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Review

A State-of-the-Art Review of Smart Energy Systems and Their Management in a Smart Grid Environment

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Abstract: A smart grid (SG), considered as a future electricity grid, utilizes bidirectional electricity and information flow to establish automated and widely distributed power generation. The SG provides a delivery network that has distributed energy sources, real-time asset monitoring, increased power quality, increased stability and reliability, and two-way information sharing. Furthermore, SG provides many advantages, such as demand response, distribution automation, optimized use of electricity, economical energy, real-time grid status monitoring, voltage regulation or VAR control, and electricity storage. In this survey, we explore the literature on smart Grid enabling technologies until 2022. We dig out four major systems: (1) the smart grid's prominent features and challenges; (2) the smart grid standard system and legislations; (3) smart grid energy subsystem; and (4) the smart grid management system and protection system for new researchers for their future projects. The research challenges and future recommendations are also presented in the conclusion section to explore the new paradigm.

Keywords: smart grid; bidirectional communication; controllers; distributed energy resources; monitoring and measurement; security; prosumer; energy storage; protection system

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1. Introduction

The electricity grid is a network that generates, transmits, distributes and controls electric power. The traditional power grid mainly has a central generation system, limited control over frequency and voltage, a central control, limited grid status monitoring and a manual distribution system with the absence of a smart load. Smart Grid (SG) is a developed or smart form of the conventional grid having a bidirectional flow of information and electricity, creating an automated and highly advanced energy supply system [1].

A SG delivers energy more efficiently, facilitates enhanced customer utility interaction, provides pervasive voltage control, reliable frequency control, modern management techniques and responds to wide-ranged events occurring in the system [2]. For example, in response to the failure of a distribution feeder or transformer, the SG automatically recovers the power flow to load using its self-healing capability [3–6]. Similarly, the grid automatically responds to overloading or injection of the distributed generator [7]. Considering another example of customer load shaping through smart meters, this load shaping reduces the peak demand on the power system, as well as energy bills [8]. Reduction in load triggers a chain of benefits, such as energy loss minimization, smoothing of load on the network and reduction in capital investment on the system [9–11].

A SG is comprised of an energy generation, transmission, and distribution network equipped with a bi-directional exchange of both electricity and information supported by secure communication technologies having effective control that is friendlier to customers, utilities and the environment [12–14]. This description contains almost every aspect of the SG [15]. It is imperative to mention that s conventional grid can be changed into a SG, and the level of smartness can be limited to a certain extent according to the limits of investment and requirements of the consumer and the utility [16–18]. A SG is a combination or integration of energy infrastructure, communication technologies, functions and services with effective control [19]. This survey explores three major systems:

A. Smart grid main features. The main features and challenges along with some standard SG systems are presented.
B. Smart infrastructure system. It explains advanced electric power generation, energy storage, transmission, distribution, and usage;
C. Smart protection system. Enhances grid reliability, protection against failure of equipment, security, and privacy to the customer and grid-related information.

In the past, various surveys on SGs were conducted, discussing fundamental concepts and technologies applied in the SG. The authors in [20–25] surveyed the existing SG standards and pointed out solid recommendations for next-generation SG standards. The author in [26] highlighted the advantages of smart meters and gave a summary of the judicial framework related to smart metering objectives and policies. The authors in [27] discussed the industrial aspects for a smartly running distribution grid. The authors also mentioned the possible technological options to be used in the future SGs. In another work based on the surveyed electric vehicle (EV) related topics such as industrial informatics systems, namely (1) intelligent electrical energy management, (2) charging infrastructure and batteries of plug-in hybrid EVs/plug-in Evs, (3) information transmission requirements, and (4) vehicle-to-grid (V2G) [28]. The emerging SG supports electrification of other sectors as well. Authors in [29] provide a survey of electrification of transport sector in SG environment. A survey intending to find a comprehensive definition of smart distribution system is presented in [30].

Some research works have targeted various research and development activities related to SG. Oyetoyan et al. [31] have presented SG development activities in Norway. This survey provides data that can aid in research work. In [32,33], SG projects from various points of view are surveyed, analyzing the endeavors that scientific groups in Europe are making for implementing this infrastructure. The statistic that this review has revealed is that numerous solutions exist already. Various management schemes have been tested and are ready to be deployed [34]. There is evidence that many standards for information transmission and protocols exist, but quite a few of them are widely accepted energy networks. The goal in [35] is the survey of several security susceptibilities and countermeasures for the information system of the transmission grid. Another focal area that is surveyed is the wide area measurement system (WAMS) technology and phasor measurement units (PMUs).

Most of the market share of existing SG network installations are wireless mesh networks. The authors in [36] start by justifying the selection of wireless mesh network (WMNs) as opposed to any other communication technology based on quantifying the bandwidth/latency/quality of service constraints for applications of SGs. The main purpose of the paper, however, is to discuss some optimization techniques [37] that are found in the literature and can be implemented to overcome some of the challenges currently faced by WMN deployment in SGs. Cognitive radio is investigated as an optimization technique on the physical level. The paper also explores the feasibility of using wireless software defined networks (WSDN) to improve the overall visibility and manageability of WMNs. Wang et al. [38] presented a survey on bad data injection and their countermeasures. In [39], the effects of a large-sized wind energy farm connected with a SG has been studied by presenting a wind farm model, operational performance, wind farm output forecasting, power flow, voltage and reactive power balance, steady-state stability, large-signal stability, failures, and reliability. The SG can only be realized based on the achieved results of 5G communication, including extremely high throughput and extremely low delay. A comprehensive study of the real-time energy consumption, privacy and security is presented in [21]. The survey in [40] focuses on communication technologies for a low-voltage distribution grid. Three technologies, namely power line carrier, wireless mesh network and radiofrequency, are studied and it is concluded that the first two offer the best compromise between bit rate, range, and cost. Dufour et al. [41] discussed the research and development of SG. Aspects such as renewable energy penetration in the SG, micro-grids, wide-area measurement systems, scheduling of load, power balance, information transmission challenges, behavior, energy distribution control, and fault protection, have been worked on. This paper elaborates on the solution of challenges using real-time simulation. Our survey reviews the literature until 2022 on the main systems mentioned above.

This review is arranged as follows. In Section 2, prominent features of the SG are presented. In Section 3, legislations, standards, and the programs are presented, while Section 4 is comprised of the smart energy system discussing generation, storage, transmission, distribution and utilization. Section 5 presents the smart management system, while Section 6 presents the smart protection system. Section 7 concludes the study with brief discussions.

2. Advanced Features of Smart Grid

The demands and expectations of stakeholders grow with time. Therefore, new demands and requirements have convinced the industry and government to think about modernizing the grid. This opens new opportunities for jobs for professionals, research and development activities in energy generation transmission, distribution, automation, electronics, battery manufacturing, cybersecurity, privacy and communication technologies, etc. SGs have also opened business opportunities. However, an exact and thorough definition of a SG is yet to be proposed. The National Institute of Standards and Technologies (NIST) [42] reports the benefits as well as requirements of SGs, as shown in Figure 1.

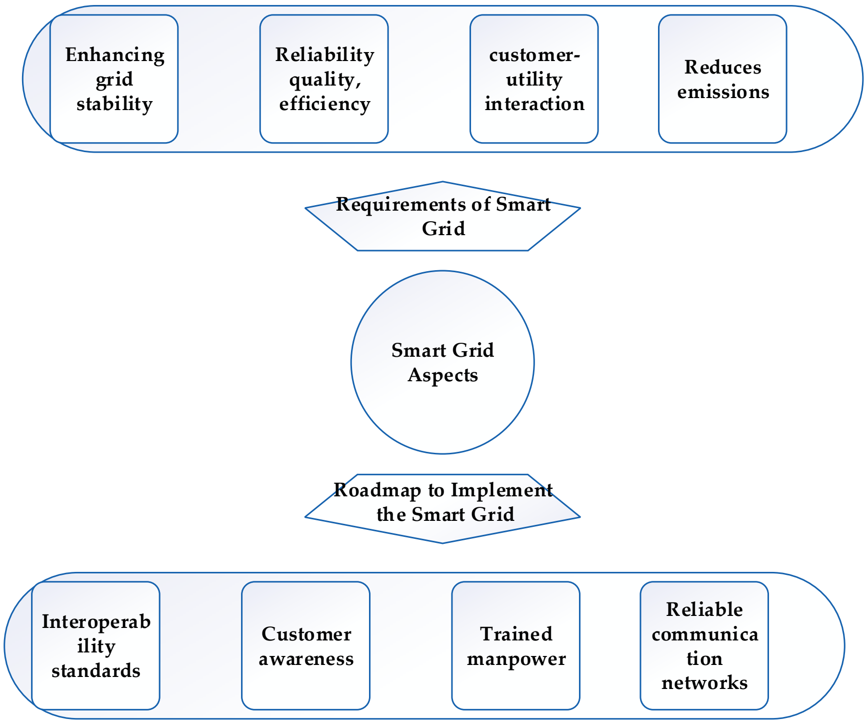

Figure 1. Requirements and roadmap of a smart grid system.

Table 1 differentiates between conventional and SGs, while Figure 2 shows the SG NIST model.

Table 1. Comparison between conventional and smart grids [43].

Existing Grid	Smart Grid
Electromechanical	Digital
Unidirectional communication	Bidirectional communication
Central generation	Distributed/scattered generation
Small No. of sensors	Large No. of sensors
Manual monitoring	Self/automated monitoring
Manual restoration	Self-healing
Failures/faults and blackouts	Highly Adaptive and intelligent islanding
Limited/restricted control	Pervasive control
Small No. of customer choices	Large No. of customer choices

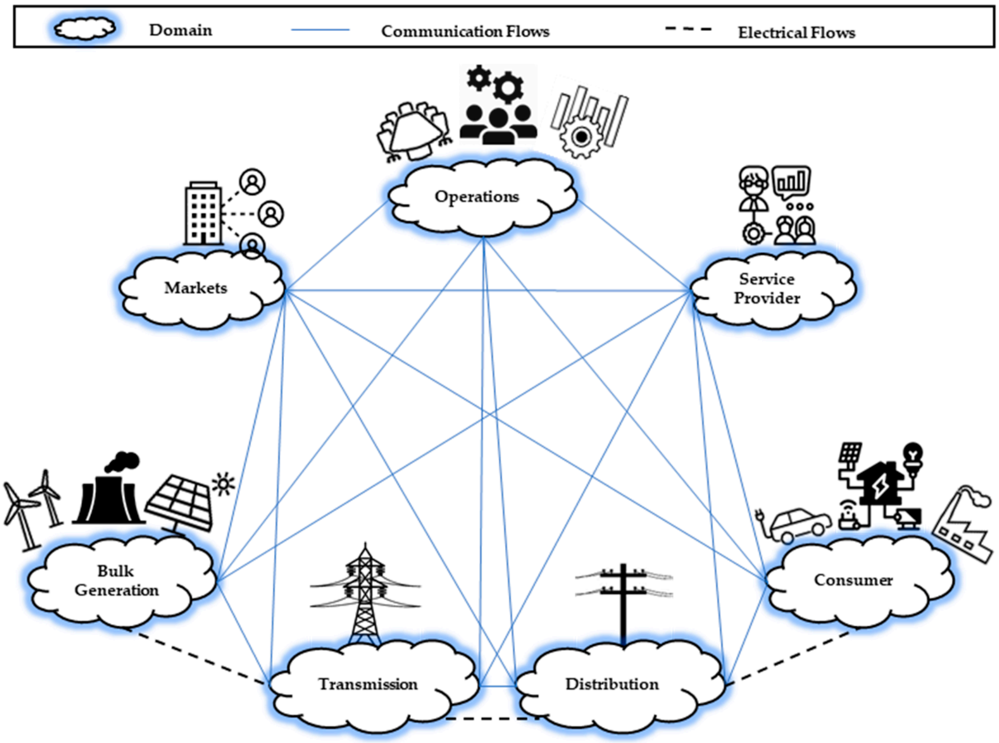

Figure 2. NIST Model for SG.

To understand the advanced grid, NIST provides a model (Figure 2), which can be used as a reference. This model segregates the SG into seven areas (domains), each encompassing one or more SG actors, having systems, equipment or programs [44]. The short account of domains and actors is shown in Table 2. For a more elaborate discussion, please refer to [45].

Our present survey splits SG into some major systems, such as smart infrastructure systems, smart management, and smart protection systems.

A. Smart infrastructure system. It consists of energy generation, transmission, information measurement, monitoring, and communication infrastructure. The SG has a bidirectional flow of electricity and information. Distributed energy sources (DES) increase the efficiency of the power network. Small scaled DES (e.g., a solar panel on a rooftop) feed the customer and the remaining energy can be put back into the power grid [46]. This happens when DES run in coupled mode with the macro grid, giving rise to the concept of "microgrid". DES can also provide power to a certain load in an "islanded" mode where it cannot exchange energy with the macro-grid either intentionally or during a fault. Bi-directional flow of information from customers to the utility and from the utility to customers results in useful information exchange, providing remote status monitoring of the customer, disconnection, reconnection, and demand profile shaping. This survey further divides a smart infrastructure system into several subsystems:

- The smart energy subsystem provides a modern setup of a smart energy generator, smart transmission and smart distribution medium, and utilization [47].
- The smart information subsystem provides information or data metering, monitoring and ways to manage it.
- The smart communication subsystem provides an information transmission medium.

Table 2. Domains and actors in the NIST SG model [42].

Domain/Area	Actors/Participants in the Domain
Customer/Consumer	Load
Markets	System operator and participants
Service Providers	Provide different services to consumers and utility
Operations	Managers of transmission/distribution
Bulk Generation	Generators of electrical power in bulk
Transmission	Carriers of the large amounts of electrical power over long distances
Distribution	Distributors of electrical power to and from customers

We separated information and communication subsystems to handle the involved structural and operational complexity of a SG as a system of systems. This also makes our survey of SG technologies comply with IEEE P2030 [48] for meeting requirements such as interoperability. IEEE P2030 is discussed in Section 3.

B. Smart management system. Provides managerial services and functionalities. The management objectives relate to an enhancement of efficiency of energy, equality of supply and demand, CO_2 emission reduction, and reduction in operational cost.

C. Smart protection system. Provides grid reliability, stability analysis, protection against system failures, energy and data network security and privacy.

3. Smart Grid Standards, Legislations and Projects

The U.S. Department of Energy (DOE) serially started a Communications and Controls Workshops on the penetration of DER in the power system in 2001 [49]. Different aspects of transformation, from conventional to SGs, are widely discussed in the DOE's workshop [50]. The United States Federal Government developed a policy for SGs and in Congress Acts described namely the Individuality and Security Act of 2007 and the American Recovery and Reinvestment Act of 2009 [27].

International standard IEC 61850 describes the automation model for electrical grids and presents a standards-compliant approach that enables optimization of SG control capability at field level. Some latest standards of IEEE are IEEE PC37.240 Standard for Cyber Security Requirements for Substation Automation, Protection and Control Systems, IEEE P2030.5 (Revision) Standard for Smart Energy Profile Application Protocol [51,52]. Lu et al. studied architecture-related issues associated with information communication in SG and showed that ETSI M2M Standards can solve such problems [53]. A services- and application-oriented approach of standards, such as ETSI M2M, supports device interoperability and SG system scalability ETSI M2M standards also facilitate device management, demand response, and efficient information security implementation [54]. The work in [55] presents novel standards for enhanced SG incorporation and computerization based on semantic services. IEC 61850 and OPC Unified Architecture (OPC UA) express a value-added service-oriented integration framework for the SG.

Roadmaps of the SG (e.g., UK [56], Austria [57], and Spain [58]) are found for its practical implementation. For the development of new standards and upgradation of existing ones, a cooperative road map/program has been required between different countries at the international level [59]. This survey discusses IEEE standards, such as IEEE P2030 [60]. Instructions and approaches for information communication and electrical system interoperability are provided in IEEE P2030. The interoperability of devices provides organizations with the capability of effectively communicating with each other and transferring meaningful data. P2030 takes the SG as a system of systems, i.e., a complex system [61]. Governments, industries, and academia have put a huge amount of money into academic research, pilot programs, and field trials. The projects cover advanced metering infrastructure (AMI), power transmission and distribution networks, smart meters, virtual power plants (VPPs), distributed energy resources, domestic applications, microgrids, and Evs. In [62], the authors discussed that in most countries, a significant amount of investment is dedicated to the projects. SGs are opening many research and job opportunities in various parts of the world. Since a SG is a complicated system representing a loose integration of energy, electronics, software, and communication technologies, cross-technology research opportunities, therefore, exist.

4. Smart Energy Subsystem

The SG has bi-directional information and electricity flow, unlike the conventional grid. The smart infrastructure system consists of a smart energy subsystem, a smart communication subsystem, and a smart information subsystem. The conventional power grid has been unidirectional [63].

The electrical system historically has been central. The power produced by hydro and thermal generators is increased from 11.5 kV to 220/500/700/1000 kV and injected in the central power pool of an extra high voltage (EHV) transmission corridor (primary transmission grid). Power flows to long distances at this EHV medium. The switchyard in service for increasing the power is called the primary transmission grid station. Power enters the secondary transmission grid station where it decreases to the 138/132/66 kV level and is injected into a secondary transmission grid (network). High voltage secondary transmission lines feed the primary voltage distribution substations that decrease the voltage from 132 kV and 66 kV to 11.5 kV. At this juncture, voltage leaves the transmission grid and enters the distribution grid. The distribution grid consists of 11.5 kV networks called the primary distribution grid which ends at the pad-mounted or pole-mounted transformer (secondary distribution substation (SDS)). The secondary distribution grid emanates from the SDS and carries voltage at a 440 V, three-phase, four-wire, star-connected system. Figure 3 shows a traditional power grid. The central power system suffers from many problems. If any type of instability occurs, such as angle, frequency or voltage instability, it can spread to all parts of the power system, resulting in a national blackout. Additionally, the transmission network proves a bottleneck to route centralized generation resulting in overloading of transmission media, energy losses, and performance degradation.

In contrast to the traditional grid, small-scale wind, solar, diesel, furnace oil, and residual furnace oil generation can be injected into the primary, as well as secondary, voltage distribution grid, depending on its size. The consumer generates power, consumes it and feeds extra power into the macro-power grid, giving rise to the concept of the prosumer. Figure 4 gives the areas of the smart energy subsystem.

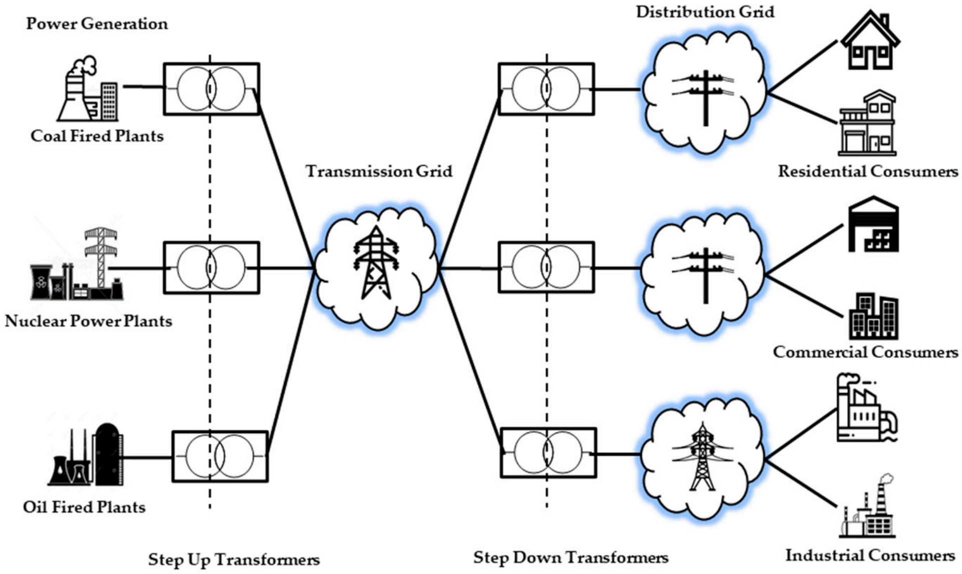

Figure 3. Traditional energy grid.

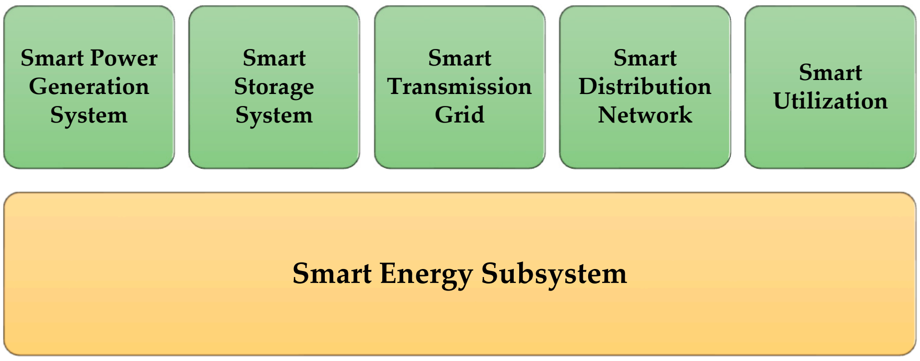

Figure 4. Smart energy subsystem.

4.1. Smart Power Generation System

Smart power generation system consists of conventional electricity sources integrated with digital communication technologies. Wind and solar energies are renewable energy resources (RERs) of electricity. Power generation from RERs for Brazil, OECD and other parts of the world is presented in [64]. Fossil fuels pollute the atmosphere, get depleted and become expensive with time. The running cost of fossil fuels is very high. However, coal is the only option that is relatively cheaper in power production. Hydroelectricity sources also have problems. Large reservoir dams take too much time and money to construct. Such projects have environmental consequences in the form of waterlogging, turning the surrounding land into barren land. The run-of-river projects does not require significant capital cost and construction time [65]. It can be suggested that coal-fired steam power plants and the small run-of-river projects are two types of power sources that require less construction time, less capital and operational costs. Developing countries, having an acute shortage of electricity and soaring per unit price, can use this strategy as a possible short-term low-priced solution [66]. Unfortunately, however, the power sector has been hijacked by a power generation mafia controlled by independent power producers (IPPs) that hinder such steps toward cheap electricity generation [67].

To survive the power sector in developing countries, its dependence on thermal power-producing IPPs must be reduced. It must opt small hydro- and coal-based projects in the short term and large-scale reservoir type dams in the long term with more penetrations of RERs.

4.2. Smart Storage System

In SG environment, RERs reduce the dependence on conventional generation sources but they are extremely fluctuant. The unpredictable nature of RERs can even jeopardize the grid stability; therefore, more robust controllers and an enhanced transient and dynamic stability of the system would be required. Modelling RERs is a challenge due to their stochasticity [68]. Energy storage systems are commonly employed to tackle the fluctuant renewables [69–72]. Various high-performance batteries such as Li-ion, super capacitors, and flywheels have been widely used. Authors of [71] presented a review on Super capacitor based hybrid energy storage system for photovoltaic (PV) integration. Authors of [68] presented economic and environmental benefits of energy storage for a prosumer microgrid. H.A. Muqeet et al. [72] presented cost benefits of battery-based energy storage systems in SG environment where consumer can exchange its surplus energy with grid network. Authors in [69] studied life degradation impacts of battery storage for an islanded microgrid. A comprehensive review of modern storage trends for EV charging stations is presented in [4].

The power electronic systems play a pivotal role while integrating renewable and energy storage in SG [70]. In [73], the authors review power quality issues associated with intermittent power source integration in the electrical network and point out the effects of electronic devices, such as transistors, diodes and flexible AC transmission systems (FACTs), on such problems. Solar and wind power penetration challenges are discussed. Bhutto et al. [74] identified both the challenges and progress for PV energy and the area-wise potential of PV energy and its existing status. Small scale hydro (1–30 MW) and run-of-the-river micro-hydro plants (1–100 kW) can play a great role. Their construction requires less time and money, and they can consequently play a vital role in bringing cheap electricity within a smaller period. Unfortunately, this water gets wasted due to the absence of large dams. The construction of reservoir-type dams has been politicized. Under such circumstances, many small and micro-hydroelectric plants can be installed along the rivers and canals to meet the country's dire need of energy [75]. However, the importance of reservoir-type dams cannot be overlooked as they play a pivotal role in bringing cheap energy in the long run.

4.3. Smart Transmission System

This grid is responsible of carrying power to long distances. Real challenges are quickly ageing components, ever-increasing demand infrastructure and the use of enabling technologies to modernize the grid. A healthy transmission grid is extremely crucial in maintaining system stability. The smart transmission grid consists of three parts: the smart control center, the smart power transmission network, and the smart substation [76]. The future smart control centers enable new features, such as metering and grid status-related data collection through meters, sensors and communication channels, analytical capabilities for analysis and state estimation, status monitoring of grid, and visualization [77].

The smart transmission network is the advancement of the existing network by adding sensors, communication technologies, computational engines, and signal processors that can bring improvement in energy use, power quality, system reliability, and security. The basic structure of a high-voltage substation did not alter with time, but the system monitoring, measurement, and controllers changed [78]. Advancements of a smart substation include data metering and transmission, state estimation, visualization, digitalization of displays, automated functioning, coordination, and self-healing.

4.4. Smart Distribution Network

The distribution grid serves the end-users; therefore, its importance in rendering quality service is quite high. The distribution system will have DER(s) that make the system more flexible, stable, qualitative and efficient, but make power flow more complicated. In [79], Takano et al. presented two domestic energy distribution systems that distribute electricity by the information added to the energy. The first proposed setup is a circuit switching system based primarily on the alternating current (AC) power distribution, whereas the other is a direct current (DC) power distribution system through energy packets. Power packetization is a challenging but interesting method, based on high power switching devices. It is proved that silicon carbide junction gate field-effect transistors can provide packets of electric power [80]. The authors in [79] discussed an intelligent power router which divides energy into packets. Headers and footers are linked with an energy unit to create a power packet. At the receiving side, each packet is steered by a router to the address described in the header and then dispatched to the concerned load, making in-house power delivery efficient.

The major purpose of distribution automation is real-time adjustments to changing loads, control over generation connected to the power distribution system, switching, self-healing or recovery during a fault or abnormal conditions and automatic energy flow control without operator involvement. This necessitates control of field devices through central or distributed control. Information gathered from meters and its transmission to controllers is realized by the communication medium.

4.5. Smart Utilization

In the SG, the utilization sector is very important. Different entities such as the prosumer [68,72], demand responsive smart homes, smart buildings [11,66], flexible loads, etc. provide smart features in power utilization. The energy management system is used to manage the available energy by demand response and various techniques [2,14,19]. Meanwhile the smart energy storage system plays vital role in smart utilization. Different types of storage systems are used to store the energy as backup. This stored energy is used for various purposes, such as energy arbitrage, energy exchange program, and power system stability purposes [81].

4.6. Prominent Features of Smart Grids

In this section, we discuss three new grid paradigms, namely microgrid, vehicle-to-grid (V2G) and grid-to-vehicle (G2V).

(1) Microgrid: Distributed generation gives a cornerstone idea of the SG called microgrid [82]. The SG has the plug-and-play interconnection of small microgrids [63]. A microgrid is a group of generators, storage, and customers [83]. The microgrid can run in either coupled mode with a macro–grid or islanded mode. In the first mode, it can feed extra power to the macro-grid, or it can take power from a macro-grid. In the second mode, it serves its load in isolation with the macro-grid. A microgrid can be disconnected at the point of common coupling from the macro-grid working independently. Figure 5 shows a microgrid.

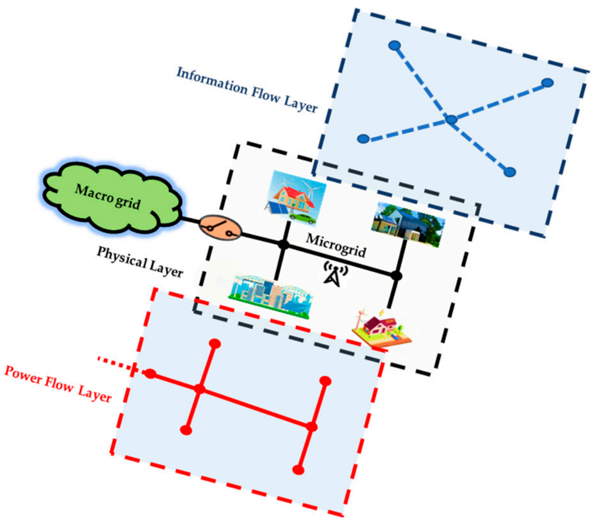

Figure 5. Different layers of a microgrid.

Multiple distributed generator environments and the capability of isolating the macrogrid from the microgrid during fault will result in a trustworthy power supply. This deliberate isolation increases reliability in local vicinity compared to that obtained from the power system as a whole [84]. In islanded mode, power exchanges do not take place, but information exchange takes place with a microgrid. This information gives a picture of the microgrid to take a timely decision to reconnect back.

(2) G2V and V2G: EV uses an electric motor for propulsion purposes. Fossil fuels are being depleted and become costly with time; therefore, EVs are gaining popularity. There are different types of EVs, such as plug-in EV, hybrid EVs, on/off-road EVs, rail borne EVs, airborne and seaborne EVs and electrically powered spacecraft.

The widespread use of EVs mainly has two concepts, named grid-to-vehicle (G2V) and vehicle-to-grid (V2G). In G2V, the vehicle gets charged from the grid after its battery gets depleted. Charging of EV(s) puts a significant load on the distribution grid. In [43], a grid-to-vehicle charging interface, charge scheduling, vehicle-to-grid (V2G) control, operation algorithm and radio-frequency identification reader are developed. It is shown that charging has been optimized. Additionally, the peak load of the grid thereby reduces, relieving the grid. The paper in [85] proposes a EV charging infrastructure that reduces the charging time as well as power quality issues. In [86], the authors indicated that the present distribution network in the Pacific Northwest can support a 50% penetration of EVs in the grid, having a 120 V smart charging. This amounts to 21.6% of the vehicle fleet of light duty. This penetration level of EV(s) has been exceeding the known capacity of present generation resources by approximately 18%. Serious problems such as system degradation, reduction inefficiency, and even network overloading can occur because of uncoordinated charging [87].

The overloading and subsequent performance degradation can be avoided by coordinated charging. Clement et al. [88] showed that coordinating the charging of EV(s) reduces system energy losses and VAR/volt variations by smoothing the network load. In vehicle-to-grid, EVs offer a new method to store and then inject energy back. EV(s) supply the energy back to the power grid in case they are parked and have a connection with the electrical network. In the United States (US), an EV is usually driven for only an hour in a day on average [89] and it is parked for most of the day. There are three methods to deliver power:

1. The EV produces energy from stored fuel and generates electric power from the generator for an electric company at peak hours. Such vehicles can act as a distributed energy source.
2. An EV supplying power to the grid uses a rechargeable battery during peak electricity hours. EVs recharge back at cheap rates in off-peak hours. Such a vehicle fleet acts as DGs increasing system reliability.
3. Solar vehicles can use excess charging to provide energy to the electric network. These types of vehicles act as small distributed renewable energy sources.

Until now, researchers have worked on the grid battery connection [90,91], possible services [90], and its emerging market [92]. Companies are conducting V2G trials. EV plays an important role in peak shaving by injecting power back into the energy grid during peak hours and in valley filling by charging back the EV during off-peak hours, thereby optimizing the use of an asset. Hutson et al. [93] use a binary PSO algorithm to obtain optimal solutions that maximize profit to owners by satisfying the system as well as the vehicle owner's constraints. PSO is an iterative stochastic optimization procedure applied to nonlinear, complex, non-differentiable, large-sized and discontinuous problems. Yannick et al. defined the possible action of public policy towards EVs. Additionally, the barriers to EV deployment and their remedies are studied in [94].

5. Smart Energy Management System

In a SG, the bidirectional flow of electrical energy and data are supported, which provides an improvement of energy efficiency, a reduction of running cost, demand–supply equality, control of carbon emission, and utility resource maximization. Some people think that if the infrastructure only becomes smart, this will be enough. However, this is not true. The new management methodologies are also essential to improve the overall performance of the power grid [95].

Let us take as an example demand response, the most valuable concept of SG. In conventional electric companies, efforts are made to match generation to demand [72]. However, this is quite expensive in the long run because the load is unpredictable and keeps on increasing seasonally, requiring spare generating capacity. Additionally, there should be powerhouses that can respond to rapid changes in energy consumption. The last 10% of generating capacity (spinning reserve) on bars could be needed in less than 1% of the time [96]. Failure in matching supply to demand can result in cascaded tripping of different branches and even in blackouts (i.e., electrical power outage). In a SG, demand response handles the consumer usage of energy against supply conditions quite smartly. A SG does not need to match the generation to load; instead, it equalizes the demand to supply by convincing the consumers or by using control technology [66].

For instance is the twenty-four-hour energy consumption on a high-temperature day in California (1999) [97]. In a SG, the smart meter reduces energy consumption by switching off less important devices during peak hours.

5.1. Main Energy Management Objectives

There are different management objective tools discussed in this section:

1. Energy efficiency;
2. Demand profile improvement;
3. Utility optimization;
4. Cost optimization;
5. Price stabilization;
6. Emission control;
7. Consumer comfort enhancement;
8. A hybrid of the above.

The first and foremost step is the demand profile shaping. It shapes load and matches load with available generation. The way to achieve demand response is to shift, schedule and reduce demand through, for example, smart meters [98–107]. If the peak demand is reduced, the system's life span, losses, emissions and investment to augment, upgrade and install new powerhouses and equipment will reduce. The authors in [98] proposed a control and optimization method and concentrated on the control algorithms for reshaping the demand profile. Caron and Kesidis [100] designed a pricing method to benefit customers to attain a utility-suited load profile.

They developed demand energy response algorithms to attain equilibria. Ibars et al. [102] smoothed the load curve and tried to avoid network overloading. Kishore and Snyder [103] proposed an optimization model to take advantage of low energy prices during off-peak periods. Afterwards, they proposed a scheme to lessen the peak demand for domestic customers. They finally presented a powerful model for optimization of energy management by using dynamic programming, which considers electricity capacity constraints. Niamh Ó Connel et al. discussed the benefits and challenges of demand response [108]. The benefits are the reduction of network loss and carbon emission, reduction in generation capacity and pricing. The challenges are devising a control strategy. The authors in [104] discovered that pricing tariffs help to achieve improved performance. O'Neill et al. [105] presented an online learning algorithm to decrease domestic energy costs and reshape the energy profile. The authors in [106] developed a generalized measure of dispatch ability of electrical energy, working on two main categories of dispatchable electrical load, and proposed models for power requirement to match consumption to the energy source.

Ghosh et al. [101] presented a scheme to incentivize consumers. According to this, consumers who are willing to decrease their demand receive a greater incentive, and vice versa. The second article of energy efficiency and demand profile is the minimization of energy loss [68]. The use of DGs in SGs makes matters more intricate. To reduce energy loss, the authors in [109] developed the optimized positioning and amount of renewable DGs to minimize power loss. Atwa et al. [110] minimized the loss of energy by optimally mixing stochastically modelled fluctuant resources. The authors in [111] proposed a decentralized optimization algorithm to reduce electrical power losses in the distribution grid. The improvement of utilities, increasing profit and reducing production and operational costs are important management objectives. Researchers understand these aims from different angles, such as customer bills or profit [100,104,105,112–117], energy bills of an individual or those of a group of customers [118,119], and electrical energy system and industry cost [99,101,104,116,120–126].

Price stability is also an active research area in SGs because real-time wholesale market prices to users form a closed-loop feedback system that can result in price instability. Roozbehani et al. [127] proposed a mathematical model to characterize the dynamic evolution of demand–supply, clearing prices of the energy market, and presented a price stabilization algorithm. Controlling the emission of gases is a highly mandatory SG management purpose in the power market, which has a meaningful impact on the environment. However, the maximization of the utility's profit or minimization of the production cost is not directly associated with emission reduction using green energy. The cost of energy generated from renewable energy sources will not always be the lowest. Therefore, as proposed by Gormus et al. [128], the atmospheric effect of power generated from fossil fuel should be taken as a cost parameter in the demand scheduling algorithm. However, consumers should accept their load to be scheduled following the low carbon scheduling requirements.

Researchers have focused on the reduction of CO_2. Saber and Venayagamoorthy [126] discussed a way to seek advantages of EVs and green resources for emission reduction. Bakker et al. [98] suggested a control scheme for the optimization of energy efficiency and increased generation from green sources. Bu et al. [112] modelled the fluctuant energy loads as a Markov-modulated Poisson process problem. Liu and Xu [129] mathematically analyzed the wind power effects on emission.

Microgrids: Guan et al. [89] came up with the result that microgrids can decrease the cost of electrical energy while pleasing constraints such as demand and supply balance and operational constraints of equipment. Vandoorn et al. [130] proposed a scheme for load control in the microgrid, working in islanded mode with a consequent decrease in energy loss and optimal use of renewables. A survey on the challenges of microgrid power management is investigated in [131].

G2V/V2G: System performance and network overloading can occur due to the high penetration of uncoordinated EV charging [132]. Coordinated charging can be achieved by particle swarm optimization (PSO) [126], quadratic optimization [133], dynamic programming [115] and stochastic programming [88,134]. PSO solves intricate, constrained and non-differentiable optimization problems rapidly, with greater precision. In the realm of EV charging, the authors in [135] devised a coordinated charging scheme for EVs and established a relation between line loss, load factor, and variations in load. They concluded that their proposed formulation reduces computation time and complexity. Authors in [136] developed a queuing theory based mathematical model to handle charging of priority assigned vehicles. Their main aim was to reduce the plug-in waiting time while maintaining the grid stability. Another work carried out by Pan et al. [137] reported the placement of EV infrastructure, for example battery exchange stations, to support the transportation and electrical system. In V2G, the battery is discharged to the grid during peak hours and then it recharges back during off-peak hours at a low price. Now the question is how to find out proper charging and discharging time of a day, to benefit both utilities and EV owners. Hutson et al. [93] investigated this area by using binary PSO (BPASO) to locate an optimal solution to maximize the owner's profit while keeping within the system and owner's bounds. Lund and Kempton [138] provided an analysis of the health impact of

V2G on the penetration of renewable in power grid. V2G technology also provides storage and can reduce CO_2 emission [139].

5.2. Energy Management Methods and Tools

Different tools for management problems are mentioned in Figure 6, while Figure 7 shows the various tools used for energy management. For optimization, the classical mathematical algorithms are convex programming [116] and dynamic programming [140]. Stochastic programming [88] and robust programming [113] are also used due to the unpredictable nature of intermittent sources. Moreover, the well-known metaheuristic algorithm PSO [141] can solve highly complicated constrained optimization problems [142] rapidly in a precise manner, without the curse of dimensionality [93].

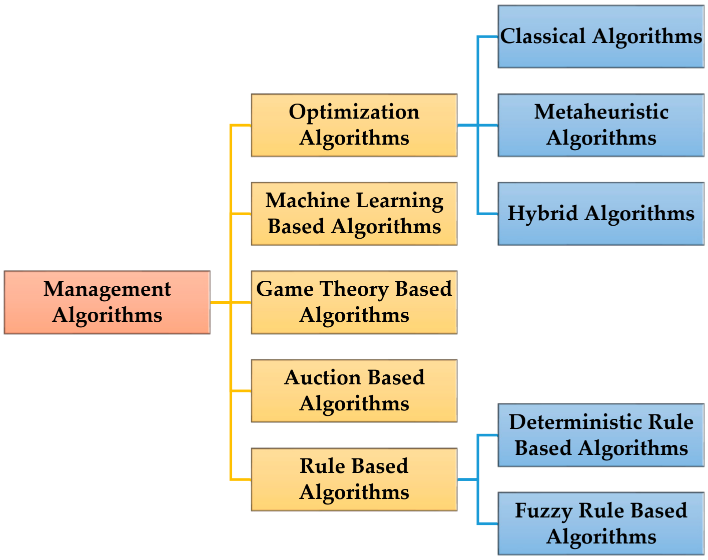

Figure 6. Energy management methods and tools.

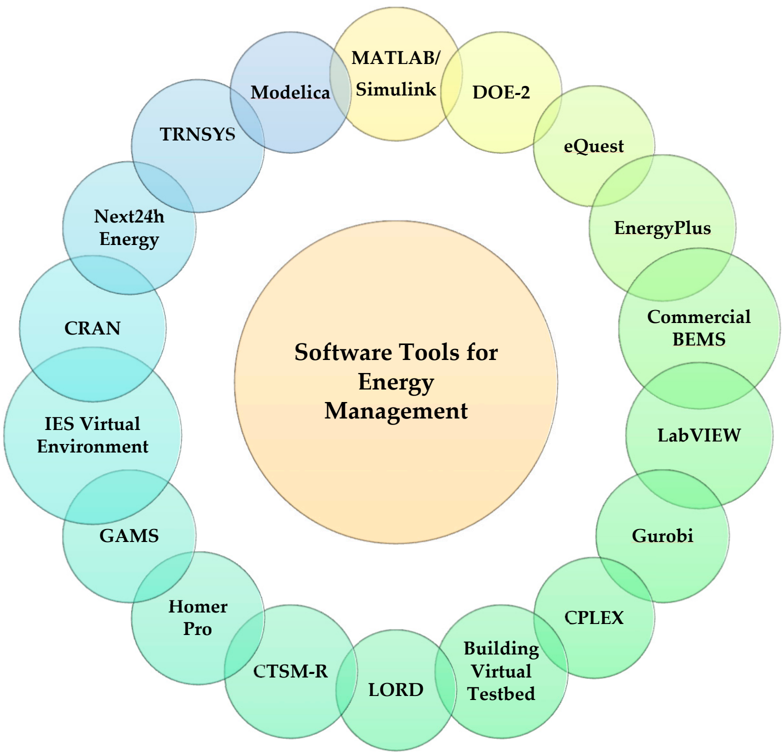

Figure 7. Software tools commonly used for energy management.

Machine learning concentrates on developing algorithms that enable any controller to evolve its behavior using empirical data, gathered from sensors and PMUs [143–146]. O'Neill et al. [105] calculated the influence of decisions of consumers and energy prices on cost using online learning applications to control domestic energy use. Fang et al. [114] analyzed renewable energy use in a microgrid in islanded mode by applying online machine learning. Game theory [147] is a brilliant tool for SG management. All users cannot be cooperative. Game theory helps to develop schemes to tackle these cases. For example, Ibars et al. [102] developed a network congestion game-based distributed solutions to obtain a local optimum for every self-centered customer. This solution is also a global optimum. In [104], the authors calculated the global optimum by using pricing tariffs at the Nash equilibrium. The oligopolistic power market having microgrids [100] can be modelled by game theory. Auction [148] can play an important role in the SG. Microgrids and DGs will be used extensively in SGs. Microgrid customers create their small market to trade energy; therefore, auction and bidding will play an effective role. In [149], a demand reduction bidding method is proposed.

6. Smart Electrical Power Protection System

This system should be able to protect the grid against faults due to human error, equipment failure, and natural disasters. It should also safeguard against cyber-attacks. A smart protection system is the lifeline of the power system [150].

6.1. Smart Failure Protection

The system's ability to perform desired functionalities while satisfying a set of conditions is reliability. Reliability depends on many factors, such as information gathering from field devices, routing them to controllers, routing the control directives back to switches and adopting standard equipment maintenance procedures [151]. The total revenue loss due to the outage was $79B in 2002 in the US, whereas the total revenue of electricity was $249B [152]. During 2003, the East Coast blackout in the America–Canada joint power system affected 50 million people for many days [153]. A review of cascaded failure analysis in the energy network is presented in [154].

6.2. Smart System Reliability

DGs will be heavily used in SGs. The use of some renewables may reduce the grid stability [155–157]. Therefore, controllers and interfaces of new architectures and designs are essential to improve stability. When solar energy is added, the cumulative inertia of the power system reduces, thereby reducing both steady-state and dynamic stability. Chen et al. [156] suggested the benefit of using distributed RERs in mitigating cascade failures in SG. Intuitively, due to the presence of microgrids, less power flows from the macro-grid, thereby increasing grid reliability and stability. They concluded that the introduction of a small number of DGs can decrease the possibilities of cascaded failure. Moslehi and Kumar [152] proved that a proper SG resource mix gives a smoother load that improves reliability.

The stability and reliability also depend on measurement and control devices, such as sensors, PMUs, governors, exciters, power system stabilizers, relays and circuit breakers, etc. [158–160]. Today, PMU-based wide area measurement systems (WAMSs) [161] are becoming increasingly popular. State enumeration techniques and Markov modelling are combined to evaluate reliability [162]. Bou Ghosn et al. [163] used an incremental scheme and developed a simulator in which the system can be designed in a scalable way to emulate the grid behavior. Godfrey et al. [164] developed a model to study the effects of communication failure on the power system.

Prediction of failures and remedial measures (prevention) holds a key place in grid stability. If failure occurs, then its identification, diagnosis and recovery are important [151]. The weak aspects of the system should be identified to predict the faults and necessary steps should be taken to prevent them. Chertkov et al. [165] proposed a method that identifies the weak node, thus helping in predicting fault. Vaiman et al. [166] used data gathered from PMU for computation of the stability region and operational margin. Wide-area situational awareness (WASA) [167] can be developed by combining sensors, meters, PMUs and communication media for failure prediction.

6.3. Smart Failure Identification

When faults occur, the initial step is to rapidly locate, identify and diagnose the reason and recover the failure to avoid cascaded events [168]. The authors of [169] took advantage of PMU data for fault detection. Tate and Overbye [170] proposed an algorithm that used network topology and PMU angle measurements to detect line outage. In [170], the authors developed a method for double line outage detection. This method uses re-outage topology and PMU angle measurements. Zhu and Abur [169] proved that the limitation of conventional data can be overcome by PMU data. Other research on outage detection and diagnosis includes [171–174]. Cai et al. [171] proposed algorithms used to trace out the information from large data. He and Zhang [174] used a probability-based graphical method to model the PMU data. Calderaro et al. [172] proposed a Petri net to model the distribution system and identify outage. Russell and Benner [173] showed the way to detect the incipient faults from waveforms.

During faults, the power grid can be segmented into islands to protect it from blackout [175]. These islands can be stabilized and re-synchronized back later. By appropriately controlling the system configuration and impact of disturbance, the system efficiency can be enhanced [176]. Smart meters may fail when either some bad data is injected into it, or the meter is tempered. Chen et al. [177] proposed a B-spline smoothing and kernel smoothing method to cleanse corrupted data. Overman and Sackman [178] proposed that distributed intelligence (control) is better rather than central. This helps in enhancing system reliability.

6.4. Security and Privacy of Information

Digitalization of power grid at all levels originate big data. Security and privacy of this data is of utmost importance for reliable and secure operation of the SG. If data are not secured, the complete system could be hijacked. In [179], the authors discussed the background of communication infrastructures, their main features, challenges and needs. Among various challenges, secure information is categorized as one the major challenges. Yan et al. summarized the cybersecurity needs and threats in SG communication [180]. The authors suggest that securing the SG requires the use of state-of-the-art protocols. Authenticity and protection of data needs to be maintained at all levels. A survey of various issues related to cyber security and their probable solutions in smart transmission systems are presented in [35].

7. Conclusions

The SG is the modern power system that facilitates both utilities and the end user in a secured way. In this paper, various aspects of SGs are reviewed, considering the upcoming challenges and solutions. From a SG development efforts viewpoint, we have learned four lessons. First, the construction projects of a SG should be analyzed well before starting. Second, ongoing projects are led by electric companies. They may not have enough design and deployment experience. However, SG evolution may require more experienced organizations to be involved. Third, the term smart in "smart grid" means that the grid realizes modern management aims and functions. The objectives focused on are load and generation equality, energy efficiency improvement, operation cost reduction, utility maximization, and emission control. This does not mean that experience and research in other sectors, such as consumer electronics and software development, is less important. Fourth, the protection part provides two lessons. The first lesson is to study the behavior of energy utility and should not underestimate security and privacy. The second lesson is that we should assess the possible risks of the introduction of new technologies. In short, SG will lead to an environmentally friendly electric network, an improved energy supply service capable of revolutionizing our everyday life.

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