Review

Survey of Smart Grid Concepts and Technological Demonstrations Worldwide Emphasizing on the Oman Perspective

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Abstract: The Smart Grid (SG) is considered as an imminent future power network because of its fault identification and self-healing capabilities. Energy sustainability, renewable energy integration and an efficient control system are the key factors to be considered in developing SG system. Among various SG concepts, the term virtual power plant (VPP) integrates renewable energy to the grid and provides higher operational flexibility, but it requires extra capital costs for control system and software. The operational activities of a smart grid largely depend on the active customer demands. This paper defines and discusses various SG system concepts such as virtual power plant, and active demand in consumer networks, and also presents drivers and roadmaps for development of smart grids worldwide. Furthermore, this work provides an insight into present research and development on smart grids around the world, and sheds light on developing and establishing SG for the Sultanate of Oman.

Keywords: smart grid; energy sustainability; drivers and roadmaps; efficient power system; smart grid in Oman

1. Introduction

Smart Grid (SG) development has constantly been being put into focus due to the increasing complexity of electrical power systems, growing demand of electricity, and the requirement of highly reliable, efficient and secured power supply. SG is considered the next generation power system that uses bi-directional flows of electricity and information. The ability of data integration, system monitoring, reliable data communication, secured data analysis, and local and supervisory controls of the smart grid can satisfy the supplier-consumer demand requirements such as reduction in the energy consumption, energy cost, and improve the system efficiency. There has been a prolific increase in the energy demand worldwide, and electricity is being considered to constitute up to 40% of the total energy generation to meet the growing energy consumption demand in the world by 2040. The monitoring capability of the SG facilitates observability of the entire power network from the energy provider to the energy consumer as well as protects the network from any kind of vulnerability. A consumer is capable of monitoring and controlling the amount of energy used.

The total primary energy utilization is expected to increase by 48% globally and the world net electricity generation is likely to increase by 69% compared to 2012 energy demand [1]. Furthermore, the use of non-conventional fuels is projected to increase at a fast rate in comparison to the consumption of fossil fuels. However, fossil fuels will still have a large share, around 78 percent, of energy use in 2040 [1]. It was stated in [2] that about 25% of the global greenhouse gas (GHG) emission occurs due to the power system network. The unavoidable losses in the current grid system with its centralized nature of generation and long ranged transmission complexity, and its inability to integrate distributed renewable resources account for the GHG emission index rising high. An aggressive approach to smart grid implementation, i.e., more extensive application of a broader range of technologies can help reducing the emission by 16% while a moderate version can decrease the emission by 5% [3]. Moreover, in the USA, electrical power outages severely affects the commercial and industrial activities, the combined cost of which is estimated to be $79 billion annually in 2002 [4]. The cost is about 32% of the total electric power market revenue of $249 billion [5]. Chadwick et al. showed the effectiveness of SG implementation for preventing large scale cascading blackout by conducting a case study on 2003's cascading blackout of the USA [6]. Monitoring the load characteristic and energy consumption at consumer end is a troublesome job for conventional grid, SG can with its bidirectional communication feature between the utility and customers cut out such concerns. Furthermore, it has the ability to communicate to smart devices of consumers, which can help to automate adjustments according to on-peak or off-peak hours. Therefore, smart grid possesses the great potentiality in providing reliable power supply as well reducing GHG emission. The birth of the SG cannot be traced back to a certain point [7]. Smart meters appeared in 1970s [8], with Advanced Metering Infrastructure (AMI) being the current industry standard tool and foundation for smart grid scenarios [9]. Reference [10] reported some of the past work on the smart grids for the period of 1997 to 2008.

Meeting the reliability in the current grid is becoming more challenging owing to the following factors of grid congestion, larger energy transfers over longer distances, ageing infrastructure and insufficient investment on maintenance, increasing electrical energy consumption along with peak power demand, and increased utilization of the distributed resources. The shortage in electrical power has direct impact on economies, societies and in countries' development. The conventional power network is less efficient due to the insufficient investment in technology and infrastructure upgradation, and the continued use of the traditional ways of operation and maintenance.

Furthermore, the detrimental environmental impacts of conventional power network are much severe due to high GHG emission from fossil fuels. It is believed that the integration of renewable power and distributed generations will reduce GHG emission by a significant amount. However, these will require monitoring and better control of existing networks, which will need the electric power system infrastructure equipped with Information and Communication Technology (ICT). Thus, the development of an SG may require substantial amount of time in order to incorporate consecutive layers of services into the current electrical networks. Comparison of a conventional grid with the SG is tabulated in Table 1.

Table 1. Conventional and SG comparison [8–13].

Conventional Grid	Smart Grid (SG)
One-directional communication	Bi-directional communication
Electromechanical	Digital
Large capacity central generation	Distributed generation with various capacities
Limited number of sensors	Sensors dominant system
Less scope for self-monitoring	Complete scope for self-monitoring
Less scope for automatic restoration	Complete scope for Automatic restoration or Self-healing
Less adaptable in case of failures and blackouts	Adaptive and allows islanding
Restricted control	Ubiquitous control
Limited choices for consumers	Wide variety of choices for consumers

Table 1. *Cont.*

Conventional Grid	Smart Grid (SG)
Hierarchical structure	Network structure
Less feasible for feedback network	The inherent and real-time control
Wide area interrupts at the time of outage	Filtering and islanding disconnection
Network restriction control	Network comprehensive control
Customers and subscriptions provided with limited services	Customers and subscriptions provided with various services
Radial Network	Dispersed Network
Slower in response during emergencies	Quicker in response during emergencies
Small volumes of data available	Large quantities of data available

The SG may be regarded as a modern electric network infrastructure, which consists of automated control, distributed resources, storage systems, large number of power converters, reliable data communication system, sensors and advanced meter technologies, cyber security devices, end user devices, and sophisticated energy management system based on energy availability and demand optimization [14–16]. The global perspective on the concept of Smart Grid technology is quite similar. However, the major focus may differ depending upon the individual needs of the country. For instance, in the USA, the focus is mainly on users and service integration, whereas in China, they focus mostly on the transmission of electric power [2]. The SG vision is about having a system that will reduce peak demand, reduce power losses, having efficient and smart devices in order to reduce the energy utilization, identify and prevent power outages by segregating disturbances that causes blackouts in the network, and these can be achieved with the help of already existing technologies [2].

The purpose of this paper is to present a synopsis of the SG with its functionalities, capabilities and characteristics. It also elucidates on the foundation of the modern electric power system such as SG that utilizes smart technologies. Furthermore, the paper also sheds light on the development of SG in Oman, discusses the opportunities and necessity for a Smart Grid, and analyzes the hurdles that might be associated with transforming the conventional grid of Oman into a smarter one. The rest of the paper is organized as follows: Section 2 discusses on the definition and motivation behind the concept of SG. Section 3 discusses the features and advantages associated with the SG. Section 4 explains the fundamental technological components which lay out the foundation for SG. Section 5 illustrates many different concepts which have intricate correlation with the SG. Section 6 demonstrates different SG policies and roadmaps undertaken by different countries. Section 7 states the present scenario and ongoing development works done in the Sultanate of Oman. Section 8 lays out the conclusion of the whole study and References Section holds the references used throughout the whole paper.

2. Definition and Motivation behind Building Smart Grid

There are yet no unanimous agreement on the standard definition of a Smart Grid, for it is a concept which is still under development. The definition of smart grid varies from experts to experts creating a wide technical outlook of the whole system, considering all the definitions that are available. For example, The European Union has defined a smart grid as "an electricity network that can cost efficiently integrate the behavior and actions of all users connected to it—generators, consumers and those that do both—in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety" [17]. Electric Power Research Institute (EPRI) website offers the following definition "A SG is one that incorporates information and communications technology into every aspect of electricity generation, delivery and consumption in order to minimize environmental impact, enhance markets, improve reliability and service, and reduce costs and improve efficiency" [18]. The International Electro-Technical Commission (IEC) definition states that "The SG is integrating the electrical and information technologies in between any point of generation and any point of consumption" [19]. International Energy Agency (IEA) defines "A SG is an electricity network that uses digital and other advanced technologies to monitor and manage the

transport of electricity from all generation sources to meet the varying electricity demands of end-users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience and stability" [20]. Australian Government New Direction Report defines SG as "the application of information and communications technology to improve the efficiency and effectiveness of the generation, transmission and distribution, and usage of power" [21]. In Australia, the smart grid system primarily includes distribution and retail value chain elements, although transmission and generation (both distributed and centralized) are also affected. In general, the primary smart grid technologies considered as part of this study reside on the distribution network, within/around the home, with the information being processed in a data center [21]. An overview of the smart grid concept is shown in Figure 1 [22].
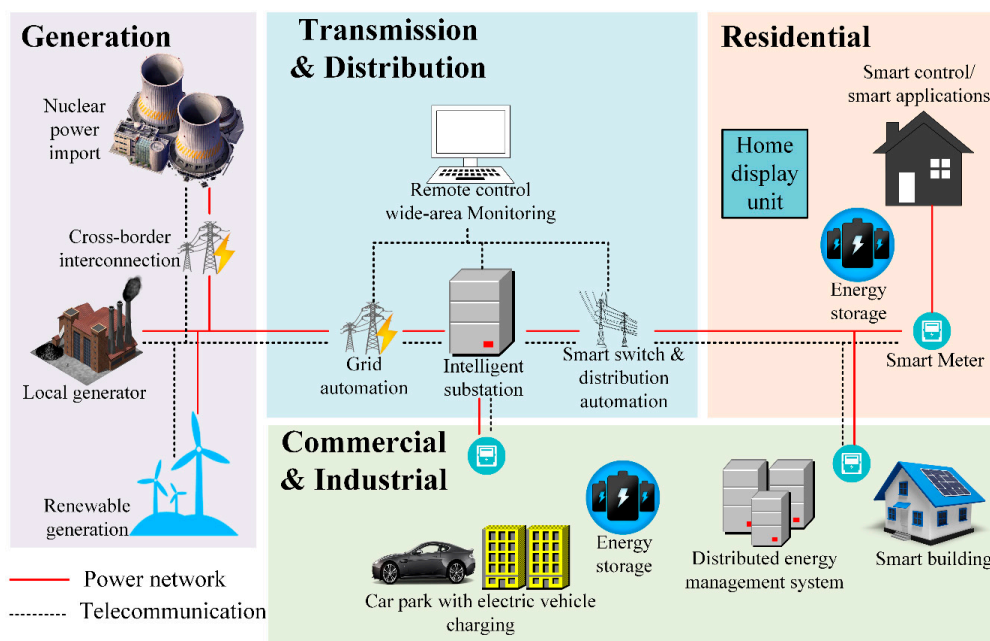

Figure 1. The overall smart grid concept. It is capable of providing electrical power from multiple and widely distributed sources, such as from wind turbines, solar power systems, and plug-in hybrid electric vehicles. It uses digital automation technology for monitoring, control, and analysis through the supply chain [22].

The electric power industry stakeholders realize the need to address diverse challenges relevant to the present power network. Such challenges are the gap between supply and demand; low system efficacy; rising cost; and global warming, to name a few. Some of the key drivers that motivates the researchers, developers, and policy makers to pay attention towards the smart grid development are:

- Increasing electricity demand: According to the International Energy Agency, the world energy consumption will be increased by 48% compared to the 2012 energy demand [1]. Rising electricity demand requires more reserve margins for unexpected outages. Demand-side management can be established to curtail the system peak demand and to increase the network efficacy.
- Ageing of the current electrical infrastructure: Energy losses occur during power transmission and distribution (T&D) are increasing due to the ageing of the present electrical infrastructure. In most advanced power system, the total losses in T&D is around 8% [2]. In India, the losses reach about 26%, which is considered the highest in the world [23].
- Increasing energy charge and electricity reliability concerns: The supply failures have caused huge economic and social losses, which stimulate efforts to enhance the system reliability. The phasor measurement units in SG provide real time monitoring of the power network [24].

- Greenhouse gas emission: Numerous countries have set the goal for gas emission reduction and power generation from renewable energy resources. SG implementation allows the integration of low or zero emission distributed generations near to the load center.

- Deployment of renewable power generations and electric vehicles: The energy share of renewable sources in global electricity production was approximately 24.5% by the end of 2016 [25]. Moreover, electric power-based transportation is gradually increasing, where the energy consumption is expected to be about 10% of the total electric power by 2050 [26]. Thus, the existing grid network may face significant challenges in order to provide reliable and stable power supply. Therefore, the operation of the EV charging and the intermittent power generation units need to be tackled in order to avoid power failures. This problem can be effectively solved by implementing SG.

- Economic development and business opportunities: SG implementation can result a significant savings by reducing the losses in the power network. This savings can be invested for other potential business in the country. Hence, the countries can provide competitive advantage for their economy [18]. Manufacturing of tools, equipment and instrumentations that supposed to be used in smart grid are good examples of business opportunities. Moreover, utility unbundling will increase energy trading.

- Increasing distance between load centers and generation sites as well as the presence of large number of distributed power generations [27].

- Customers can receive better benefits if the information such as pricing, and control on their energy usage are easily available to them. The current grid is not able to provide such information to its customers. However, smart grid can offer consumers to monitor the energy price in real time and provides control to reduce their energy consumption bills [28]. Smart meters enable meter readings remotely and instantaneously leading to cost effective way and less time consuming [14].

In a word, SG system might be a key factor for improving controllability, integrating renewable energy into the grid system, and providing a solution to meet increasing electricity demand.

3. Features and Advantages of Smart Grid

A smart grid consists of many different state-of-the art information and communication technology (ICT) and sensory devices and offers a wide range of advantages to both the utilities and the customers, which are, for example [29–35], Lowering the utility bills; Reduction of the peak demand; Economic and job growth; Integration of more renewable energy resources; Self-governing control, which increases the system reliability; Enhancing capacity and efficiency; Enhanced resilience against malicious attacks; Integration of different types of energy storages including plug-in electric vehicles; The communication between the service provider and customers is two-way; Improved market efficiency; Better power quality and reliability; Better utilization of facilities and deferring building of new power stations; Empower predictive maintenance and self-curing; Accommodate of decentralized power generations; Automated maintenance and operation; Reduce GHG emission; Several varieties for consumer; Providing opportunities for new services, products and markets. The features of the SG which individuates itself from conventional grids, are the sophisticated devices that it uses and the services that it provides in return which are unattainable in conventional grid systems [28]. Some of the prominent features of the SG include:

- AMI: Smart meters rigged with advanced communication protocols are utilized in SG to record energy consumption over an interval of an hour or less. AMI devices lay the foundation for SG. The functionalities of these meters include sending information to the utility for system monitoring and controlling, as well as for preparing financial statements for the customers [36]. The customers can monitor and adjust the energy consumption in real time. In addition, the remote operation capability of these meters allows the energy providers to control the customer loads in order to manage loads and demands. A metering system that includes the aforementioned features is called AMI. The benefits of AMI are shown in Figure 2 [37].

- Smart Monitoring and Measurement: Measuring system parameters using sensors is very essential for monitoring, controlling and operating the system efficiently and reliably. Sensor networks equipped with communication protocols are widely used in measuring, monitoring and controlling the systems. Such systems include electrical, electro-mechanical, communications, and oil and gas, etc. [38]. Specifically, in [39], it was recommended to embed sensor networks into the power grids in order to monitor conditions such as the failure of conductors, hot spots, and acute mechanical circumstances in the power grids. Such networks along with the Internet of things (IOT) can certainly enhance the monitoring and controlling process of the physical and electrical conditions of the modern grid network in real time. Hence, a combination of sensor network and IOT in smart grid application will elevate the capability of the SG in determining the proper control steps that the system operators need to execute.

- Phasor Measurement Unit (PMU): PMU is an advanced measuring instrument that is integrated with a widely available communication technology such as global positioning system (GPS). It has the capability to monitor and measure synchronized system parameters from different locations around the power network based on a common reference time. Such parameters include voltage constraints, low frequency oscillation, thermal constraints, frequency deviation etc. The system operators utilize such devices to collect high frequency sampled measurement data in order to identify the system status so that the system operator can initiate the protective/controlling measures quickly and dynamically [30]. The schematic diagram of the PMU is shown in Figure 3 [40]. This device has been used for wide area monitoring system in many countries around the world. Such countries are China, France, Brazil, South Korea, Mexico, Japan, Norway, and USA [38]. A large-scale integration of PMU devices in smart grid application would increase the reliability and efficiency of the SG system. Including sensors and PMUs application, the assets optimization, and the application of demand response, demand side management are very essential for SG development.
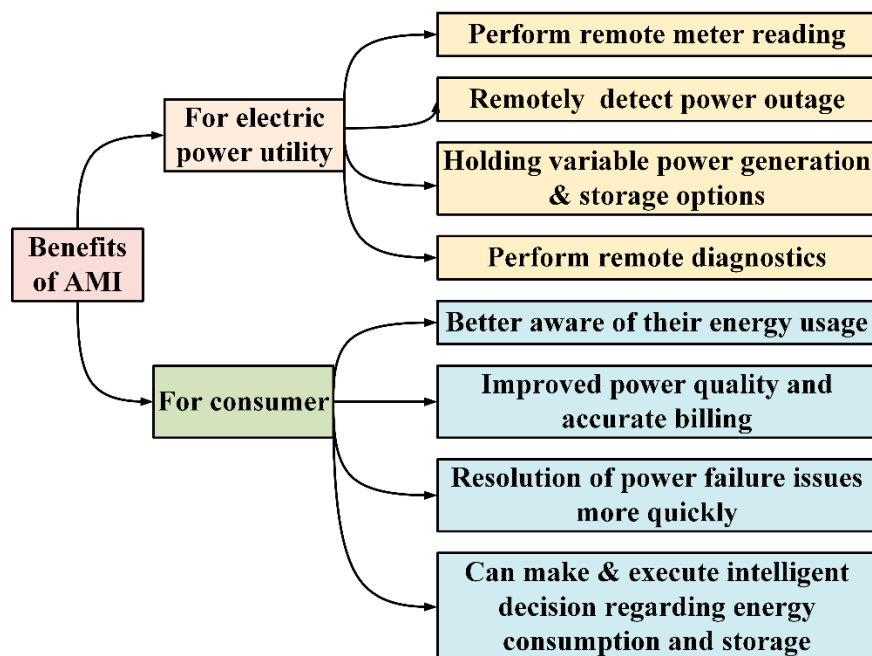

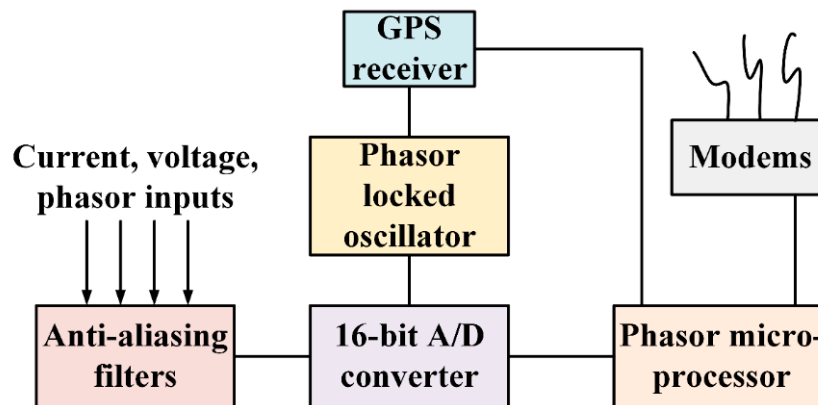**Figure 2.** Advantages and features of AMI [37].

Figure 3. Operational block diagram of Phasor Measurement Unit (PMU). This device is used to measure and monitor synchronized system parameters from different locations within the power network based on a common reference time [40].

A comparison among AMI, smart monitoring system, and PMU is tabulated in Table 2.

Table 2. Comparison among AMI, smart monitoring system, and PMU [41,42].

Topic	AMI	Smart Monitoring and Measurement system	PMU
Tools	Smart meters	Sensor networks and IOT	Phasor Data Concentrator (PDC), Global Positioning System (GPS)
Work	Vulnerability assessment, risk assessment	Standard, risk assessment	Vulnerability assessment
Target Area	Privacy of information, communication system, cyber-physical system	Sensor data	GPS data
Communication Type	Digital	Digital and analog	Digital
Communication Protocol	ANCI C12.18, C12.19, C12.22, IEC 62056, and Open Smart Grid Protocol (OSGP)	IEEE 802.16 (Wimax), IEEE 802.11, IEEE 802.3	IEEE C37.118 (Synchrophasor Measurement)
Network Type	Home Area Network (HAN)	Local Area Network (LAN)	Wide Area Network (WAN)

Among these systems, AMI and PMU are currently being used most commonly in SGs. As these systems produce a big amount of data, these systems are more prone to cyber-attacks, especially PMU. In PMU, attackers may hack into the phasor network and inject corrupted data. It is also possible for the hackers to create abnormal conditions in operations by jamming or spoofing GPS signals of PMU. Leakage of valuable information and smart grid safety vulnerabilities may arise with the incorporation of these systems, so strong cyber-security must be ensured for the implementation of these systems:

- Advanced Distribution Operation: It allows fully automated operation and functionalities of the control devices in the distribution system. Such an advanced system can sharpen the self-healing capabilities in smart grid operation. It performs the following functions [38,39,43,44]:

  (a)   Control voltage and manage power flow in an automated fashion;
  (b)   Monitor the distributed system in real time and respond to the demand automatically;
  (c)   Forecast demand, control, and manage power distribution network in real-time asset management of distribution systems.

The schematic diagram of the advanced distribution automation system is shown in Figure 4 [45]:

- Distributed Generations: Distributed generations generate electricity from various different primary energy sources at various different locations. The application of distributed generations is increasing day-by-day due to its modular form of configurations and its utilization near to the load center. Distribution generations are currently available in various forms. Microgrids are the primary aspects of distributed generation, integrating renewables such as solar, wind, hydro and geothermal energies, mostly replacing the conventional sources of energy. But the generation depends on the weather conditions, location and time profiles, causing intermittency which poses significant challenges in renewable energy generations [46]. Key parameters to address the discrepancies are currently being studied using different prediction technologies. Other aspects of the distributed generations are Grid to Vehicle (G2V) and Vehicle to Grid (V2G). In G2V, Electric Vehicles (EVs) are generally fueled by charging it from an energy reserve system such as a battery storage system which is charged by an external energy source such as PV, utility grid or other energy systems. However, the uncoordinated charging operation of vehicle fleet may introduce a momentary spike as new load into the grid system. One solution to this disadvantageous effect is to optimize the charging profile of EVs in a coordinated manner so that not all vehicles are charged at one time [30]. Reference [47] showed that charging EVs in a coordinated manner could reduce losses in system power and deviations in system voltage by smoothing power during the peak time. In V2G, EVs are capable to deliver electricity to the utility given that the EVs are parked and have a secure connection with the utility grid. The advantage of power supplied by EVs is that it can help in balancing the loads during "peak shaving". In [48], a particle swarm optimization method has been applied to identify the optimal solutions to escalate the benefits of the vehicle owners considering the practical constraints of the system. The block diagram of V2G and G2V is represented in Figure 5 [49].

- GHG Emission Reduction: Smart grid can certainly help in reducing greenhouse gas emission by accommodating a large number of renewable power generations. It is indicated in the IEA report that 50% of the gas emission has to be reduced by 2030 from the energy efficiency point of view. It is also indicated that about one quarter of the gas emission can be reduced by integrating renewable energy sources and bio-fuels, while 10% of the emission could be reduced using nuclear, carbon capture, and storage system [50]. Using wind or solar based distributed generators can be an effective solution in meeting with the profuse demand of electricity as well as reducing the GHG emission. However, integration of renewable power generations to the utility grid becomes more challenging for increasing the level of penetration from renewable power. The main challenges of solar and wind energy are intermittence and fluctuant of the energy, which causes voltage fluctuation; low capacity factors (the typical capacity factor for PV 10%–20% and for wind 20%–40%); lack of correlation with the load profiles; relatively large forecast errors and more complicated; congestion in power transmission due to large scale system installations; congestion in distribution grid due to distributed renewable resources. Introduction of energy storages into the power network can minimize such problems. In addition, application of Demand Response (DR) concept can further reduce such problems. Hence, an integration of distributed generation, distributed energy reserve, and DR can be utilized for SG development to tackle the issues suffered by the power network.

- Bi-directional Communication System: Bi-directional communication system has already been being used in many areas including oil and gas plant monitoring and control. This two-way communication technology has the potential to utilize in monitoring and controlling the SG network centrally.

- Automatic Healing Capability (AHC): Automatic healing capability of a SG is very essential for its reliable and efficient operation. Smart grid with this feature can automatically detect the abnormal scenarios such as over current, over and under frequency, voltage surge, fault current etc. in the network. Such information can be sent to the SG control center to initiate automatic recovery/healing of the system for a particular abnormal scenario.
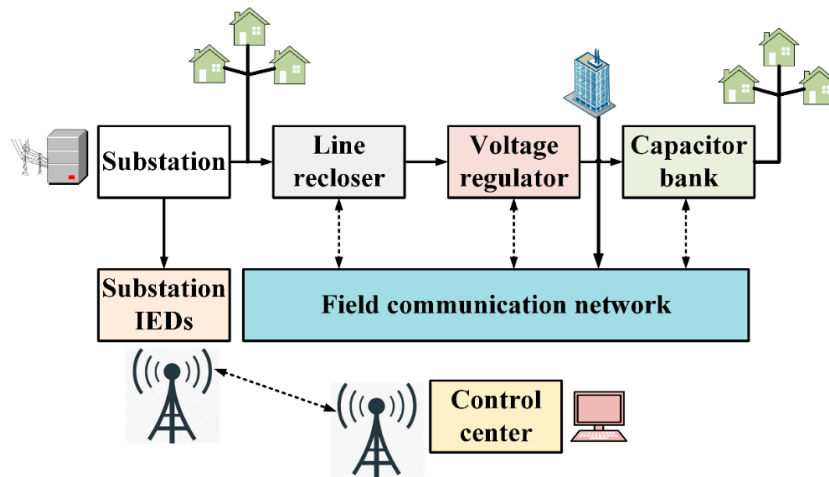
Figure 4. Operational block diagram of an advanced distribution automation system. It can monitor the system in real time and can respond automatically to the demand [45].
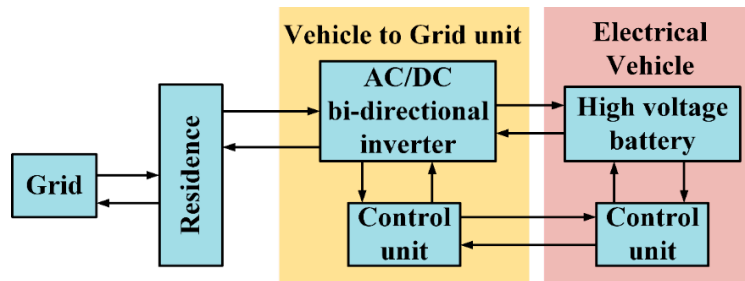

Figure 5. Block diagram of V2G and G2V for SG system. V2G and G2V together are one instance of bi-directional power flow in SG system. V2G can help in balancing the loads during peak-shaving [49].

Bi-directional communication system may increase the operational performance of the SG by providing more controllability, whereas AHC increases the efficiency and power quality (PQ) of the SG. Both of these systems are very important for improving the performance of SG.

4. Technologies for Smart Grid

The technologies that the world currently has at hand are quite enough to build up a fully functional smart Grid. The development in energy storage systems, communication technologies with 5G coming in vogue quite recently, efficient and secured data transfer systems, edge computing, high precision measurement tools like AMI and PMU, Supervisory Control and Data Acquisition (SCADA) systems, and with new technologies under research makes the pathway towards a smarter grid to become smoother. The already available technologies that marked SG into a reality and those that deserve special highlights are mentioned as follows.

4.1. Energy Storage

Energy storage is a key component which contribute to different services such as energy maintenance, energy management, load shifting, frequency regulation, peak shaving and energy arbitrage in SG system. Energy storage systems are the game-changing technology in grid-connected systems, determining factors pertaining to generating, storing and selling back to the grid by customers. Some of the available energy storage means are electrochemical (batteries and fuel cells), electromechanical (flywheels, pump hydro, and compressed air), electrostatic (ultra-capacitors) and electromagnetic type (superconducting magnetic storage) [51,52]. Electrochemical batteries, however, has a growing demand in the market for their downward price and upward performance [53]. Their use in advanced automotive technology, such as plug-in EVs [54] are garnering interest, as the

retired EV batteries can be replenished for further use as second life batteries in energy storage systems (SLBESS) [55]. Energy management through such energy storage units in SG domain will reinforce grid stability, reliability and efficiency. In addition, energy storage can mitigate the intermittency and fluctuation of renewable energy sources such as wind and solar. It also increases the penetration level of solar and wind power in SG system. It has been reported that energy storages have already been using for load-shifting, frequency support and power quality improvement in power system network [51,52,56]. For real-time energy storage arbitrage (storage of energy during cheap price for future use during high price), several optimization algorithms are utilized to determine the arbitrage policy [57]. In load shifting, the energy stores during off-peak is utilized to supply power for the peak demand by the load. The frequency regulation is performed both in transmission and in distribution stages. However, the system power qualities can be improved by smoothing the voltage and frequency fluctuations in the distribution side. The output of renewable energy sources with and without energy storage system is shown in Figure 6.
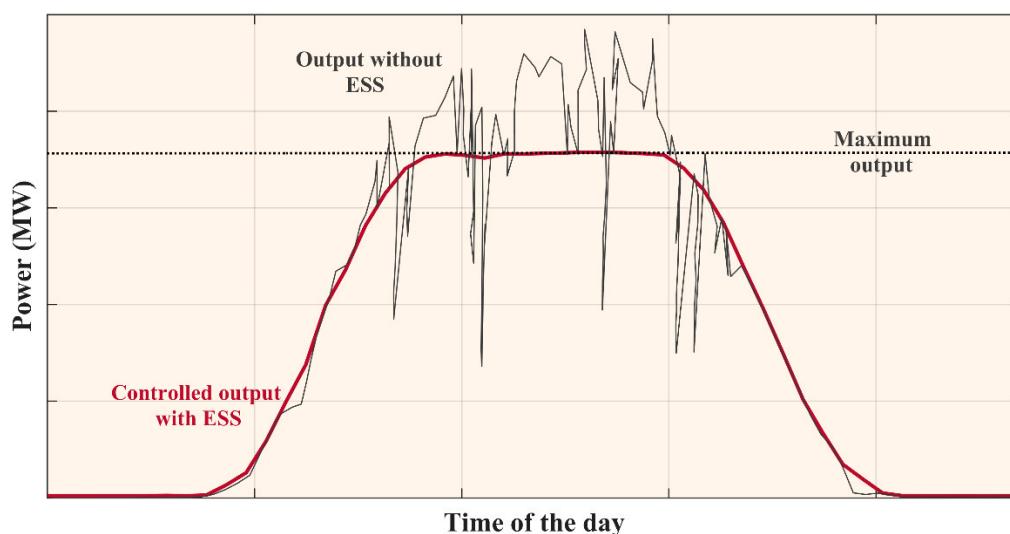

Figure 6. Power output of renewable energy sources with and without energy storage system.

4.2. Telecommunication Systems

Traditionally, SCADA systems have been used for distant monitoring and controlling of the conventional power systems. The backbone of a SCADA system is the communication network. Such network structure generally utilizes wireless radio connection, dial-up lines, Ethernet, and IP protocol to support the communication requirements in a SCADA system. However, such communication mediums may face challenge of data congestion due to high volume of data information in SG systems [58]. Therefore, a communication structure/system that would handle big data flow would be required for future smart grid application. The communication system in a SG is required to provide high-level quality of services such as reliability, availability, wide area coverage, highest level of security and privacy [59]. The wireless data communications are more advantageous in compare to the wired communication. Such advantages are cost effective for installation, speedy placement, maneuverability and remote applicability [60]. Wireless technology based on IEEE 802.15.4 protocol is recommended by the reference [61]. Such protocols are ZigBee, Wireless HART, and ISA100.11a. Furthermore, satellite technology offers effective solution in remote monitoring and controlling because of its comprehensive coverage ability and speedy placement [62]. It has also realized that microwave communication technologies are reliably utilized for point-to-point communications because of its secured data exchange capability at a large bandwidth [38]. However, wire-based communication networks such as fiber-optic and power line communications are also

expected to integrate into SG system [36]. The power and telecommunication network of smart grid is represented in Figure 7 [63].
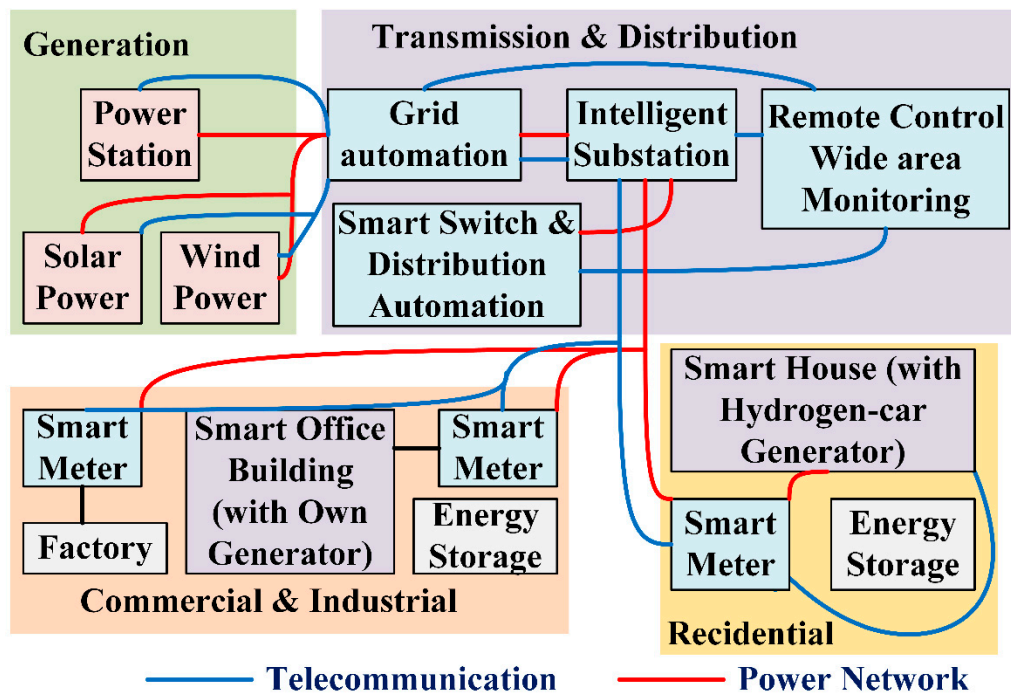

Figure 7. Power and telecommunication network in smart grid. It works as the backbone of SCADA system. It contains wireless radio connection, dial-up lines, ethernet, and IP protocols. Fiber-optic and power line communications are expected to integrate into SG system [63].

4.3. ICT Infrastructure for Advance Protection System

The SG protection is expected to respond not only grid infrastructure faults such as the failure in equipment and natural catastrophe, but also unplanned cyber-attacks. A layer-based ICT infrastructure is required to incorporate into SG system in order to avoid illegal access, and allows the system resiliency during a cyber-attack [64].

Three coordinated layers, such as predictive, inherent adaptive and corrective protections, based ICT infrastructure has been proposed in reference [65]. The ICT infrastructure must have the ability to address the malicious attacks on transmitted information in the SG. The consequences of the malicious attacks include delay in information transmission corrupt data, or make the network inaccessible to exchange information. In the data integrity attacks, attempts are made to purposely modify or corrupt data in the SG. Whereas, in the information privacy attacks attempts are made to spy on communications to obtain the targeted data such as customer's account information [30,65]. Smart protections along with layer-based ICT infrastructure have been proposed by several researchers in order to address malicious attack [66,67]. ICT infrastructure of smart grid is represented in Figure 8.
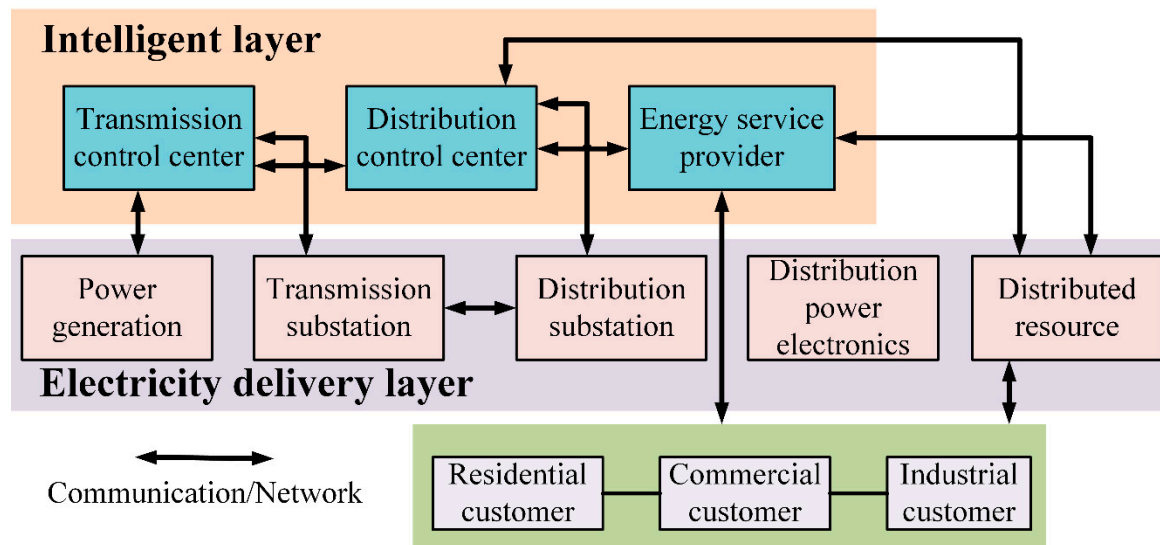
Figure 8. ICT infrastructure of SG. It consists of intelligent layer and electricity delivery layer. This layer-based ICT infrastructure is capable of avoiding illegal access and protecting against cyber-attack.

4.4. Smart Management Unit

Smart management unit is another key aspect for effective and conducive operation of the SG system. The objectives of the smart management unit include efficiency improvement, operation cost reduction, balance between generation and load, and control the gas emissions. Several researchers have proposed different techniques based on optimization, machine learning, game theory, and auction theory in order to meet the objectives of the smart management unit [29].

4.5. Modern Enabling Technologies

Distributed architectural frameworks including modern enabling technologies were proposed in [29]. Such technologies are multi-agent platforms for system automation; PMU technology for enhance and reliable telemetry; FACTS-devices for faster and efficient control; advanced and intelligent sensors and devices; integrated, however, reliable and secure communication network; fast and large size computing capacities IOT and communication protocols for enhanced data exchange facilities and process control; and deployment of cybersecurity which is consistent with the standard.

5. Various Concepts Aligned with the Smart Grid

The topic of smart grid has many dimensions and can be considered as an umbrella for many concepts. Some of the widely popular concepts include as follows:

Grid resiliency is the first and foremost concern of a smart grid, which have a greater scope for adaptability than conventional grids due to their adaptability, self-monitoring and self-healing capability. Resiliency is defined as the retraction to the previous stable condition after the grid has been exposed to a disturbance. It can either indicate its adaptation to the change, or its recovery from the instability. Resilient technologies are mostly implemented in the critical infrastructures. Smart grid are comparatively more resilient than concurrent grid groundwork, possessing more potentiality in dealing with various contingencies due to bad weather or poor engineering. In order to augment the smart grid robustness against catastrophes, proper resilience planning, along with in-depth analysis of response and recovery schemes with respect to the cyber-physical system and existing infrastructures are to be studied. Various forecasting technologies such as Machine Learning and Deep Learning tools are being built to analyze the system behavior and predict anomaly to sustainably improve the grid resilience.

Microgrids are seen as the key to integrating renewable energy sources into the smart grid. A microgrid can be defined as a small-scale grid, which has its own generating supplies, loads, and storage units, which are connected together. Usually, it can operate independently from the main grid. It should have its own control and energy management system. If the main grid is available, the microgrid may also be connected to the grid, but in case of disconnection, it should be able to supply its own loads. A microgrid usually uses renewable energy sources; however, other conventional generating units may also be used. Normally, it is connected to the main power grid through a single point of common coupling [68]. The microgrid can function in an islanded mode when the common coupling is disconnected. The islanding operation is expected to provide a high reliability [69,70]. The Global Smart Grid Federation (GSGF) was formed in 2010 to accelerate the development of smart grid technologies. The GSGF has also reported a number of projects related to microgrids [71]. The microgrid system is being transformed by exploiting new digital technology. Some examples are smart metering, smart sensors, automation, digital network technologies, Internet of things (IoT) and power-consuming connected devices [72]. The Virtual Power Plant (VPP) is a power plant, which is formed by combining a group of distributed energy sources such as wind, PV, fuel, energy storage, grid, etc. It also consists of different types of load such as civil load, industrial load, interruptible load, etc. Battery swap station, where EV's can charge and also supply to the grid is also available here. The VPP should be made in a way to have similar characteristics of conventional generating units with a total capacity comparable to typical conventional power plants. Its energy management system should be developed to make the VPP dispatchable [2]. The basic elements of virtual power plant are shown in Figure 9 [73].
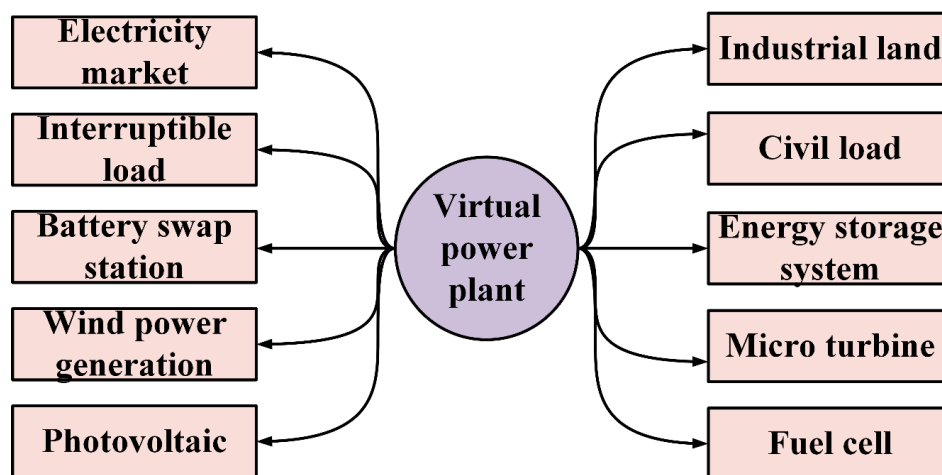

Figure 9. Basic components of virtual power plant. VPP is formed by combining a group of distributed energy resources (DERs). It also consists of different types of load. It has similar characteristics of conventional generating units in case of total capacity [73].

Demand response is defined as reduction in the load initiated by the consumer, in response to the price signals. The system should be designed in a way to shift the load to the time when the renewable energy generation is at its high level. Non-emergency demand response to reduce the peak load can provide substantial benefits in reducing the need for additional generators [74]. To implement demand response strategies, some control schemes and metering techniques should be developed.

Integration of smart appliances [7], is done through pieces of smart equipment that can communicate with electric grid. They may be turned off during peak hours. For example, a study on households using smart washing machines reported that demand automatically shifted to periods when electricity is not expensive [75]. Advanced storage and peak-shaving technologies can be used to reduce the peak load [76–78]. Electrochemical technology-based battery energy storage system (BESS) is mostly used for peak-shaving. Sodium Sulphur (NaS) batteries can be used for peak-shaving

and power quality (PQ) improvement of the grid. The peak load shaving using BESS is shown in Figure 10 [78]. Devices inter-operability show the number and scale of use of smart devices and sub-systems in a smart grid will be very high, which makes the system interoperability crucial [75]. Advanced restoration technique will improve with automatic schemes using advanced measurement, and analysis and control technologies. Some of the concepts can be implemented without major changes in operating procedures. However, there are other concepts that will require some major changes in the operating procedures.
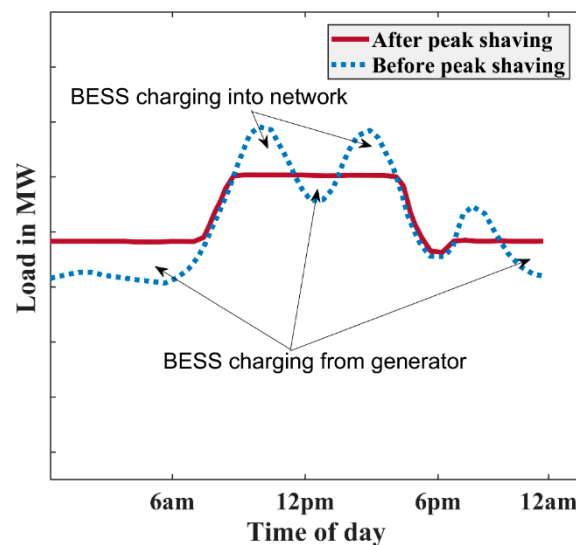

Figure 10. The peak load shaving technique using BESS. It is the mostly used energy storage system (ESS) for peak-shaving. By using BESS, the PQ of the grid can also be improved [79].

Smart Homes and Smart Cities also uses SG. A smart city uses information and communication technologies to increase operational efficiency, share information with the public and improve the quality of government services, etc. A smart home uses IOT devices to enable remote monitoring and management of appliances such as lighting, cooling/heating, and other electric devices. Smart Grid can take active data on the load behavior of these devices and communicate with them in on-peak hours, off-peak hours and request user end adjustments, be it manual or automatic in-built adjustment feature of the smart devices. This can greatly make electricity consumption more efficient in the user ends. Active loads and two-way power flow used in a smart grid allows consumers to have renewable energy generators. The customers can act be consumers and producers of energy, so named as prosumers. As such, the loads will transform from passive loads to active loads. Therefore, the conventional one-way power flow from the utility towards the consumers will change to a two-way power flow. However, a change in regulatory and legal aspects for defining rights, obligations, and liabilities will be required. In addition, the customer needs to be educated that he is no longer still a consumer but an active player with rights and obligations. Smart cities can utilize SG devices which can be seen to be used to gather real time data on traffic, transport, water and energy supply etc. and supply information to cloud for the appropriate authority to monitor and assess the condition of urban areas and act on the collected data. Also, they can be used to convey better public services with respect to particular needs in particular cityscapes. The co-constitution of Smart City and Smart Grid is gaining traction in India, Sweden and many other places, because it provides ease in carbon-governance, policy implementation alongside creating a smart energy system [80]. The co-constitution is highly important because without thinking of a smart energy system, it would be quite complicated to develop a smart city model. Smart Grid has been also defined as one of the fundamental building blocks of a smart grid alongside with smart transportation, smart governance and smart healthcare [81]. A schematic diagram of smart city utilizing the smart grid concept is shown in Figure 11 [82].
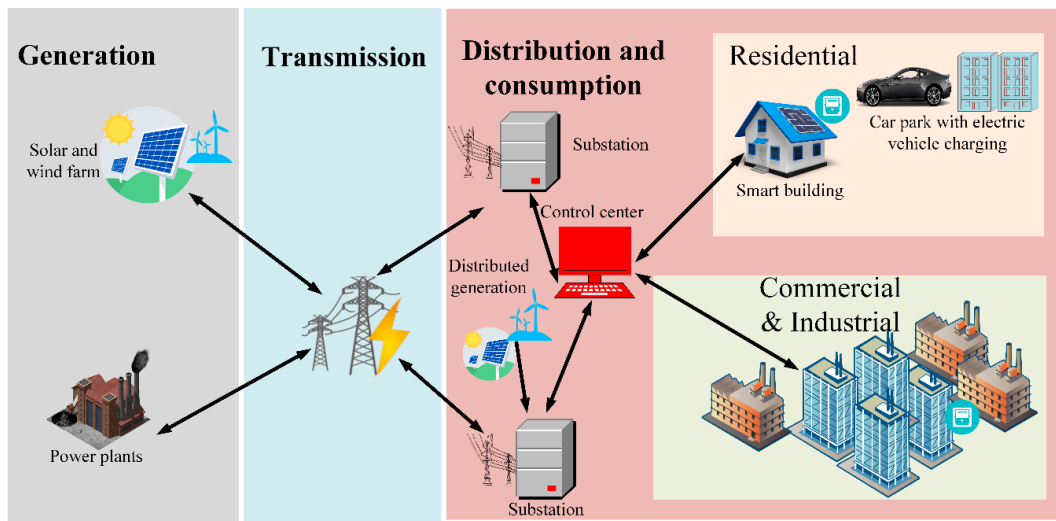
Figure 11. Schematic of a smart city utilizing the SG concept. SG provides integration of renewable energy resources (RESs) into the main grid and more controllability over the grid system. It also enables bi-directional power flow between the grid and consumption side [82].

A new real-time electricity market will be generated which provides 5-min real-time electricity prices. As more RESs penetrate in the power grid, the high share of fluctuating and less predictable power production will increase the need for balancing services. In a real-time market, the operator will have additional balancing power. The development and expansion of data communication and smart meter capabilities will empower the customers and small-scale energy provider to acknowledge to market price signal and aid in system stabilizing. It is expected that the electricity price will be dynamic in nature. Therefore, a smart automated controller will be required to make an optimal decision based on the price signals and the customers' preferences that are more static. The real time market architecture is shown in figure. The Smart grid projects are being undertaken by various countries. In some countries such as Australia, Canada, USA, Japan, South Korea and the UK, the smart grid forms an integral part of government planning to attain energy sustainability and reduce the emission [10]. The basic market of advance power system is shown in Figure 12.
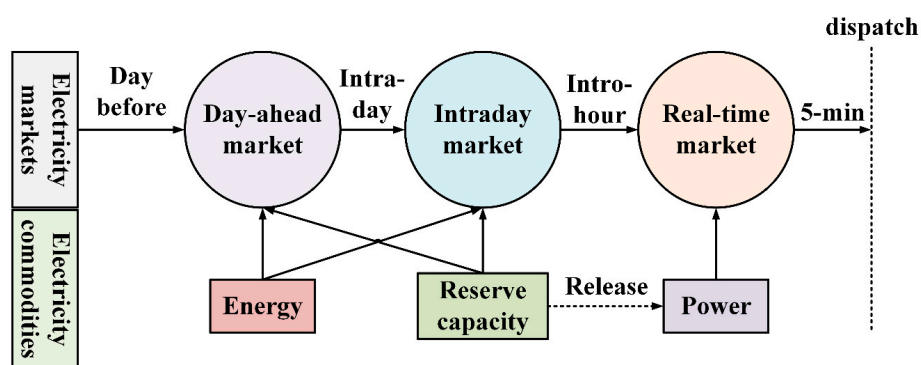

Figure 12. The basic market architecture of advance power system. A smart automated controller makes an optimal decision based on the price signals and more static customers' preferences in this market architecture.

6. Smart Grid Policies

An important SG policy is related to the personal data protection and privacy of the consumers. This regulation sets rules on who and under what circumstances can access personal data. This policy includes laws on data exchange to allow market competitors in gaining knowledge about the market while a high level of data protection, privacy and security is maintained [83]. In addition, providing

cyber security for operators, market participants and consumers is of vital importance. Smart meters are designed to measure electricity in both direction such as inflow and outflow of the meter. This is called net metering, which enables customers to export their extra renewable energy production to the main grid in addition to importing electricity from the grid when they need. One of the main purposes of using smart meters is to provide dynamic pricing to customers and to manage the energy consumption in a more efficient way [84]. In this regard, energy-consumption dashboards have been designed and implemented [2]. A framework is needed to set distribution tariffs. However, some tariff methodologies may be suitable in one country, but not fit to another country. For example, a time-based tariff may be useful in changing demand patterns in some power grids, but it may not work properly in some other countries [85]. "The scope and pace of smart-grid deployments vary according to the diverse needs, regulatory environments, energy resources, and legacy systems of different states" [86].

Various countries around the world have undertaken or are preparing themselves for making their grid smarter by adopting different approaches and roadmaps according to their individual needs. The US Federal Government established policies for smart grid, which was echoed in two Acts: The first one is the Energy Independence and Security Act of 2007 [86,87] that specifies and establishes a coordinated fund program to attract investment in smart grid [88]. The second policy was the American Recovery and Reinvestment Act of 2009 [89]. In Europe, over 450 million customers ranks as the second largest energy market in the world [85]. The drivers of the SG development in Europe are the digital single market, security, power quality and environment [90–92]. Europe targets to receive 20% of its energy from renewable energy sources by 2020, reduce the greenhouse gas emission, and utensil smart metering in 80% of households by 2020 [93]. By 2020, South Korea agrees deliberately to reduce emission by 30%. It also aims to introduce smart meters in half of the Korean homes by 2016, as well as to integrate 10% of generation from the renewable sources by 2022 [72]. Australia is committed a smart meter roll out after energy shortage in 2006 and 2007. It aims to integrate 20% of its energy from renewable sources by 2020. Australia is currently reforming incentives for SG and developing strategies to establish demand-side regulation and time-of-use tariffs [7]. Canada aims voluntarily to reduce greenhouse gas emission by 17% to below 2005 levels by 2020. Smart Grid Canada was established to increase SG awareness, enhance research and development of novel energy technologies and endorse policies [94]. By 2030, Japan's targets are likely to raise its energy independence to 70%, reducing CO_2 emission from residential sector by 50% [95]. Japan's largest utility company installed 27 million household smart meters in 2014, services using smart meters rolled out in 2015 [95]. The energy policy of China gives priority to energy conservation, by relying on local resources, protecting the environment, promoting innovation and improving the livelihood of people [96]. Large-scale system should be divided into several small basic tasks, and these small tasks can be coordinated based on well–defined interfaces and relationships [35,97]. The German Roadmap of SG as laid out by DKE German Commission for Electrical, Electronic and Information Technologies for DIN and VDE, in cooperation with E-ENERGY have produced a strategic and technical roadmap for the standardization requirements to fulfil the German Vision of the Smart Grid. The objective of the roadmap as defined by DKE is to create a future power grid which can provide energy sustainability and move towards greener power infrastructure by creating transparency, increasing energy and cost-efficiency, implementing safe and reliable system operation throughout the whole grid [98].

Different SG policies adopted by different countries mainly differ from each other due to geographical and environmental conditions, economic condition, and government policies (Table 3). A common trait in the SG policies taken by all of these countries is that they are mainly focusing on energy independency, security, and eco-friendly power generation. However, the approach taken by Japan seems to be more eco-friendly, secured, and efficient. They have a specific strategic plan on these factors and have already started implementing their plans to gain world's highest energy efficiency in industrial sector and to lead global share markets in the energy-based products and systems sector.

Table 3. Comparative illustrations on smart grid roadmap policies, point of focus, and motivation for different countries [20,21,72,86,88,91,94,96,98–101].

Country	Roadmap Policy	Point of Focus	Motivation
USA			
	- Energy Independency and Security Act of 2007 - American Recovery and Reinvestment Act of 2009 - Secure Energy Future Policy 2011	- Energy independence and security, clean energy generation, consumer protection, efficiency improvement in products, buildings, and vehicles. Increase, promote research and deployment pf greenhouse gas capture and storage medium, and to improve energy performance at national levels. - Develop and secure local primary energy sources and supply to reduce dependency on the foreign energy sources, provide options to the customers to reduce energy cost and use in affordable manner, and research and development for clean technologies to attain in clean energy future.	- California energy crisis in early 2000s - Northeast blackout in 2003 - Superstorm Sandy in 2012
Europe			
	- EU (Commission of the European Communities) policy 2007 - The Smart Grid objectives in the EU (European Commission (EC) April 2010)	- Provide a user centered approach and new services to enter the market. - Establish innovative and economic drivers for renewing the electricity network. - Create liberalized market and cherish competition. - Maintain secured supply, and ensure integrity and interoperability. - Enable utilization of renewable power generations, and best utilization of centralized generation. - Consider appropriate impact of environmental limitations and social aspects. - Empower demand side cooperation.	- Advancement in operations and efficiency of the European internal energy markets - Maintain and improve the quality and security of supply. - Combat with the climate change and support Kyoto Protocol including other commitments.
South Korea	Korea's Smart Grid roadmap 2030	- Development of monitoring and control system of the power grid - Self-healing power grid - Introduce smart meters for the Korean homes - Smart energy management system - Establish nationwide charging facilities and ICT based electric vehicle operating system - Large-scale energy storage development - Develop smart electricity pricing and trading system	- Establishment of smart grid nationwide by 2030 - 10% energy integration from renewable sources by 2022
Australia	Australian Standards for Smart Grids—Standards Roadmap	- Foundation standards such as data security protocols, communication and interconnection protocols, smart grid vocabulary. - supporting foundation actions such as operation of microgrids, system security, microgrid connection to the national power grid, distribution system automation, and GIS protocols for smart grids.	- Smart meter deployment after energy shortage in 2006 and 2007 - 20% energy integration from renewable sources by 2020 - Establish demand—side regulation and time-of-use tariffs.

Table 3. *Cont.*

Country	Roadmap Policy	Point of Focus	Motivation
Canada	Two level (Federal and Provincial) policy development is ongoing by the regulatory authorities from both levels.	- Advanced metering infrastructure - Development of self-healing grids - Development of microgrids - Demand response management - Multiple rate structure or time of use pricing - Voltage and reactive power control	- Introduction of clean energy legislation - Feed-in Tariff program. - Market needs.
Japan	The Strategic Energy Plan of Japan: (3E+S) policy	- "Last Mile" smart grid investment - Home side management - Solar power for home application - Integration of more renewable energy sources - Consumer focused	- Build a low-carbon society - Gain energy independence by 70% - Technology based
China	- The 12th Five-Year Plan on National Economic and Social Development - Decision of the State Council on Accelerating the Fostering and Development of Strategic Emerging Industries	- Policy and standardization - Strengthen smart grid planning - Accelerate smart grid construction - Reduce growth of GHG emission - Improving energy pricing mechanism - Improve grid asset utilization	- Supply security - Smart distribution grids with advanced sensors and control technologies.
Germany	The German roadmap e-energy/smart grids 2.0	- Standardization of German smart grid requirements - Power system management - Energy storage and distributed generations - Security and safety - Technologies for power system and home automation	- Create future sustainable power grid - Establish greener power infrastructure

7. Smart Grid Scenario in Oman

A conceptual pathway for building a SG based on the current power system network in Oman was presented in reference [102]. For example, Oman Power and Water Procurement Company (OPWP) announced the first IPP utility scale solar project, which has 500 MW of generation capacity from photovoltaic (PV) system will be located in Ibri in Al Dhahirah Governorate on an 1800-hectare site. The cost is estimated to be $500 million. The plant will be connected to the Main Interconnected System (MIS), which would be run by Oman Electricity Transmission Company (OETC) and will meet power requirements of around 33,000 homes. This PV plant will reduce CO_2 emissions around 340,000 tons per annum. Moreover, the commercial operation is expected to be by early 2021 [103]. Since 2019, Oman is planning boost up the smart grid communication and security system to receive quantum-safe encryption [104]. For the purpose of building highly reliable and resilient grid communication technology, ABB is in work to construct infrastructure for the OETC to incorporate state-of-the-art Supervisory Control and Data Acquisition (SCADA) system with ABB's utility grade FOX615 multiplexer. In 2017, Nama Group declared the commencement of the real-time operation of the centrally implemented Automatic Meter Reading (AMR) scheme in partnership with CESI Middle East FZE [105], the initiative is mainly for customers consuming more than 150 MWh of electricity per year. In September of the same year, the Council of Financial Affairs and Energy Resources has approved to intermix 10% renewable energy in electricity supply in Sultanate of Oman by 2025. Since January 2017, the customers such as industrial, commercial, and governmental who consume more than 150 MWh per year will pay by the scheme called cost-reflective tariffs (CRT). Although the

total customers in these categories represent only 1% of the total accounts, these customers consume 30% of the total energy. Hence, it tends to draw 20% of the total subsidies given in the electricity sector.

The sultanate of Oman has pledged to reduce greenhouse gas (GHG) emissions by 2% by 2030 by integrating renewable energy [106]. In January 2017, the new standards for connecting small-scale solar PV generations into the grid was completed as was announced by the AER in Oman. This would enable the purchase of electricity from roof-top PV systems connected in distribution networks [107]. In January 2015, the government has doubled the price of gas (US$3.01/mBtu) supplied to industrial estates with 3% annual rise [108]. The AER has further implemented new requirements for rural areas in March 2013, which should be fulfilled by Rural Areas Electricity Company (RAEC). A component (25%) of renewable energy technology (solar or wind) should be included in each project submitted to the Authority [109]. In Mid-January 2016, the fuel pricing policy was reformed in Oman to accommodate gasoline and diesel prices in every month comparing with the international benchmark. Distribution companies started to install digital meters in some areas. The non-technical loss in the MIS has been reduced from 24.6% in 2004 to 9.2% in 2016 because of AER application of incentive-based price control mechanism. A project is currently undertaking to implement Wide Area Monitoring (WAN) system for OETC, which will be used by Load Dispatch Center (LDC) in OETC for real time operation. The monitoring and relaying systems would be based on PMU, which will enhance the monitoring capability of the LDC.

Sultan Qaboos University has been heavily working on developing models for a smarter grid system in the sultanate of Oman. With regular summits [110], seminars [111], and conferences [112] being held around Oman specifically focusing on the transitioning of the Omani National grid into a Smart Grid, the university's academics and students have always played an important role. For example, in the Oman Energy and Water Conference, held on 23–25 May 2016, some recommendations were presented by the academics of the university which included developing a smart grid roadmap for Oman, installing grid-connected rooftop PV, establishing 400kV modern substations based on Gas Insulated Switchgear, expanding large scale windfarm projects, doing bulk interconnection among the power modules to reap benefits from the 400 kV planned GCC interconnection, incorporating hybrid renewable energy systems such as, PV-Diesel, Wind-Diesel, PV-Wind-Diesel-Battery etc. The recommendations also included to set a target to reduce 50% of the diesel consumption by implementing hybrid renewable energy systems. College of Engineering in Sultan Qaboos University is currently developing a small-scale pilot smart grid system. The system consists of PV, wind turbine, batteries, data network and bi-directional meter. The system is connected to the grid but also can work in island mode. The layout of the SQU SG system is provided in Figure 13 [102,113].
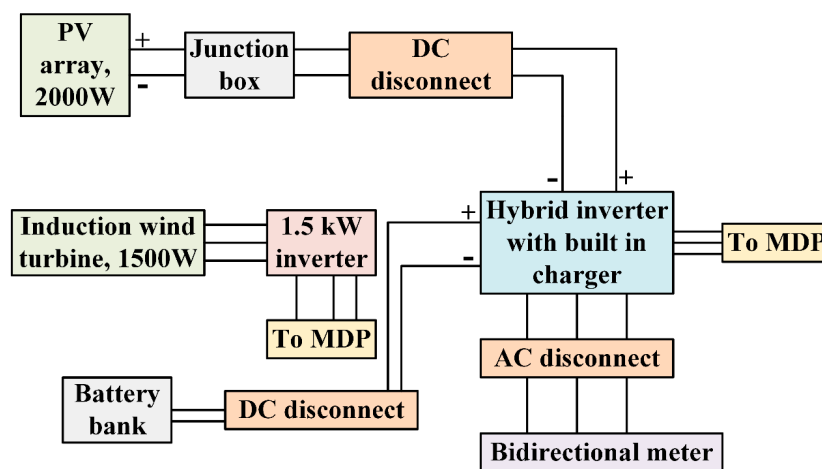

Figure 13. Layout of the SQU smart system consisting of PV Array, Wind Turbines, Battery banks, data network and bi-directional meter grid. This SG system is expected to contribute to the 50% reduction of diesel consumption of Oman [102,113].

The College of Engineering in SQU has built an eco-house, as shown in Figure 14. The objectives are to design, build, operate a highly energy-efficient house to promote green architecture design and construction practice, and to promote awareness about zero-energy homes. The Eco-house is opened to public as a permanent exhibition, information and research center. The performance of the Eco-house has been monitoring and testing using a Data Acquisition System (DAS), and the output is being published on website [96]. The tests have covered the following:

- Maintaining a comfort zone in order to keep all living spaces in a temperature range of 25 °C to 27 °C.
- Striking an energy balance by comparing the energy produced to energy consumed, and by producing at least as much energy (kWh) as is consumed during the test period.
- Using home appliances lighting and electronics, which includes an operating refrigerator, freezer, cloth washer, and home electronics during test hours.
- Testing the efficiency of a solar heater that delivers 150 L of water at an average temperature of 43 °C in 30 min.

The house is equipped with a 20 kW rooftop PV and the excess energy generated is supplied back to the grid. Figure 15 demonstrates the amount of power produced by the PV, the load of the house, and the energy fed into the grid back during the summer season.

Figure 14. SQU Eco-House equipped with a 20kW PV Array which can supply both to Grid and to the household electrical commodities. The RES here works as distributed energy resource (DER) for the SG.

SQU approved the establishment of Sustainable Energy Research Center (SERC) that was suggested by the College of Engineering, which will pursue excellence in developing policies and programs. The themes of the research center are energy policy and strategies, renewable energy, smart grid, and energy efficiency and management.
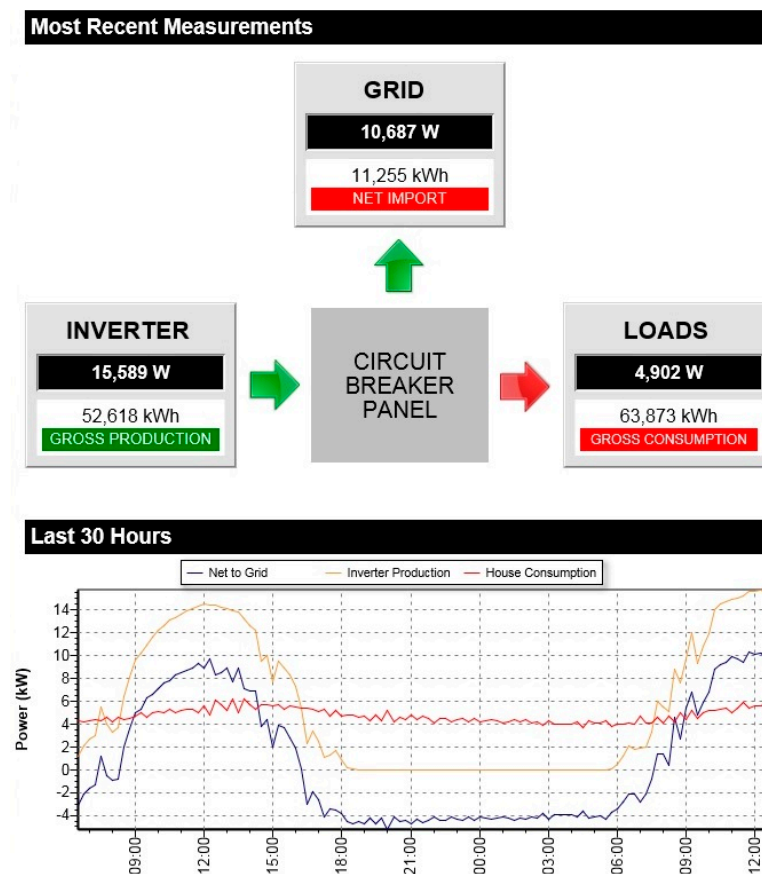
Figure 15. The load of the SQU Eco-House (Figure 14) during the summer and the amount of energy fed back to the grid.

8. Discussion and Conclusions

SG can provide a package solution of many issues such as reliability, efficiency, system resiliency, energy savings, integration of large amount of alternative energy sources, to name a few. The following conclusions can be drawn out from this study:

- The main purpose of SG is to exploit the current technologies to address challenges in order to achieve secure energy supply.
- Integration of AMI, smart monitoring and measurement, and PMU into SGs provides more controllability over the grid system. However, data corruption and cyber-security related issues arising from these features need to be resolved by ensuring more advanced cyber-physical structure and stronger cyber-security. Advanced system can increase the self-healing capabilities in SG operation. Technologies need to be mature enough before applying them in a smart grid. In addition, SG offers new business opportunities for different kind of companies.
- SG needs supporting policies, strong political commitment and global collaboration.
- The electric utilities need sufficient experience in designing and developing highly reliable and secured information and communication system. The interoperability of the SG components with adaptive communication technology should be of prime consideration.
- Customer is the core pillar of the SG systems from the business point of view. Therefore, the power providers require finding an approach to encourage customers in order to sell this new idea. Education and awareness are also required for the public about this new power network. Sharing experiences through demonstration projects, collaborative development on SG standards and policies, disseminating best practices and training of new cadre can accelerate deployment of smart grid projects and will be beneficial to developing countries.

- The cost needed for full installation of SGs is usually high. Since the government is the main stakeholder in such investments, a mechanism is required that appeal to the private investors.
- Motivation of research, development, and innovation activities implementation are essential for any successful outcome. Government needs to find mechanisms to provide rewards and incentive for the universities, utilities and industrials to invest in SG research, buildup, and demonstration projects.
- Many countries have conducted research, and undertaken pilot projects. Oman is still in initial stages of research in this area. Universities in Oman are stepping forward and leading the way in investigating and developing tentative models for SG implementation in their country but much more collaboration among utilities, government, industries and academics are required to design and come up with a perfect scheme for SG implementation in Oman. It is hoped that more prioritized initiatives will open up more possibilities on utilization of SG application in Oman in the future.

In summary, SG is not an option but a need for building an environmentally secure future. The concept of smart grid has emerged from a perception to a goal that is gradually being pursued, and Oman does not want to stay behind all the others, with increased focus on research and development in this field. Concrete energy policies developed in different counties will facilitate smart grid initiatives all throughout the world with mutual collaboration, information exchange between countries and utilities being a necessary precondition.

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