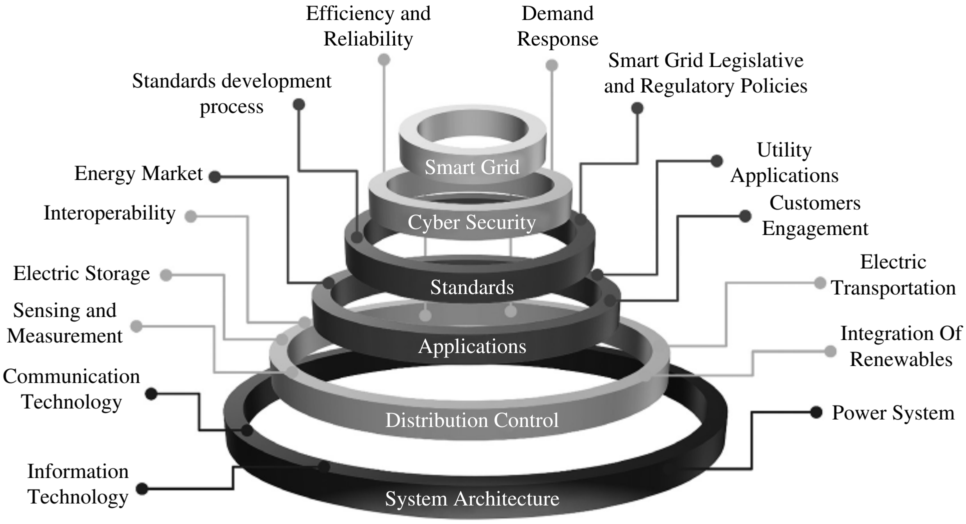

Figure 1.6 SG components.

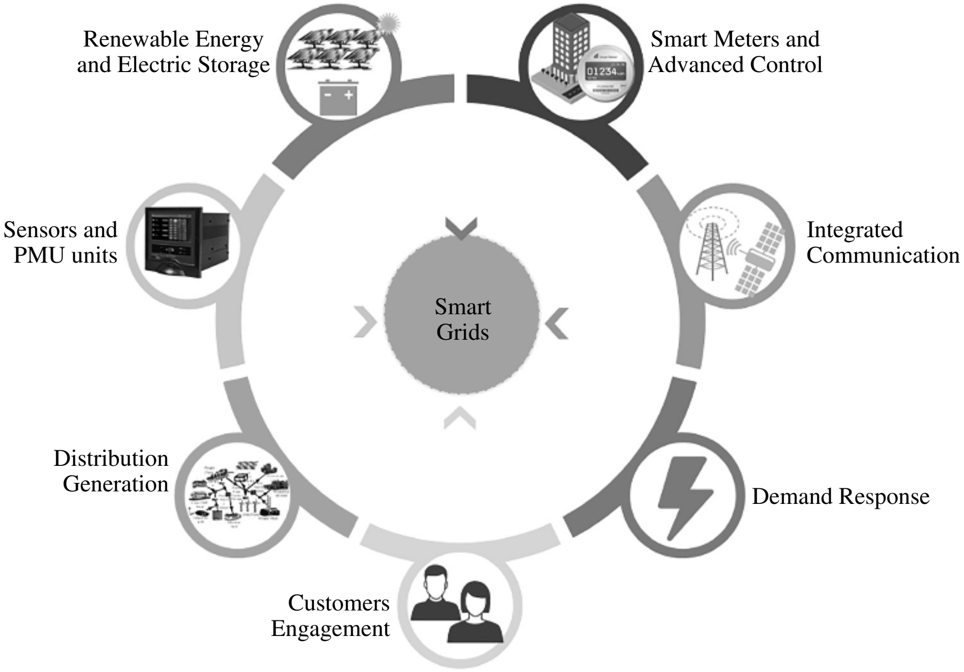

Figure 1.7 Main key technology areas of smart grid.

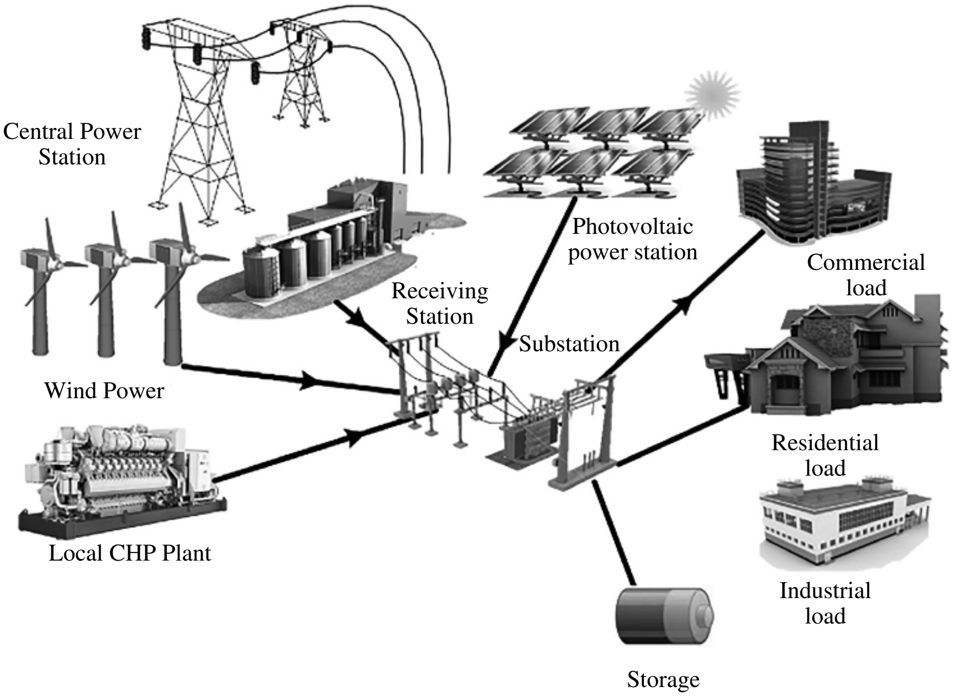

Figure 1.8 Distributed energy resources paradigm in smart grid. Ref [20]. Reproduced with permission from IEEE.

wind, and geothermal. Such systems can be controlled and coordinated within an SG. Using the distributed generation makes the grid active of bidirectional flow of power [21, 22].

DERs can offer potential benefits to the electric grid such as improving energy efficiency, enhancing energy security, and ensuring faster recovery of electricity services. DERs may serve in a single structure connected to an isolated grid, become part of a microgrid, or be connected to the distribution system. Distributed generation can support the delivery of clean, reliable power which supports reducing electricity losses over transmission and distribution lines. The impact of the DERs depends on different factors [23]; such as:

- Size and penetration level of the DGs.
- Type of the DGs, unit ratings, unit impedance, and used transformers used, etc.
- Mode of operation and the interconnection methods with the grid or with the local loads.

On other side, the penetration of DGs increases the complexity of power grids and presents significant stability and control challenges, which may cause greater voltage and frequency deviations and coordinating problems. To overcome these challenges, a coordinated control and managing system must be used to provide the continuity of service, while still meeting customer demands and ensuring the vulnerability of the power system.

1.5.2 Energy Storage

ES is an essential technology for obtaining effective utilization of renewable energy while ensuring continuous energy supply and grid support. Therefore, the storage provides a way to settle the peaks and valleys of supply and end disruptive electricity supply. Storage technologies needs more advances to accomplishing higher power and energy capacities to enabling large-scale deployment. ES systems are combined with advanced power electronics as the interface with the electrical grid. The technical benefits of ES are various forms of grid support [22]. Distributed storage systems may have enormous potential to provide various services to the grid such as supporting the grid's voltage and frequency, providing spinning reserves, enhancing national grid security, and improving grid resiliency. Distributed ES systems are installed at a number of locations on and off the grid. Such systems have two main elements for charging and bi-directional energy flow as shown in Figure 1.9. Most of the existing large- and utility-scale storage resources are hydro and pumped storage. ES can also provide many financial benefits [24].

Effective storage relies on storing and discharging electricity at the required time, and in a way that relies on clear and automatic pricing signals transmitted to smart storage systems. Such storage can give a solution to some challenges, for example, the power congestion at the distribution level, hence avoid/defer potential upgrades in grid infrastructure. However, there are many storage related challenges that must be taken into consideration such as [25]:

- Policies enhancement on net metering, DR, grid reliability standards, generation-based incentives vs hybrid solutions, and the need to consider energy efficiency policies at equipment level vs efficiency at the systemic level.
- Distortion of price signals due to subsidies or lack of real-time pricing signals for consumers.
- Need to consider life-cycle vs capital costs for the selection of government-funded projects.

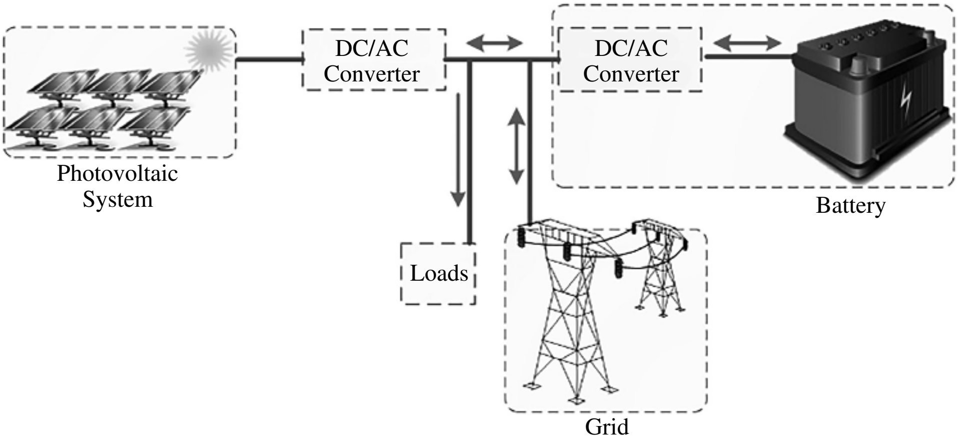

Figure 1.9 The distributed energy storage system.

- Awareness of available technologies and opportunities in various sectors.
- Cost of technology role for the localization and system integration.
- Need for innovative business models.
- Need for financing mechanisms.

1.5.3 Demand Response

The concept of DR has emerged as a solution to demand-side control in the microgrid [26]. Using smart meters and the bidirectional way of communication in the SG opens the door to the technology to participate in the electricity market improvement [27]. The DR programs can be defined as the most successful solution to solve the peak-load burden on the grid and engage customers in the wholesale market operations. A greater number of active consumers can change the profile of the load by minimizing or maximizing the demand as per the generation instructions. This ensures that the load will follow the generation, rather than the generation following the load as in the current energy paradigm. However, these types of programs attract a number of customers’ schemes, but designing it remains a major challenge. Most DR programs and the challenges faced when implementing these programs will be presented in detail in Chapter 11.

1.5.4 Integrated Communications

Communication infrastructure is essential for the effective functioning of SGs. The implementation of communication technologies guarantees the decrease of energy consumption, ensures best implementation of the SG, and provides coordination among all SGs’ components from generation to the end-users. Examples of existing communication network technologies used for SG are fiber optics, WLAN, cellular communication, WiMAX, and power pine communication (PLC). Detailed discussion of the integrated communication in the SG and a comparison of communication infrastructure between the legacy grid and the SG communication standards and research challenges and future trends are presented in Chapter 8.

1.5.4.1 Communication Networks

The communication system connects various components of SG architecture for real-time control, monitoring, and data utilization. Integrated communication is the connector for all SG technologies. The communication infrastructure of the SG is predicated upon three types of networks: Home Area Network (HAN), Neighborhood Area Network (NAN), and Wide Area Network (WAN). Figure 1.10 shows the diagram of the SG communication infrastructure [28]. **HAN** is installed and operated in a small area (tens of meters) and has a lower transmission data rate of hundreds of bits per second. HAN consists of a broadband internet connection used to communicate and share the data between devices over a network connection and smart meters. HAN offers more efficient home energy management [28]. **NAN** is installed and operated in an area over hundreds of meters. A number of HANs can be connected to one NAN to transmit the data of other NAN networks and to local data centers for storage and further analytics. The NAN has a 2 Kbps transmission data rate. Different technologies can be used to implement the NAN network such as PLC, Wi-Fi, and Cellular [29].

WAN is installed and operated in an area of tens of kilometers and it contains several NANs and LDCs. The communication between SG components such as renewable energy generation, transmission, distribution, and the operator control center are predicated upon a WAN network [30]. SG communication infrastructures share the same main challenge, which is how to be merged effectively. A number of technologies can be employed to the SG to achieve an effective merge between communication infrastructure. These technologies are ZigBee, WLAN, Cellular networks, and Power Line Communication (PLC).

ZigBee is utilized in applications requiring a small data rate, prolonged battery life, low price, and safe networking. Applications also include wireless light switches, traffic control systems, meters for in-home-displays, and extra consumer and industrial devices that require a short-range of wireless data transmission at relatively low rates. The benefits of ZigBee application in the SG are low cost, decreased size, and relatively decreased bandwidth. The drawbacks of the ZigBee are the small battery which suggests a short lifetime, small memory, limited data rate, and low processing capability [31].

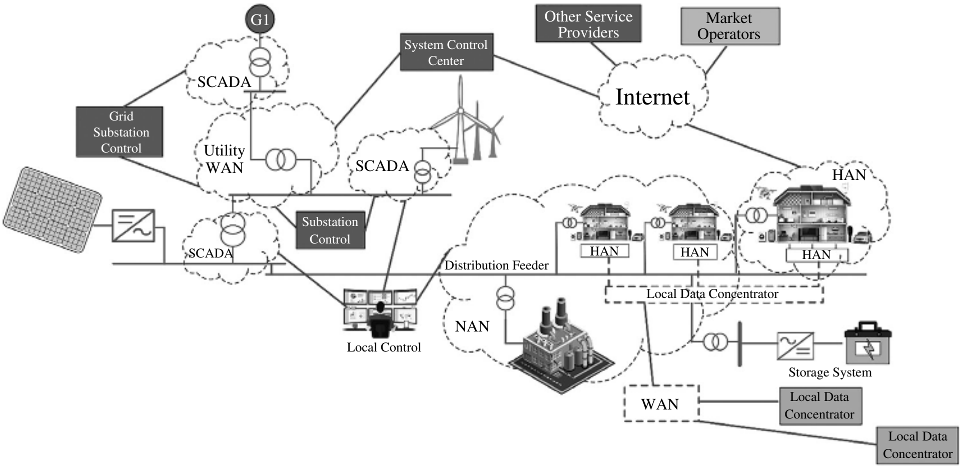

Figure 1.10 Schematic diagram communication infrastructure for the SG.

WLAN is a wireless local area network (WLAN) that links two or more devices through the use of spread-spectrum or Orthogonal Frequency Division Multiplexing (OFDM) [32] and generally delivering a connection through an access point to the internet. This provides customers with the chance to roam around in a local coverage area and at the same time maintain connection with the network. The benefits of WLAN are low price, huge installations worldwide, and plug and play (PnP) devices. The main drawback of WLAN is possible interferences with other devices that communicate on similar frequencies.

Cellular networks are vastly employed in the majority of countries and possess a well-recognized infrastructure. Cellular networks could be utilized for communication among a number of components and devices in the SG. There are a number of current technologies for cellular communication including GSM, GPRS, 3G, 4G, 5G, and WiMAX [33]. The benefits of the cellular networks are presently available infrastructure across a vast area of implementation, elevated rates of data transmission, existing security systems implemented in cellular communication. The main drawback is that cellular networks are shared with other customers and are not fully devoted to SG communications.

1.5.4.2 Power Line Communication (PLC)

PLC permits data exchange among devices by electrical power lines. PLC is employed by including a modulated carrier signal to power cables. The benefit of the PLC is the currently recognized infrastructure that decreases deployment costs. Drawbacks include the existence of higher harmonics in the power lines that interfere with communication signals and the limited frequency of communication. Installing a number of smart meters and communication infrastructure should be implemented according to certain standards that are acknowledged by all companies and utilities taking part in building the SG. Different organizations are working on SG standardization such as the European Committee for Standardization, American National Standards Institute (ANSI), International Telecommunication Union (ITU), Institute of Electrical and Electronics Engineers (IEEE), and others. The well-known standards for SG communications are IEEE P2030, which provides guidelines for interoperability of the electric power system with end-use applications and loads; IEEE P1901 used by all classes of Broadband over Power Line (BPL) devices, entailing devices utilized for the connection to internet access services and devices utilized in buildings for LANs, smart energy applications, transportation platforms (vehicle), and other data distribution applications; IEC62351, which deals with cybersecurity issues of the SG; IEC62056 for electricity metering data exchange; PLC G3 to allow data and control messages to be transferred to generation, transmission, and distribution systems. There are more standards for SG communication including 802.15.4, ISO 1802, IPv4, DNP3, IEC61970, etc. [34]. More details on the standardization will be discussed in Chapter 17.

1.5.5 Customer Engagement

In the traditional grid, consumers have a passive role while occupying a marginal position in the energy market. Customer engagement has been negligible in the aspect of energy monitoring, controlling, management, generation, storing, and trading. However, with the introduction of the SG paradigm, the consumers have a crucial and active role in all aspects above. The SG technologies open the opportunity for active engagement through real-time insight in their energy consumption patterns, price changes, local renewable energy production, storing, and energy sharing. Customers engagement is the language of energy DSM in the SG which is used to achieve supply–demand balancing, load shifting, and increased reliability, high efficiency, and resiliency in the electric system. Electric utilities are putting more focus on energy demand management to realize three main tasks: enhancing energy efficiency, direct load control, and to meet a dynamic DR [35].

Energy management on the demand-side acts on the consumers for controlling electrical energy usage. There are a number of solutions to attain demand management and flexible energy consumption. Direct load control and dynamic DR programs are addressing the biggest priorities and challenges for the successful implementation of demand management in SGs. The participant customers can rely on their generation sources to meet their demand (typical usage requirements) whenever possible. Customer engagement, through (DSM) market prices change, increases with time. Figure 1.11 shows the global market of customer engagement. The global energy management systems (EMS) (industrial, home, and building) market size was USD 9.8 billion in 2017 and is expected to increase to USD 72.73 billion in 2024 [36, 37]. The right-side column of the Figure 1.11 indicates the spending per region. The EMS is becoming a crucial tool for both the utility and the customer to monitor, analyze, shift, optimize, and control energy and assets in real-time.

1.5.6 Sensors and PMU Units

Sensing and measurement technologies collect data to evaluate and monitor the state operation and equipment health status which support the grid's functionality and higher reliability. Also, this serves customers in improving their electrical usage by giving them information regarding their daily demands. Sensing and measurement technologies include sensors, phasor measurement units, and advanced metering infrastructures (AMI). All this supports a wide-area monitoring system, time-of-use, assets functionality, real-time pricing, and the

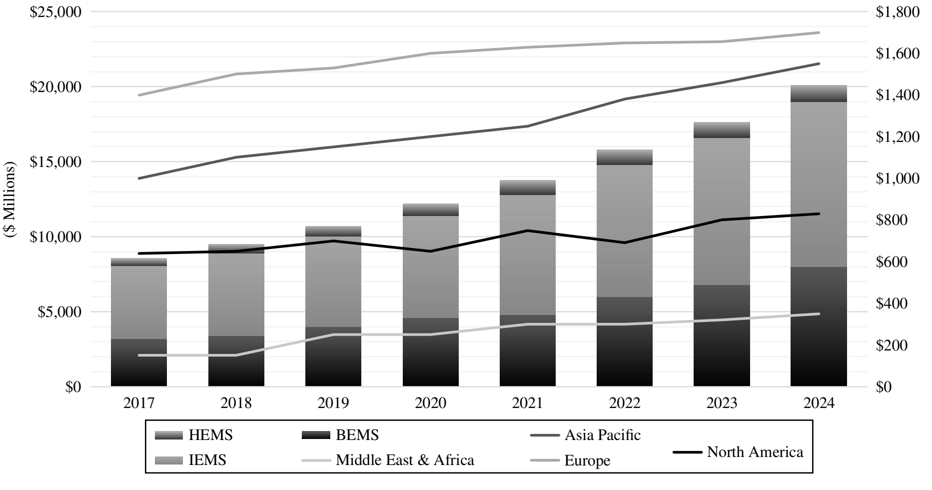

Figure 1.11 Customer engagement demand side management spending by region, 2017–2024 (USD Million).

system proper operation. A phasor measurement unit is a high-speed sensor integrated with the power grid to monitor power quality by allowing data to be obtained at certain instants of time. Phasor measurement units can be considered as a health-meter of the grid as they collect different measurements of voltage, phase, and current to be analyzed. This will help to reduce blackouts and provide a wide-area situational awareness.

1.5.7 Smart Meters and Advanced Metering Infrastructure

Smart meters are a two-way communicator that helps create a bridge between the utilities and the end consumer. In comparison to existing meters, smart meters have included functionalities by using real-time sensors, power outage notification, and power quality monitoring. Smart meters function digitally and permit automatic and complex transmissions of data between utilities and customers. Sharing information through smart meters can be linked to a Home EMS, which allows the consumers to see it in a comprehensible format which helps them to control their energy usage. To have a safe and reliable grid, various devices and algorithms that allow for rapid diagnosis and analysis should be developed.

AMI includes the implementation of various technologies that allow for a two-way flow of information, providing consumers and utilities with information on electricity cost and use, including the time and amount of electricity used. AMI gives a wide range of functionalities such as [38]:

1) Remote consumer price signals, which can provide time-of-use pricing information.
2) Collect, store, and report users' energy consumption data for any needed periods.
3) Enhance energy diagnostics from detailed load profiles.
4) Obtain location and degree of outages remotely.
5) Provide the possibility for remote connection and remote disconnection.
6) Allow identification of electricity theft and losses.

1.6 Smart Grid Control

The future SG is expected to be a flexible and manageable interconnected network consisting of small-scale and self-contained sub-areas, integrated with the large-scale electric power grid as the backbone. Utilizing micro sources, such as renewable energy sources and combined heat and power plants, into the SG makes them feed their local loads in an economic and environmentally friendly manner [39]. Therefore, the SG control architecture should therefore be dynamic and multilayer to handle real-time operation and provide tradeoff between performance and implementation. Advanced control uses high-speed communication infrastructure, distributed intelligent agents, analytical tools, and operational functionalities. The advanced control systems in the SG monitor the essential components, provide timely response, and enables the detection, prediction, disconnection, and self-healing of faults in the system.

Hierarchical control systems of the SG are distinguished between multilevel systems and multilayer systems. The multilevel system is based on the cooperation of independent controllers which cooperate to control the trading of the power. The multilayer

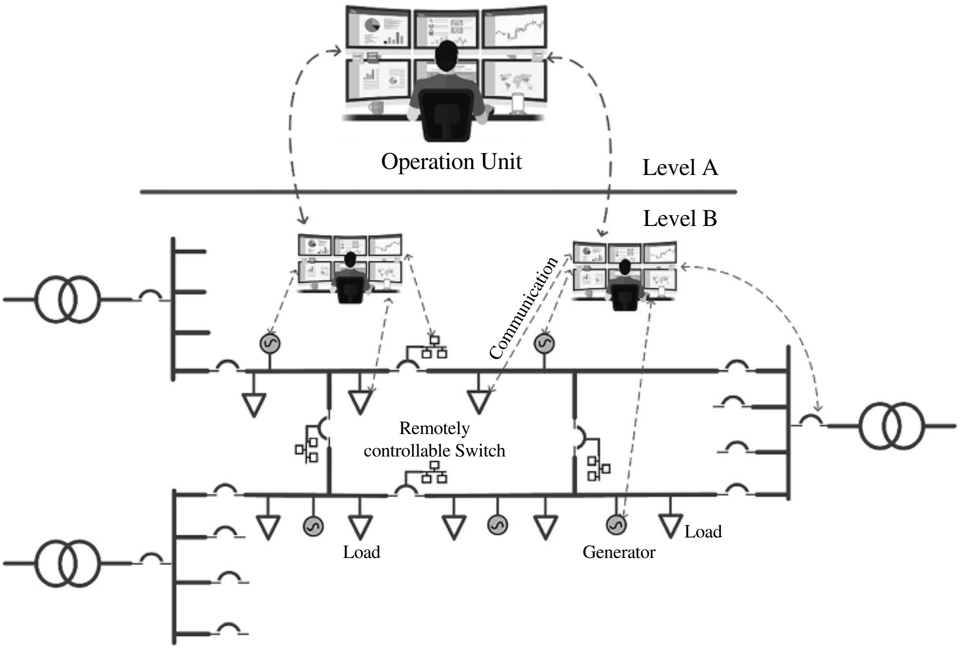

Figure 1.12 Distributed operation architecture with two levels.

system is based on individual actions with each controller having its own objective. A multitude of different architectures of the SG exists to realize such integrated systems. They are known as "distributed," "decentralized," "local," or "central." [40]. If an information exchange exists among the independent controllers, the control architecture is assumed to be distributed as shown in Figure 1.12. The system could be fully or partially distributed, and this is reliant on the condition that the information is shared between all controllers or among a subset of controllers. A decentralized control architecture-independent controller controls distinct subsystems. In particular, no information is exchanged among them as shown in Figure 1.13. The local architecture restricts the control on a single device or a single facility. The input data should be in existence locally, and no external communication exists as shown in Figure 1.14. In the event that a central operation unit manages all other devices in a system and aggregates and processes all the corresponding information, a central operation architecture is the case as presented in Figure 1.15.

1.7 Smart Grid Characteristics

SG implements ground-breaking products and services together with intelligent monitoring, control, communication, and self-healing technologies which can be characterized by the following goals and functionalities:

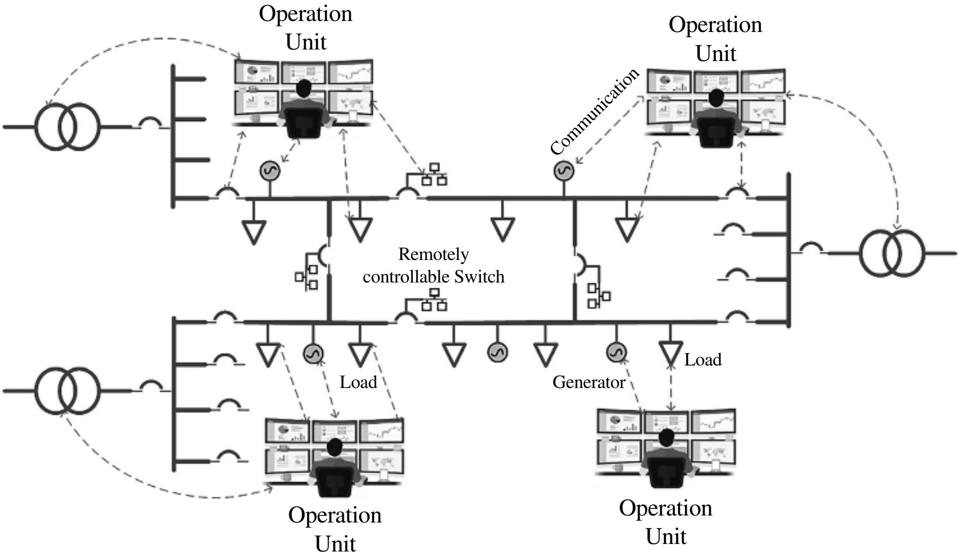

Figure 1.13 Decentralized operation architecture.

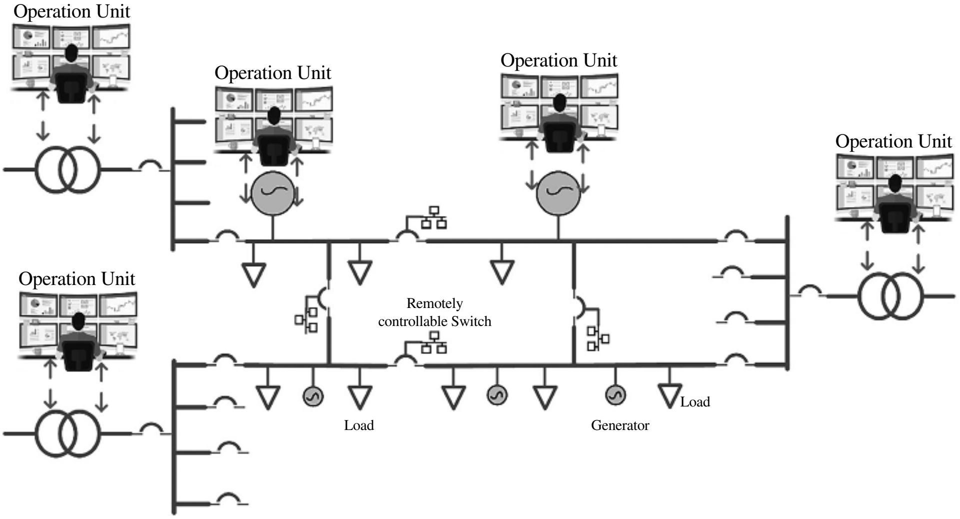

Figure 1.14 Local operation architecture.

1.7.1 Flexibility

SG distribution, transmission, and generation infrastructures allow for bidirectional power flow and are flexible to accommodate various types of generations, storage, loads, and emerging technologies such as electric vehicles (EVs) and mobile storage. SG allows the integration and operation of generators of all sizes and types at different locations [41]. SG accommodates all renewable energy sources and storage options and flexibly responds to differing

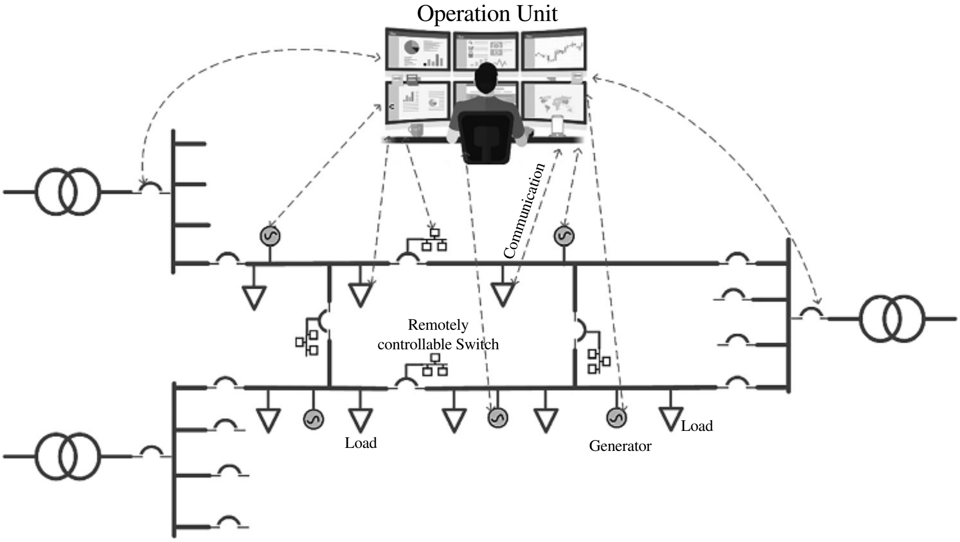

Figure 1.15 Central operation architecture.

humanity expectations and innovations, now and for decades to come. The SG paradigm will also be flexible to customers' active role regardless of the many existing obstacles.

The residential sector is not being targeted by many programs in the traditional grid paradigm as it is hard to deal with due to a multitude of factors such as high acquisition costs and limited access to the individuals. However, currently, new smarter devices can be incorporated with a number of residential appliances to respond locally to the price signals in an automated manner. The flexibility of demand creates values for the grid and customers by minimizing customer bills, shifting consumption to lower prices at off-peak hours, and reducing demand (during peak periods). Flexibility within demand can also help suppliers in some events to defer investments in central generation, distribution, and transmission.

The SG will be flexible to the customers' active participation. Consumers will utilize the grid in a number ways, more consumers will be "prosumers": both producers and consumers of energy and to additionally store the energy. The grid will no longer be merely a "delivery pipe" for electric power. All connected to the grid will be masters, no slave and master roles for them in future SGs [42]. The grid can constantly deliver power against disturbances (in extreme climate conditions and periods of natural disasters) without outages over a large area and could maintain information security against various attacks [43].

1.7.2 Improved Efficiency

Energy efficiency and product innovation programs are coupled together to make industrial and consumer sectors more efficient than they have been for a long time [44]. A SG with distributed energy generation allows for lower transmission and distribution losses which make the whole system more efficient. All parties connected to the grid work smartly for programs that improve the efficient use and delivery of electricity.

1.7.3 Smart Transportation

Electric transportation has been evolving rapidly during the past few years. The installation of smart EVs in the energy market can compensate for the need of major grid's infrastructure expansion. This compensation can be achieved if the EVs battery technologies allow for vehicle to grid (V2G), grid to vehicle (G2V) and vehicle to building (V2B) power flows to perform large-scale mobile storage and are combined with suitable pricing schemes to support the grid performance and economy. EV technology might be one of the most significant accelerators of SG adoption. Also, battery cost, size, and weight declination are considered as some of most important research topics related to EV deployment [45].

1.7.4 Demand Response Support

SG permits generators and loads to interrelate in an automated way in real-time, which allows customers to play a major role in optimizing the operation of the whole grid. Also, giving the consumers timely information enables them to reduce their energy bills by modifying their consumption patterns to overcome some of the constraints in the power system. DR and DSM are essential programs in SGs. DSM is applied for long-term planning such as for shifting the load peak over time. DR ensures short-term load response to improve the energy consumption profile over time. This could be realized by creating a dynamic electricity price. Consumers have the choice and authority over their consumption patterns. Various financial incentives could be created to adjust the level of demand and generation at strategic periods of the day. Figure 1.16 presents a classification of DR programs. Implementing DR programs into the operational aspects of the system has different benefits such as reducing the peak load and avoiding the need for new power plants and infrastructure oversizing [46].

DR programs are categorized into two main programs, time-based programs, and incentive-based programs. In the time-based DR programs, the change in electricity prices can vary automatically at different times based on customer electricity consumption as per the

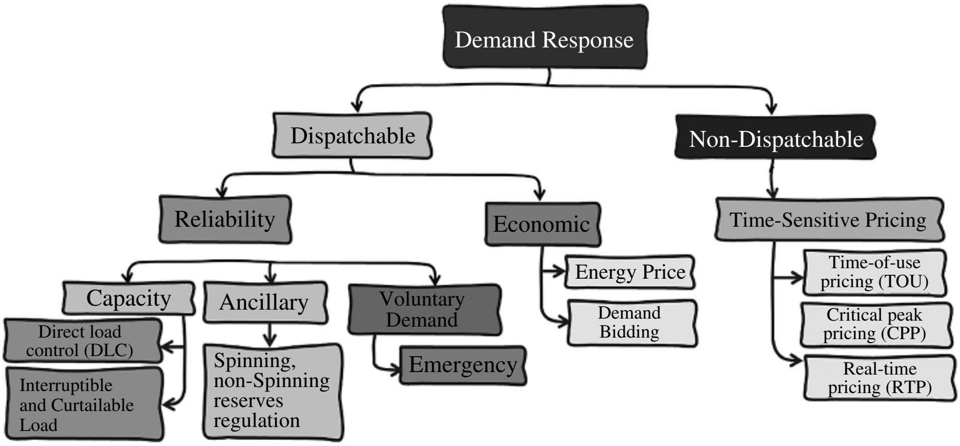

Figure 1.16 Classification of DR.

contracts signed with the operator. While, with the incentive-based DR programs, the customer is offered some incentives to participate in a fixed or varying period. The benefits will increase by triggering an incentive price to affect customer behavior by decreasing demand consumption.

Currently, DR is only used by large commercial consumers, and its operation is based on informal signals such as phone calls by the utility or by the DR provider asking the consumer to lower their energy consumption during peak times for energy demand [47]. There are four main obstacles in the face of the uptake of DR:

1) The shortfall of market integration.
2) Improving incentive-based DR programs.
3) The need for increased adoption of enabling technologies.
4) More communication in the power grid which is associated with privacy and security concerns.

1.7.5 Reliability and Power Quality

The SG utilizes technologies such as improved fault detection, state estimation, and enabling self-healing of the network without the need for specialized personnel. This leads to a reliable supply of electricity and minimized vulnerability to attacks or natural disasters. Smart grid operates resiliently in disasters and during physical, or cyber-attacks. Advanced control methods and monitoring oversee essential elements of the grid, enable rapid diagnosis and solutions to events that affect the grid's integrity, power quality, and smooth operation. The grid can monitor both on-line and in real-time as well as assess its current state and predict its future situation. The SG has robust risk warning procedures to employ preventive capabilities, automatic fault diagnosis, self-fault isolation, and self-restoration [48]. With all-new energy resources and entities, optimization and handling the system will become more challenging, even with the availability of new technologies and tools. Interdependencies and interactions between distribution and transmission systems will keep rising. The increase in the grid's complexity will require many technological, computational, and business operation requirements such as [49, 50]:

1) Self-learning systems.
2) Increased coordination between transmission-level balancing areas as well as additional balancing abilities at the distribution level.
3) Balancing abilities using both load-side and supply-side operations.
4) Privacy and security to be applied in all parts of the system, down to end-use devices.
5) PnP capabilities in SG enhanced levels.

1.7.6 Market-Enabling

The SG enables systematic communication between suppliers (their price of energy) and consumers (willingness-to-pay) and allows both the consumers and supplier increasing transmission paths, aggregated supply, DR initiatives, and ancillary service provisions [51].

1.8 Transformation from Traditional Grid to Smart Grid

There is a huge need to transform the traditional grid structure to SG. The current electric grid is on the way to SG at various rates of acceleration. Much has been accomplished to mitigate the possibility of blackouts, especially in utilizing new technologies that can assist electricity grids to be more reliable. Many of these technologies are smart and widely deployed now, whereas others are still in the demonstration and planning stages. Advanced components are already being used to analyze and diagnose the grid state and assist in its healing within a limited period of time. Figure 1.17 shows the transfer process from the traditional grid to a SG which indicates moving from one-way power flow (simple interaction) into two-way power flow (multi-interaction). A detailed comparison between the traditional power grid and SG are presented in Table 1.1. This shows that the majority of SG features are originated from the massive amount of generated information, an uncountable number of internet-connected control, and programmable auto-operated equipment [52, 53].

1.8.1 The Necessity for Paradigm Shift to SG

Maintaining economic growth and improving the quality of human life are reliant on the availability of affordable and reliable electricity. Up to now, conventional grids function in almost the same way as those of 130 years ago, i.e. power flows in a single direction across

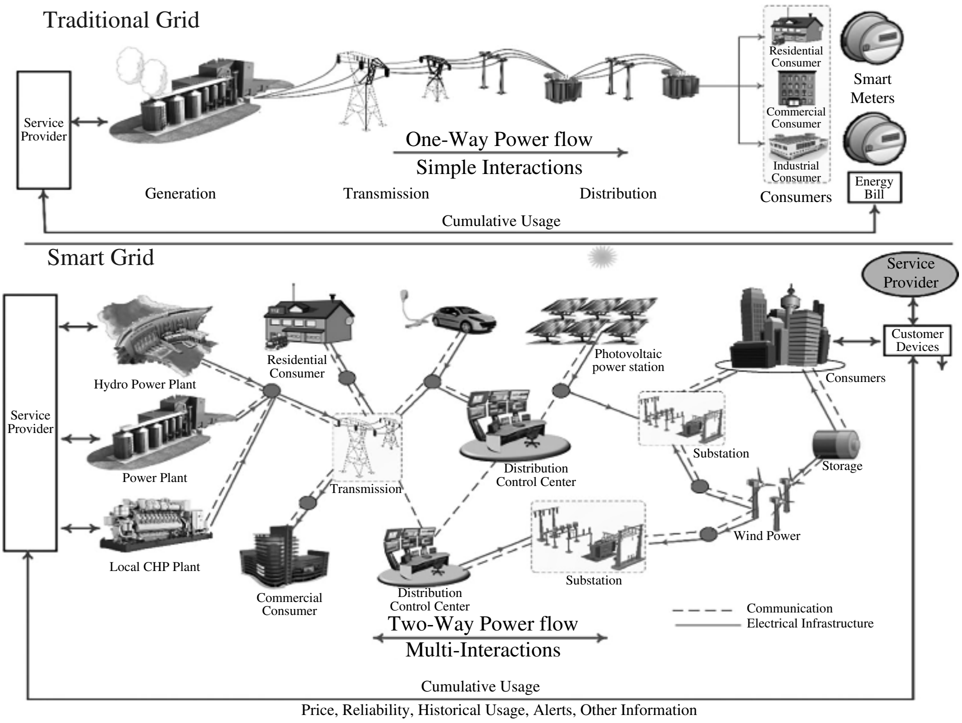

Figure 1.17 The difference between the conventional power grid and smart grid structure.

Table 1.1 A detailed comparison between conventional power grids and smart grids.

Characteristics	Traditional grid	Smart Grid
Technology	• Electromechanical • Mechanical devices electricity operated • No communication between devices • Little internal regulation	• Digital • Digital devices • Increased communication between devices • Remote control and self-regulation
Flow of power and communication	• One way • Power flow starts from the main plant using traditional energy structure to the customer	• Two way • Power flow goes to and from various grid users
Generation	Centralized	Distributed
Fault location	Difficult to determine	Can be determined remotely as well as predicted
Monitoring	Manual	Self- monitoring
Equipment failure	System responds to deal with post failure and blackout incidents	Adaptive and can be isolated and automatically reconnected.
Control	Limited control system	Pervasive control system
Operation and maintenance	Manually equipment checks	Remotely monitor equipment

the grid, from the central power plants to the customers. The reliability is maintained by conserving the excess capacity, which is inefficient, uneconomic, and environmentally unfriendly. Current grid topologies cannot be used with the distributed renewable energy sources and two-directional power flow. The alternating nature of renewable energy sources creates additional challenges. The aging grid also faces new problems due to increased demand, and nonlinear loads. Such a grid experiences an inability when the demand for power delivery and consumption boosts, which has happened frequently worldwide in recent years. The main reason that acts on the decrease of the traditional power grid's reliability is the lack of information exchange [54]. The current grid is of limited ability to react quickly to handle congestion, instability, and power quality challenges. The inflexibility of the existing grid cannot support the high integration of renewable energy. These limitations can lead to blackouts, equipment outages, and unscheduled downtime. Approximately 90% of all power outages and disturbances have their origins in the distribution network, therefore, transforming to the SG paradigm ensures a significant improvement of the grid's reliability. Furthermore, electric utility customers currently have a passive role; they have no access to the real-time consumption and pricing information that allow them actively participate within the power grids and optimize their energy usage and bills during peak and off-peak times. The two-way communication and power flow within the SG allow for effective energy control and energy management. This feature also allows achievement of both environmental and economic sustainability.

In summary, transforming to SG paradigm will help in the wide-scale integration of energy sources, enhancing network reliability, and improving power quality and load profile.

1.8.2 Basic Stages of the Transformation to SG

Successful transformation to SG requires a real, national level roadmap. Many countries have already established their SG roadmaps [55–60]. Each country has its own unique definition of a SG based on their own policies, goals, and objectives. The transformation roadmap should be developed based on different technical and economic realities and challenges facing each country. To develop a complete SG Roadmap that responds to the nation's electric power sector goals, some basic stages should be involved to define the priorities of their energy sectors. Also, there is a need for specific objectives, actions, and tools to fully achieve the roadmap set goals. Examples of steps and targets that countries put to transform traditional grid into SG are:

1) Install smart meters and AMI around the entire country by a specific time.
2) Significant percentage of cars to become electric within a specific time.
3) Specific reduction of country's emissions by a specific year.
4) Significant level of renewable generation by a specific time.
5) New tariff system.
6) Activating a DSM and customers activated role before a specific year.
7) Establish effective information and big data centers with a clear strategy for secure data storing and utilization. Timely publish current and historical data that is not confidential nor sensitive.
8) Building human capacity by adopting specific training programs on SG areas.

1.9 Smart Grid Enabling Technologies

The current technology revolution is leading to unwitnessed shifts in the economy, society, business, and individuals. A great effort is being made worldwide toward clean energy in order to protect the environment and improve operational efficiencies and customer services for better grid availability and reliability. The transfer of the traditional grid to a SG requires modifications and upgrades at various levels of the electric grid [61]. Nowadays, information and communication technologies are being developed very quickly and can significantly support the SG vision. This transformation is pushed by several factors, which include electrification, decentralization, and digitalization as shown in Figure 1.18. Those drivers work in harmony to assist in enabling, scaling up, and reinforcing advancements in SGs. Decentralization enables active elements of the system but requires a high level of coordination. Digitalization supports electrification and decentralization by having better management, which includes automatic control, consumption real-time optimization, and interaction with customers.

1.9.1 Electrification

Electrification is the process of powering by electricity and, within the context of the SG principle [62]. As the electricity generation in the SG moves toward more renewable

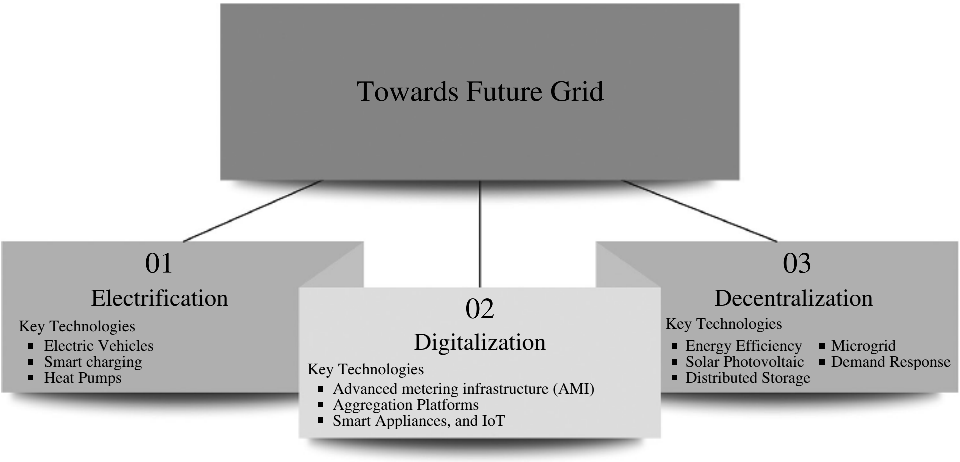

Figure 1.18 Three trends of the grid edge transformation.

sources, this trend enables more environmental gains and adding to it more end sectors such as heating, transportation, away from fossil fuel resources. This trend also increases the efficiency of energy utilization. An example of electrification is using EVs in transportation. This technology has been evolving rapidly over the past five years. The EV range was improved to exceed 480 km for particular models. Batteries' costs which were above $1100 per kilowatt-hour in 2010, have fallen 87% in real terms to $156/kWh in 2019 [63]. These reductions have reduced the cost gap with traditional internal-combustion engine vehicles. It's expected to have economically competitive EVs, although multiple electrification challenges within the infrastructure can limit the successful adaptation rate of EVs. The deployment of EVs boosts electricity consumption and offers a huge opportunity to maximize the utilization of the grid. This can be achieved if the charging/recharging technology is combined with suitable pricing and flexible usage. Electrification and economic growth are highly correlated [64].

1.9.2 Decentralization

Decentralization is the transformation of the bulk, "one-way direction" of energy into a distributed, multi-directional flows, known as multi-lane highways [65]. A decentralized electrical grid has several environmental and security benefits. Microgrids coordinated with distributed energy generation give systems significantly enhanced reliability and grid efficiency. Distributed power generation and microgrids are independent of the grid which means this power is provided to the local loads even when the main grid is not available. Decentralized generation allows the reduction of power outages for critical facilities, for instance, hospitals or police stations or any facility that may need continuous power. Hence, decentralized grids are more energy-efficient than centralized electricity grids [47]. Consequently, implementing renewable energy sources in the current power grid does not automatically imply that the current power grid is decentralized. The transformation from a centralized to a decentralized electricity grid requires a number of technologies with various implications that need to be considered to become a reality such as [66]:

1) Distributed generation (from renewable energy resources).
2) Distributed storage.
3) DR.

1.9.3 Digitalization and Technologies

Advancements in digitalization enhance the grid's utilization and management. Technologies that are digitalized have been increasingly used to allow devices across the grid to exchange beneficial data for the customers and grid operators. There is a huge interest in utilizing innovative Internet of Things (IoT) sensors, smart meters, network remote automation, distributed and centralized control systems, digital platforms, to spot the light on the grid's proper optimization and aggregation, enable real-time operation of the network, and enhance grid's situational awareness and utility services [67]. The rise in the deployment of AMI shows clear opportunities for enhancing the quality of service, the observability of the network, and data gathering for short- and long-term utilization. The grid's various digital data provides opportunities for fault detection, energy consumption and generation, as well as prediction of faults and outages. Digitalization of the network is an obvious opportunity for cost-effective development and management of the electricity system with high returns in cost and quality to serve. On the consumer side, chances for the use of smarter customer technologies are being increased. The installation of digital technologies in the network should not be slowed down by outdated regulations. As more digital devices are deployed, the communication between these devices will be increased. Broadband communication infrastructure will support a wide range of services (both network and consumer services). Not having updated policies and standards can slow down the development of this infrastructure and hinder innovation in this space. There are more challenges for digitalization including available infrastructure and replacement cycles [68]. Technologies related to the SG have evolved from previous attempts at utilizing electronic control, metering, and monitoring. Back in the 1980s, automatic meter reading was implemented to keep track of loads from heavy consumers and emerged into the AMI of the 1990s [69]. These meters can record and store how electricity is utilized at various times of the day. Smart meters give continuous information so that monitoring can be achieved in real-time and could be utilized as a gateway for "smart sockets" in the premises and for DR-aware equipment [70]. The main technologies in the SG consist of three main parts: electric energy technologies, operation technologies, and information and communication technologies as described in Figure 1.19. Energy technologies include renewables energy, distribution generation, DR, EVs, ES, integrated gasification combined cycle, etc. The operation technologies refer to a variety of hardware and software that detect or cause a change through direct monitoring and/or control of physical devices, processes, and events in the SG [71]. It includes the EMS, distribution management system (DMS), DSM, SCADA, outage management system (OMS), asset management system (AMS), flexible alternating current transmission system (FACTS), wide area monitoring systems (WAMS), process control application (PCA), etc. The information technologies include enterprise resource planning,

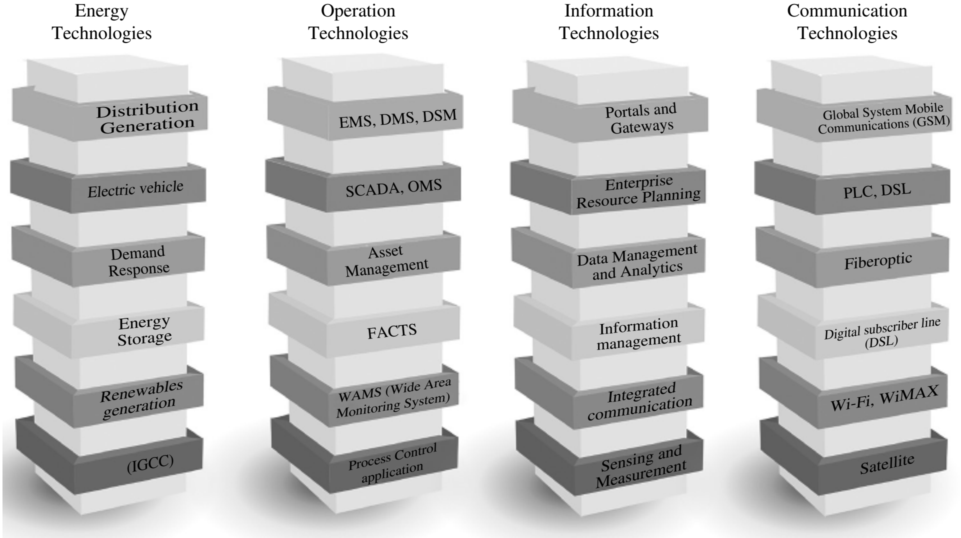

Figure 1.19 Technologies for the evolution of the SG.

portals/gateways, information management, sensing and measurements, asset management, data collection, storing, mining, and analytics. Communication technologies, which include Wireline and Wireless technologies. The Wireline technologies include PLC, fiberoptic, Digital subscriber line (DSL). Wireless technologies include Wi-Fi, Worldwide interoperability for microwave access (WiMAX), Global System for Mobile Communications (GSM), and Satellite. The technology in SGs can be divided into different areas, each consisting of sets of assets, starting from generation through transmission, distribution, and different consumers [72, 73].

1.10 Actions for Shifting toward Smart Grid Paradigm

The electric grid's modernization should begin with a careful assessment of existing technologies within the power grid. Proper utilization of the existing power plants, transmission, and distribution lines and other facilities are the key factor in accomplishing grid modernization within the available financial and technical resources. The country should determine its current level of technology deployment followed up with a focused financial study and analysis of missing grid modernization aspects and associate them with timeline and cost. There are specific analyses that should be conducted for shifting to the SG paradigm. Each utility should conduct its own different analyses and implement specific strategies within a defined timeline. Examples of required analyses are [74, 75]:

Gap analysis: refers to identifying the incomplete actions between current status and future targets to achieve the desired outcomes. Also, it identifies the gaps in a particular grid's technology evolution and developed pillars. This will be used in the development of any shortcomings, as well as the implementation plans. The next step is to assess the current status, concerns, degree of technology deployment, and success rate.

The simple form of gap analysis is comparing the current situation to the objective statement for each focus technology and pillar. An example of the gap analysis on increased reliability and efficiency of electricity transmission and distribution system is shown in Figure 1.20.

Cost–benefit analysis: refers to the analysis that should be conducted to identify the associated cost of the actions in the various pillars that are necessary to mitigate the gaps which are identified in the gap analysis. This should be done to measure the physical performance of the application of the SG in a way that is quantifiable and with high certainty and accuracy. The cost-effectiveness analysis takes a step further and provides scientifically based measurements and protocols to identify the physical impacts and monetary costs that come with the SG projects. The payback time for all sectors would then be identified which will help in promoting and adopting the SG paradigm at a very wide scale and get support from policymakers and market players.

Risk analysis: refers to the analysis conducted in order to identify the risks associated with taking actions in the various pillars. The risk assessment has an important role in the adopted SG road map in order to timely mitigate the associated risks.

Barrier analysis: refers to the conducted analysis to identify any potential barriers that must be overcome in adopting and achieving the SG era. These may relate to policies, regulations, technology, human resources, finances, etc.

1.10.1 Stages for Grid Modernization

The process of grid modernization can be divided into four main stages as shown in Figure 1.21. The requirements, benefits, and risks associated with each stage are summarized below. Also, individual countries and grids operators should have updated policies and regulations supporting the transformation to a SG.

Stage 0: Includes manual control and local automation with little local and remote automation.

Stage 1: Includes the substations automation and remote control to be built on stage 0 by adding intelligent electrical devices (IED), remote terminal units (RTU), streaming

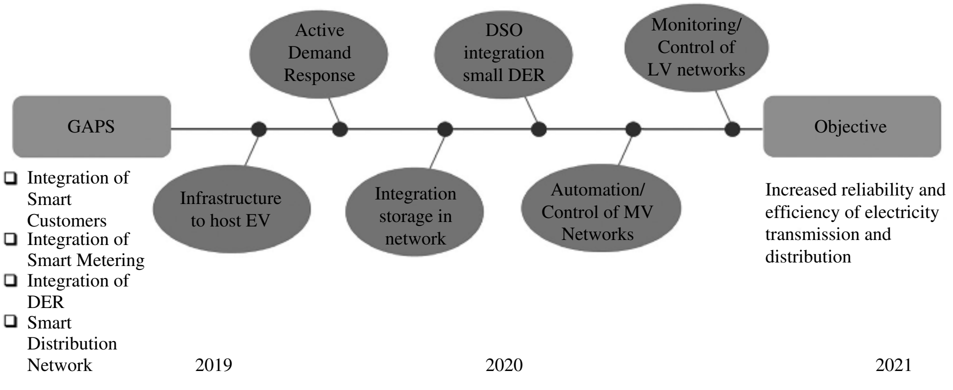

Figure 1.20 Fishbone diagram showing gaps.

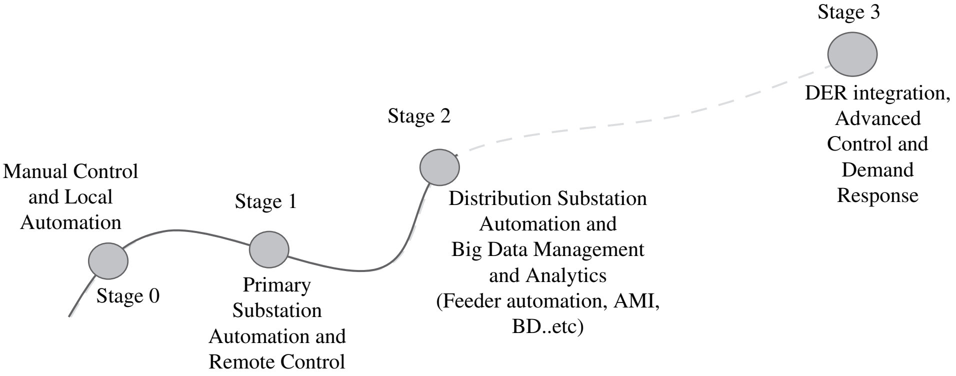

Figure 1.21 The main stages for achieving grid modernization.

sensors, and data communication facilities to achieve local and remote monitoring and control capabilities at HV/MV/LV substations.

Stage 2: Includes feeder automation and remote control built on Stage 1 by extending remote monitoring and advanced control to the outgoing feeders. This stage includes information from communicating meters to large industrial customers for improved control, management, and decision making.

Stage 3: Includes large-scale penetrations and integration for DER, control, and management with big data management analytics and distributed data centers, DR, and self-healing application. Also, adding ES, static VAR sources, and developed communication and control facilities to successfully implement high penetrations of DERs on the distribution feeders. This stage of grid modernization also entails the use of AMI to achieve on-demand reading of consumer meters along with DR capabilities. Also, adding the intelligent energy management system (IEMS) and home energy management system (HEMS) will help with improved control, management, and decision-making.

SG implementation requires special support and mechanisms including economic incentives, technology-specific actions, new policies, and feed-in tariffs. Without these particular requirements, the grid will not fully satisfy the national energy sector goals and future generations’ needs.

1.10.2 When a Grid Becomes Smart Grid

Seven principal characteristics are considered a must for any network to be declared as a “Smart Grid”:

1) Be self-healing from power disturbance events (Self-Healing).
2) Enable active participation by consumers in DR (Demand Response).
3) Operate resiliently against physical and cyber-attacks (Resiliency and Immunity).
4) Provide power quality for twenty-first century needs (21st Power Quality).
5) Accommodate any level and type of renewable generation and storage options.
6) Enable new technologies, products, services, and markets (Modern Services).
7) Optimize assets and operating efficiently (Optimal Asset Management).

1.11 Highlights on Smart Grid Benefits

Smart grid plays a critical role to enable the overall electric power sector objectives. The role of SG within the energy sector policies and regulations is shown in Figure 1.22. The general goals of SG are to ensure delivery of electric energy in an efficient, sustainable, resilient, and environmentally friendly manner. This allows for ambitious power sector targets that trigger new investment needs and call for new ways to control, manage and operate network infrastructures.

SG is therefore a conceptual goal whose achievement will require continuous grid modernization with the use of conventional and advanced technologies and operations. Through its pillars, SG provides great benefits to different parties connected to it. Utilities will gain reduced maintenance cost and lower distribution cost, while grid operators will ensure better monitoring and control capabilities which lead to greater efficiency and resiliency. Finally, consumers will gain better supply quality and continuity and will have control over their profile of consumed power and reduced electricity consumption. SG adaptation will benefit the nation and serve the environment by reducing electrical energy consumption, achieving continuous electricity supply, and ensuring clean and sustainable energy. The SG vision presents a power system that is more intelligent, more decentralized, and more controllable than today's grid. Integrating numerous intelligent SG technologies and operations in power generation, transmission and distribution are considered as the required trend for the energy paradigm shift.

The benefits that could be obtained from adopting the SG are divided into two types, direct benefits, and indirect benefits. Direct benefits include the following:

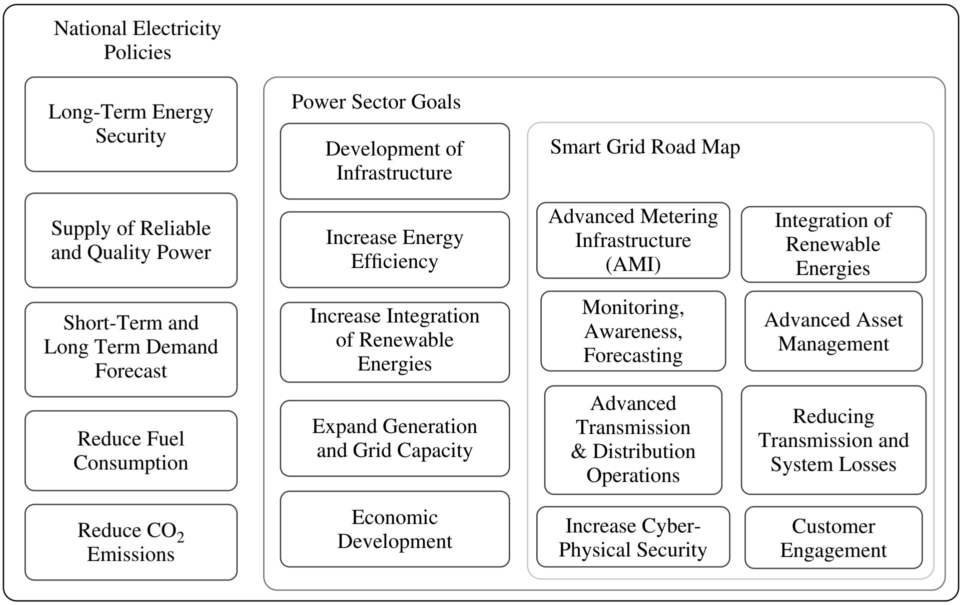

Figure 1.22 SG role in the electricity power sector.

- Enabling active participation of consumers, which transforms the centralized grid control to less centralized and more consumer interactive based.
- Improving energy system resiliency, flexibility, and load management.
- Increasing operating efficiency.
- Reducing transmission and distribution losses.
- Anticipating and responding to system disturbances (achieving self-healing and resilient system).
- Providing power quality for the digital economy.
- Allowing for a high level of renewable energy penetration.
- Accommodating the needs for a high level of EV integration.

Indirect benefits of the SG include the reduction of the overall expenses by reducing both long-term capital expense and operating expense. As demand increases, utilities must provide the required power to meet the peak loads which results in extremely high-cost infrastructure. Smart management of energy supply and demand will help reduce the need to build more power plants in addition avoiding oversize of transmission and distribution infrastructures which, in turn, decreases the long-term capital cost. In addition, SG adaptation enables the utility to reduce power outages, decrease the risk of premature failure and, in turn, increase resiliency of the overall grid. Furthermore, new economic growth and job creation are important indirect benefits of the SG.

1.12 Smart Grid Challenges

The power system is migrating from the conventional grid to the SG which faces many obstacles and challenges. With all-new energy resources, smart devices, and entities, the complexity of the system will significantly increase. Optimal design, operation and handling of such systems will become more challenging, even with the availability of new technologies and tools. Chapter 18 identifies the most important challenges facing the development of the SG. Here we briefly touch upon specific points as the main challenges facing the transformation to the SG energy paradigm.

1.12.1 Accessibility and Acceptability

Customers' acceptability, privacy, costs, cybersecurity, and regulatory considerations possess a substantial influence on the advancement of SGs. Undeniably, customers play a vital part in SG expansion: they are needed to transform their part as customers from passive to active, having full knowledge of their consumption, and capable of managing it depending on the availability of energy which is considered a challenge [76]. The SG technology should be accessed, accepted, and adopted by various grid operators and end-users. Success of this transformation depends on all levels of acceptance, without exception.

1.12.2 Accountability

Accountability is essential to enhance the security of the SG including privacy, integrity, and confidentiality. Accountability refers to a system that is recordable and traceable, consequently, including various parties responsible for those communication principles for its actions. Accountability logic is considered as an essential process to examine the accountability of a secure system [77]. All grid players hold responsibility for its success and utilization, but also include various levels of accountability. This should be identified and made clear to all grid players.

1.12.3 Controllability

SG technologies contain a large number of different controllable elements, systems, and subsystems which require coordination and proper management. As an example, DERs are connected to the grid directly or through a power electronic interface. The voltage source inverter (VSI) is connected to the grid as an interface to support the suitable modification of the grid voltage and frequency [61]. The entire grid is becoming more power electronics dominated with very low inertia. Controllability of such a system becomes a major challenge for stable and efficient operators.

1.12.4 Interoperability

The IEEE definition for interoperability is "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" [78]. The SG is an interoperable system that should be capable of exchanging meaningful, actionable information, addressing safe, secure, efficient, and reliable operations of power systems. The systems will distribute a pre-defined purpose of the exchanged information, and this information can expect suitable types of responses. The reliability, fidelity, and security of information exchanges among SG subsystems and components should achieve required performance levels [79]. The GWAC (Grid Wise Architecture Council) [80] has looked at, interoperability between components of the same system, or between different systems and suggests several implications to be derived;

1) The infrastructure should permit exchange of data and its transfer from senders to receivers; thus, network connectivity should be assured.
2) The implementations of the participating solutions should be able to make sense of the data given. Therefore, common symbols, protocols, and implementation-specific interpretations thereof are required.

In the context of the SG, interoperability includes seamless, end-to-end connectivity of hardware and software from end-use devices to the power source, improving the coordination of energy flows with real-time information and analysis. Interoperability is an essential part of the success of SGs. According to the National Institute of Standards and Technology (NIST) [81] "Once appropriate levels of interoperability are achieved, policymakers, investors, engineers, and other stakeholders can turn their attention to solving a broad set of challenges: improving the efficiency of power delivery, transitioning to cleaner energy sources, and enabling new markets that surround electricity delivery." The NIST-coordinated interoperability effort is organized to include a wide set of stakeholders among the industry, and it is examining the purpose of standards across a wide range of SG interoperability areas [79].

1.12.5 Interchangeability

Interchangeability defines the process of two or more components interchanged by joint replacement without affecting system performance [82]. Interchangeability needs devices to aid in the present functional behavior on their communication interfaces or permit alterations in functionality to be reinforced by the corresponding communication protocol [83]. Thus, interchangeability deals with additional requirements with regard to the functional behavior of devices at their communication interfaces.

1.12.6 Maintainability

It is essential to ensure the grid's ability to maintain reliable operation and undergo timely modifications and repairs to ensure high-quality power regardless of external factors variations [84]. The SG sub-systems and components should be able to perform their functions for the pre-defined period of time. Maintainability is an essential part of SG reliability.

1.12.7 Optimality

SG is characterized with the variations in power sources that are produced from conventional and various renewable sources. Also, the load capability for peak demand decreases will the increase of power network complexity. This requires highly distributed and optimal schemes and elements that ensure the grid's reliability and economic operation. Economic, size, and technical optimality should be ensured at the generation and demand sides [85]. Optimal placement and sizing of the distributed generations, charging stations, system modularizing, measurement systems, etc. are essential for creating SG energy paradigm and its scalability.

1.12.8 Security

It is essential to create a secure SG at various levels, control, communication, and physical. The SG should have measures to protect its massive amount of data and to secure consumers' data privacy. Security needs a system-wide solution for the various anomalies that could hinder physical and cyber levels of the grid [86]. The SG should be resilient against various coordinated and non-coordinated attacks.

1.12.9 Upgradability

Upgradability is related to smart-grid equipment adaptation criteria and substation equipment service life. Designers go through complex procedures related to substation equipment requirements. The equipment should implement long life cycles that consider reliability, upgradability, and interchangeability [87]. SG areas consist mostly of a long-life lasting equipment as opposed to typical IT systems. Test and replacement of these devices usually requires hard work and should consider the high cost due to their large-scale implementation and high importance usage. Furthermore, utilizing cryptographic strategies that surpass current security conditions is considered delaying the probable requirement of further upgrades [88].

1.13 Smart Grid Cost

Grid operators are required to entirely assess the estimated costs, benefits, and potential risks of implementing the SG applications in order to define a reasonable investment plan for grid modernization. The investment plan should include a list of practical projects and applications to be implemented, their cost, and realization timeframes. Such a plan should mainly rely on the available technical and financial resources in order to achieve the maximum guaranteed return on investment (ROI) with minimum risk. SG will benefit both grid operators and their customers through new technologies development and new applications. The investment on SG is influenced by the targeted power grid reliability, security, efficiency, and resilience. However, disturbances, faults, blackouts, equipment damages, outages, customer interruption, loss of data, and losses of resources over time can result in investment delays in this sector which will also negatively affect a nation's economic growth. SG achieves a significant level of ROI rate and may deliver the highest and long-term returns to the electric operators and customers, as shown in Figure 1.23 [89].

The SG implementation is a continuous process that includes a set of technologies and additional features that can be added gradually to reach the most effective supply and demand balance in addition to reliable and clean electricity. A market study by Electric Power Research Institute (EPRI), indicates that the investment level at utility-scale in the power grid is between \$17 and \$24 billion per year over the next 20 years [36]. Figure 1.24 and Table 1.2 list the major components of the SG total cost [90].

Low refers to an EPRI low estimate of \$ total SG costs; HIGH refers to EPRI high estimate of \$ total SG costs. The wide variety in these estimates of the investment that is needed to realize the grid modernization reflects the uncertainty of the current industry modernization stage [91]. Again, these costs are modest when compared with the yield fruitful benefits from SG implementation.

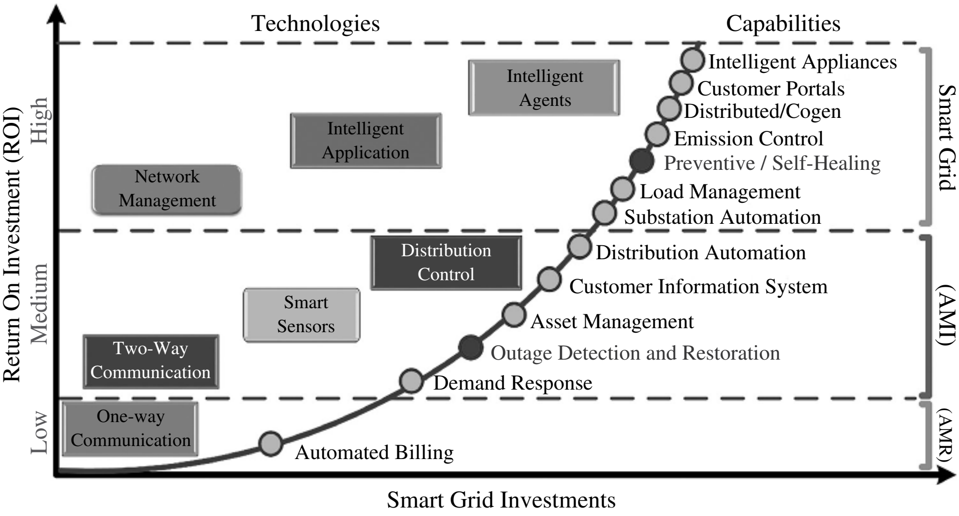

Figure 1.23 SG investment. Adapted from [89].

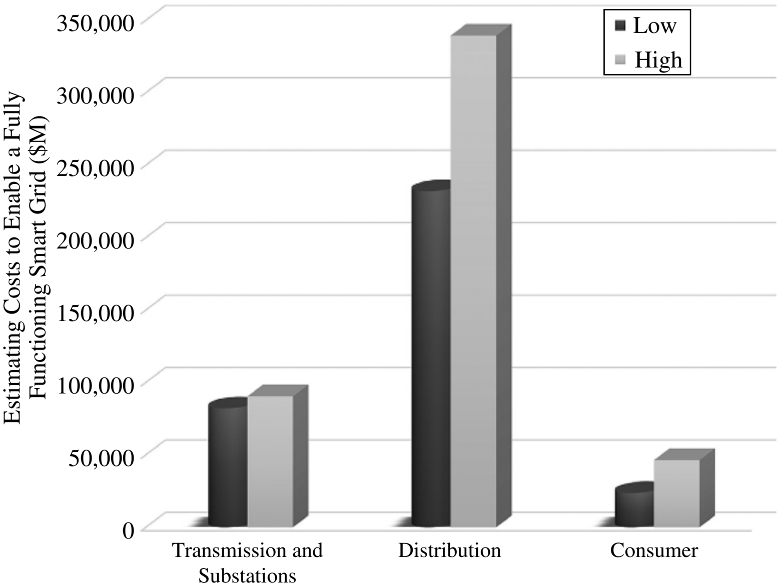

Figure 1.24 SG costs Ref [90]. Reproduced with permission from EPRI (Electric Power Research Institute).

Table 1.2 Investment costs of a fully functioning SG ($ M) [90]. Reproduced with permission from EPRI (Electric Power Research Institute)

	Low	High
Transmission and substations	82 046	90 413
Distribution system	231 960	339 409
Consumer Engagement	23 672	46 368
Total	337 678	476 190

1.14 Organization of the Book

This book is comprised of 18 different chapters dealing with different SG related issues. Chapter 1 provides an elementary discussion on the fundamentals of the SG; its concept and definition, characteristics, and challenges. The chapter provides also the benefits of moving toward SG

Chapter 2 presents an overview of different renewable energy resources; their current status and also future opportunities, as well as the challenges of integrating them into the electricity grid and the operation in distributed mode as part of the SG.

Chapter 3 describes the power electronics technology for distributed generation integrated into the SG. An introduction to typical distributed generation systems with the power electronics is presented. Power electronics converters in grid-connected AC systems and their control technologies are introduced. Then power electronics enabled autonomous AC power systems are discussed with the coordination and power management schemes. This chapter presents the basic control of power converters. Then autonomous DC power systems are illustrated. Finally, conclusions are drawn with future works.

Chapter 4 is dedicated to the impact of the Energy Storage Systems (ESS) on the future grid and presents how these technologies have the potential to shift energy utilization away from peak demand periods and increased costs, enhance the reliability and resilience of the power grid and considering the large integration of intermittent renewable resources. A detailed presentation of different ES technologies and the development of the current technologies and future status are introduced. One of the topics presented in this chapter is the use of ESS in SG applications, technical and financial benefits for the deployment of these technologies in the future SG.

A comprehensive review of microgrid including their characteristics, challenges, design, control, and operation either in grid-connected or islanded modes are introduced in Chapter 5. This chapter presents a detailed study of communications issues between microgrids.

Chapter 6 is devoted to one of the most important applications of the SG which is smart transportation. This chapter presents an overview of electric vehicles; their current status and also future opportunities, in addition to the challenges of integrating them into the SG. The impact of EVs on SG operation and Modeling EV mobility in energy service networks are also depicted in this chapter.

Chapter 7 describes the zero energy buildings (ZEBs) definition, design, modeling, control, and optimization. Furthermore, generalizing its concept into the SG community. This chapter discusses the benefits and barriers of the current state and the future trends of (ZEBs) as a step to reduce the energy consumption in the building sector.

The goal of Chapter 8 is to shed light on the SG features multi-way communication among energy production, transmission, distribution, and usage facilities. The reliable, efficient, and intelligent management of complex power systems necessitates employment of high-speed, reliable, and secure data information and communication technology into the SG to manage and control power production and usage is described in detail in Chapter 8.

Chapter 9 presents two main parts when studying the SG, SG infrastructure, and SG applications. SG infrastructure entails three main layers: power system, information, and communication layers and these are discussed in this chapter. Although the cyber system made the grid more energy-efficient, it has introduced threats of cyber-attack such as operational failures, loss of synchronization, damage of power components, and loss of system stability. Because of this, information security is a major element for information and communication infrastructure in the SG to improve the grid efficiency and reliability as well as considering privacy which is described in detail in Chapter 9.

Chapter 10 elaborates on the evolution and benefits of moving the energy grid to a SG. The main obstacle that faces this transfer is the difficult management of an unprecedented deluge of data. Unfortunately, utilities still do not make full use of this huge volume of data. To achieve high performance in SGs, several techniques and approaches must be used to manage all the data in order to generate viable values from this big data which can improve the utility's chances of reaping optimal long-term returns from its SG investment as presented in detail in Chapter 10.

The SG principle transfers the future generation electricity network to a smarter and intelligent grid by enabling bi-directional information and active participation from all parties connected to it. Coordination and communication between both sides, generation, and consumption is an important topic for research which is discussed in detail in Chapter 11. Driven by concerns regarding electric sustainability, energy security, and economic growth, it is essential to have a coordination mechanism based on heuristic rules to manage energy demand and enhance the survivability of the system when failures occur or at peak periods achieved by the principle of DMSs clearly defined in Chapter 11.

Chapter 12 presents the business model concept, its main components, and how they can be used to analyze the impact of SG technology to create, deliver, and capture value for the utility business. Then, the value chain for both the traditional and smart energy industry are discussed. After that, different electricity markets have been described. This is followed by a review of previously proposed SG business models with its future levers. Finally, the chapter highlights the potential of applying blockchain technology in the electricity market.

Chapter 13 sheds light on fully motivating the residential space in the SG which is still an unresolved problem. This chapter mentions the importance of offering power systems researchers and decision-makers suitable knowledge about the fundamental drivers of consumer acceptance of the SG and the methods to be followed for their engagement in order to implement SG technology and make it feasible earlier.

Cloud computing is considered the next-generation computing paradigm because of its advantages in network access, massive computation services, storage capacities, and various application opportunities including the SG. Chapter 14 defines the fundamental relationship between SG and cloud computing services. The architectural principles, characteristics of cloud-computing services as well as the advantages and disadvantages of those characteristics for the SG are discussed. Furthermore, opportunities and challenges of using cloud computing in SG, and the major categories of data security challenges of cloud computing are also touched upon.

Chapter 15 discusses the latest taxonomy of Artificial Intelligence (AI) applications in SGs is discussed, including load and renewable energy forecasting, power optimization, electricity price forecasting, fault diagnosis, and cyber and physical layers security.

Chapter 16 discusses the current state of simulation-based approaches including multi-domain simulation, co-simulation, and real-time simulation, and hardware-in-the-loop for the SG. Furthermore, some SG planning and analysis software are summarized with their advantages and disadvantages.

Many issues require to be handled before the SG becomes a major player of the main utility grid. One of the important issues with the SG is standards. These standards include the generation sources, the smart home appliances, and the EMS that need to communicate with each component of the SG to activate the energy trade between customers and producers. Chapter 17 presents an overview of SG standards; new standardization studies, SG policies of some countries, and some important standards for the SG.

Chapter 18 depicts the concepts of distributed generation, micro-grid, smart-grid, and distributed operation pose more complexity and challenges to the modern power systems. This chapter presents the challenges and barriers that modern smart-grids face from different perspectives.

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