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An Extensive Review of Smart Grid Technology: Enhancing Energy Efficiency and Reliability

*H.M.D.M Herath, Dr. N. A. Weerasekara, K.L.D.P. Perera.

*Department of Civil and Environmental Technology, Faculty of Technology, University of Sri Jayewardenepura, Sri Lanka,
Faculty of Engineering, University of Peradeniya, Sri Lanka,
*deshanh56@gmail.com

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Abstract—This research article investigates the improvements and components of smart grid technologies designed to improve energy efficiency and operational reliability. The debate covers important topics such as Energy Management Systems (EMS) for optimizing energy production and consumption, Distribution Automation technologies for enhancing grid dependability, and Advanced Metering Infrastructure (AMI) for real-time data exchange. The study also discusses recent breakthroughs in Grid Modernization, innovative energy storage options, and the integration of renewable energy sources. The evaluation addresses difficulties such as cybersecurity risks, interoperability issues, and economic impediments, as well as initiatives such as Demand Response Programs and Real-Time Monitoring to improve grid performance. Case studies of successful smart grid installations offer practical insights, while future developments in artificial intelligence, blockchain, and next-generation technologies are examined for their potential to expand smart grid capabilities.

Index Terms—Smart Grid, Advanced Metering Infrastructure, Energy Management Systems, Renewable Energy Integration, Cybersecurity

1. Introduction

Development, living conditions, and technological development have raised energy consumption. This raises the usage of power to levels that may be unmanageable if neglected. This is a concerning condition not just for global environmental preservation but also for the supply of sustainable energy. Cities account for around 75–80% of overall energy use, therefore 80% of greenhouse gas emissions [1],[2]. Long days are being spent using a conventional, centrally regulated system for the delivery of electrical energy. Most people call this electricity grid. Globally, electric networks share similar structure, dynamics, and principles despite technological improvement since the usage of electricity. Focused on only few of the fundamental purposes of generation, distribution, and regulation of energy, these conventional power grids [3] Present structure of the electrical grid is unstable, has large transmission losses, low power quality, prone to brownouts and blackouts, delivering insufficient electricity, discouraging the integration of distributed energy sources. Real time control and monitoring are lacking in conventional non-smart technologies provide a difficult problem for smart grids trying to be a real-time fix.

Dealing with these problems calls for a whole revamp of the power supply system. Apart from the motivating power for the implementation of the "smart grid" idea, environmental factors also have advantages. Dependency on renewable resources and effective energy consumption will also assist to lower human carbon footprint. Smart Grid technologies offer a means of effective transmission and distribution of electric power as well as a solution for improved development of this resource. Its adaptability makes installation simpler and calls less area than those of conventional grids. Aimed for grid observability, establish controllability of assets, improve performance and security of power system and especially the economic aspects of operations, maintenance, and planning [4] is the concept of Smart Grid design. Thus, it is also under consideration that smart grid technology may be applied at the micro-grid level, which finally connects to all other micro-grids to create a sizable Smart Grid network. These smart grids have great promise and might be a dependability of electricity transmission and distribution solution in underdeveloped nations without infrastructure. While generation of energy has 40% of the carbon dioxide releasing share in the US just 20% of total carbon dioxide is emitted by transportation. This is so because of the growing demand for power. By effectively distributing electric power, smart grids which eventually help to lower greenhouse gases and pollutants like NO_x and SO_x have been under consideration as a major role to solve this problem [5]. It will also enable the client to project its demand and the greatest possible energy economy. Fig. 1 shows a snapshot of the deliverance of the Smart Grid.

Research on smart grids has a lengthy background beginning with the initial idea introduction in 1997.

This review paper will address the advances and components of smart grid technologies required to increase energy efficiency and alleviate operational challenges. Important areas include Energy Management Systems (EMS) maximizing energy output and consumption, Distribution Automaton technologies improving grid reliability, and Advanced Metering Infrastructure (AMI) permitting real-time data sharing will be discussed. Furthermore, emphasized in the paper will be technological developments in Grid Modernization, including creative energy storage technologies and renewable energy sources integration. While addressing obstacles including cybersecurity dangers, interoperability problems, and economic constraints, it will also go into tactics such Demand Response Programs and Real-Time Monitoring for enhancing grid efficiency. Case studies from effective smart grid installations globally will offer pragmatic insights; the paper will close with a view of future developments in artificial intelligence, blockchain, and next-generation technologies reshining the future of smart grid.

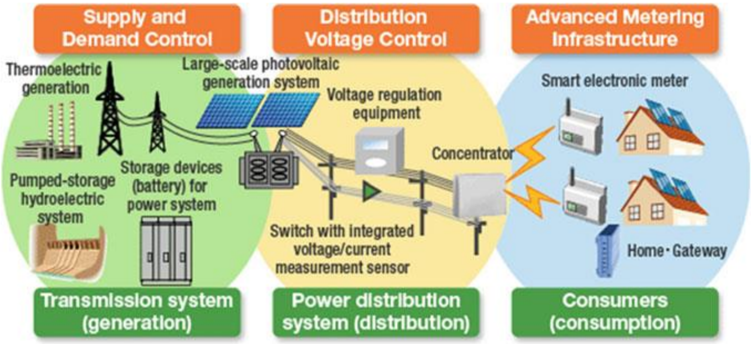


Fig. 1. The Smart Grid [6].

2. Evolution of Smart Grid

The current power system is the result of fast urbanization and the previous century's infrastructural advances all throughout the world. Although they operate in many different countries, the utility corporations have usually embraced the same technology. Nevertheless, geographical, political, and financial aspects particular to every utility business have shaped the development of the electrical power system [7]. Notwithstanding these variations, the fundamental topology of the current electrical power system has stayed the same. The power sector has molded varied degrees of automation, development, and change in every stage since its origin by clearly separating its generating, transmission, and distribution subsystems.

Fig. 2 shows the current energy grid as a strictly hierarchical structure in which power plants at the top of the chain guarantee power supply to loads at the bottom of the chain. The system is basically a one-way conduct whereby the source lacks real-time knowledge regarding the terminating point service characteristics. The grid is thus over-engineered to resist maximum expected peak demand throughout its combined load. And the system is naturally ineffective since this peak demand is rare. Furthermore, reducing system stability is an unusual increase in demand for electrical power combined with slow improvements in the infrastructure supporting it [8].

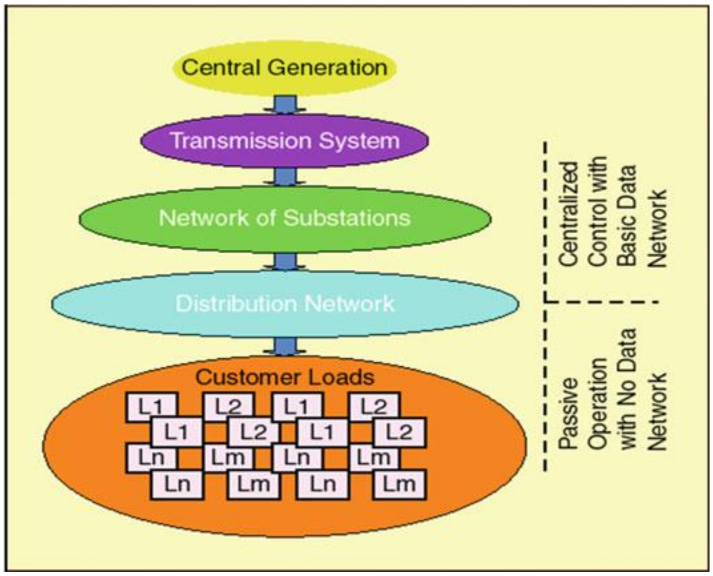


Fig. 2. The existing grid [7].

The shift towards the Smart Grid must begin at the bottom of the chain, in the distribution system as about 90% of all power outages and disruptions originate in the distribution network. Furthermore, accelerating the need to modernize the distribution network by introducing technologies capable of demand-side management and revenue protection is the fast increase in the cost of fossil fuels combined with the inability of utility companies to increase their generating capacity in line with the growing demand for electricity. The most recent infrastructure expenditures have been directed on the metering side of the distribution system, as Fig. 3 demonstrates. Automated meter reading (AMR) devices were first included into the distribution network of earlier efforts in this field. Remotely, AMR enables utilities to access consumer status, alerts, and consumption information from their sites. Fig. 4 shows, even if AMR technology first seems appealing, utility firms have come to see that demand-side management is the main problem it fails to solve. AMR's one-way communication mechanism limits its functionality to reading meter data [8].

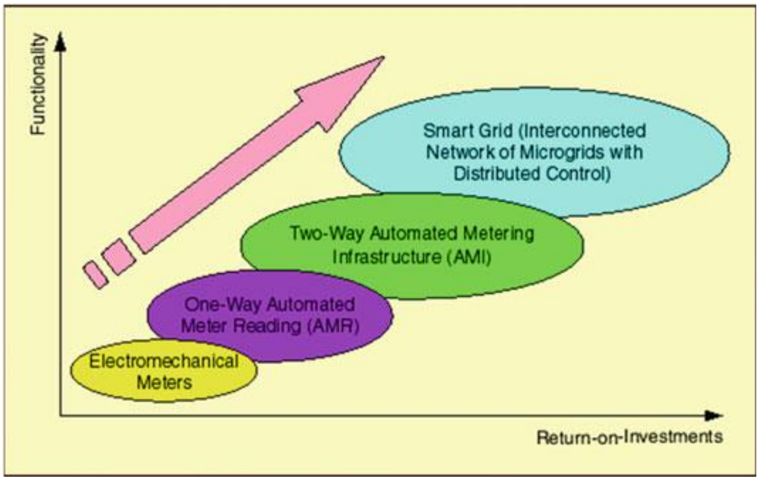


Fig. 3. The evolution of the Smart Grid [7].

It prevents utilities from acting in corrections depending on data gathered from the meters. Starting differently, AMR systems prevent the shift to the Smart Grid, in which case ubiquitous control at all levels is a fundamental concept. As such, AMR technology was fleeting.

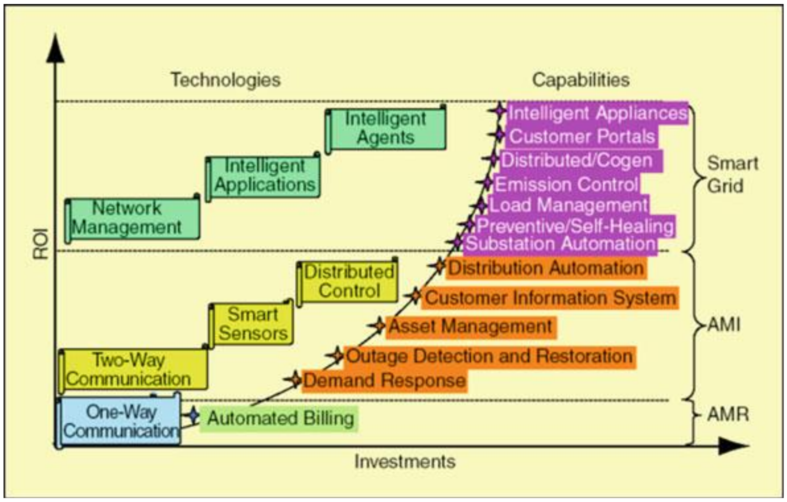


Fig. 4. Smart grids pay back on investments.[7]

Utilities all overturned towards advanced metering infrastructure (AMI), instead of investing in AMR. Along with the flexibility to change consumers' service-level criteria, AMI gives utilities a two-way communication channel to the meter. Utilities can satisfy their fundamental load management and revenue protection aims by using AMI. Apart from providing instantaneous information on individual and aggregated demand, they may also set specific consumption caps and use other revenue strategies to help to control their expenses. The rise of AMI signaled a coordinated effort by interested parties to hone the often-shifting ideas around the Smart Grid [8].

3. Smart grid components

Smart changes to the power system's generating level will include improved stability and dependability, intelligent controls, and a focus on renewable resources.

3.1. Monitoring and Control Technology Component

Conventional power systems transmit electricity from the power plants via the transmission and distribution networks to final customers. Transmission and distribution networks are built to provide electricity at the consumer side at a predefined voltage level. Usually, solar power generation is connected to the distribution level of the power system. Consequently, it is conceivable for the power generated by the PV to create a "counter" power flow from the consumer side to be transmitted to other customers via the distribution system. Two difficulties may develop from this phenomenon: voltage fluctuation across the system arising from intermittency of the PV production [9] and an increase in the voltage in regions with high PV output. Smart intelligent networks, self-monitoring and self-healing, and the flexibility and predictability of generation and demand robust enough to handle congestion, instability, and reliability concerns describe intelligent transmission systems.

This new robust grid must tolerate shock (durability and dependability) and be trustworthy to enable real-time changes in consumption. Consideration of these challenges leads to the development of voltage control systems comprising optimal power flow calculation software. These systems have been created to swiftly assess power flow to project the voltage profile on the distribution network, and occasionally they integrate control voltage regulating devices to ensure the right voltage. Through optimum power flow computation, one creates the ideal control signal. Fig. 5 outlines the system for distribution and automation employed by electrical power suppliers.

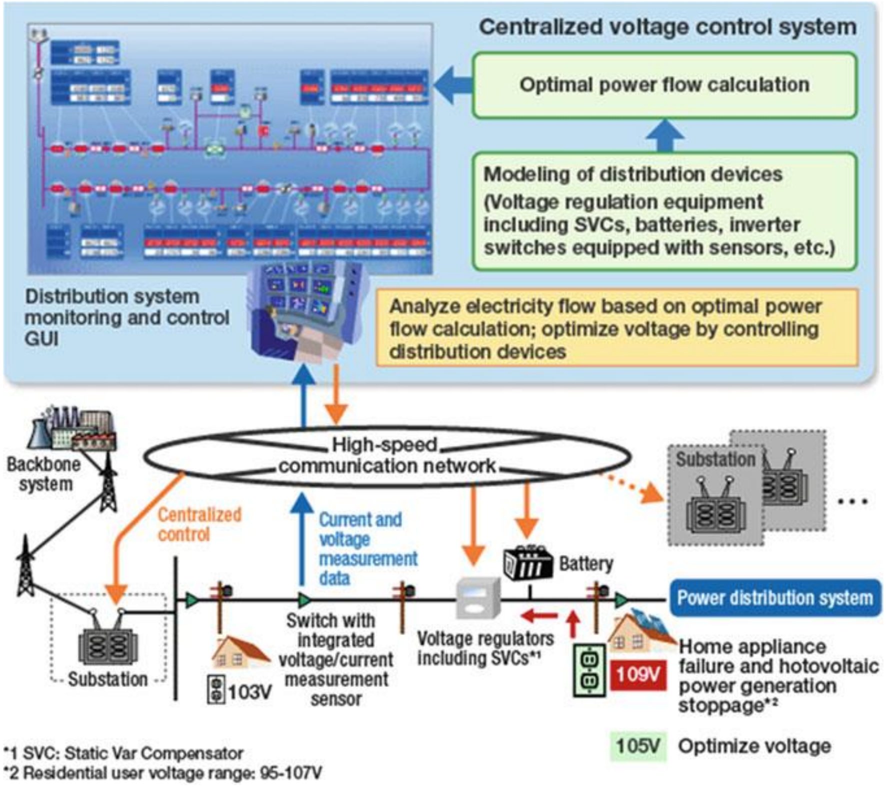


Fig. 5. Automaton system for electrical power companies' distribution [6].

3.2. Transmission Subsystem Component

An integrated power system relies on its transmission infrastructure to connect key substations and load centers. Transmission lines must withstand dynamic variations in load and emergencies without service disruptions. The transmission subsystem uses real-time monitoring, including PMU, state estimators, sensors, and communication technologies, to provide smart transmission capability. To improve Smart Grid performance at the transmission level, strategies include designing analytical tools and advanced technology with intelligence for performance analysis, such as dynamic optimal power flow, robust state estimation, real-time stability assessment, and reliability and market simulation tools [9].

3.3. Components of Smart Devices Interface

The generating components' real-time information processes include smart monitoring and control devices. These resources should be smoothly incorporated into centrally distributed and district energy systems. Smart devices require both physical and logical models. Such a model must define what a smart device brings to a smart Space in terms of environmental services. There are two models: Home Plug and Play (HPnP), which is slightly outdated but still usable, and Universal Plug and Play (UPnP), which is an open standards body. These standards bodies model devices based on the services they provide and provide interaction models for device communication. WSDL is an emerging standard for abstractly specifying services. In addition to defining a smart device's services, it's important to depict changes in its state and how it responds inside a smart environment. The model should include interactions between smart devices, changes in their functioning, and smart services inside the smart area. Various models exist now that use similar methodologies to model devices [13].

3.4. Smart Grid Distribution Subsystem Component

The distribution system is the final step in the transmission of power to end customers. Intelligent support schemes at the distribution level will monitor automation through smart meters, communication linkages between customers and utility control, energy management components, and AMI (9). The automation function will include self-learning modules for defect detection, voltage optimization, load transfer, automatic invoicing, restoration, feeder reconfiguration, and real-time pricing. Electrical providers are developing advanced meter infrastructure (AMI) to enhance customer service and lower meter reading expenses. The smart meter is a crucial component of this AMI. A smart meter detects power use and can interact with a central hub. Creating a reliable and cost-effective communication network between meters and centers is a significant task. Next-generation wireless mesh networks need the development of AMI technologies and systems for reliable and flexible measurement and management of electricity meters [9].

Wireless mesh networks use a multi-hop network to transmit data between electrical meters. This network helps cut data acquisition time and expenses. Wireless mesh networks provide economic savings, but actual deployment requires overcoming difficulties. Simultaneous data transfer across meters at the same frequency might result in signal collision, prohibiting accurate data collecting. Fig. 6 shows the current advanced metering infrastructure utilized by electrical power providers.

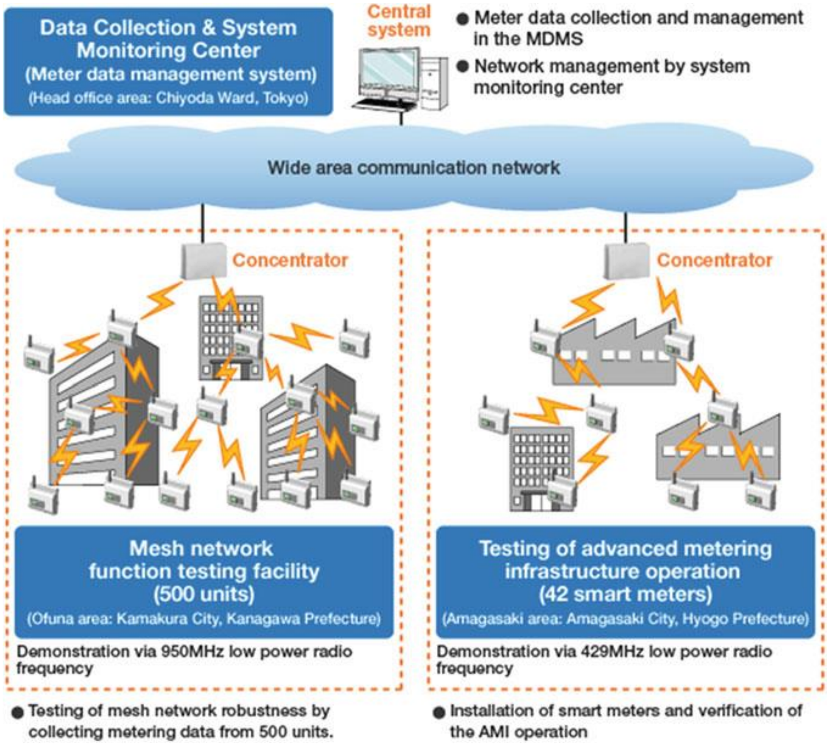


Fig. 6. Advanced Metering Infrastructure for Electrical Utilities [6].

3.5. Energy Storage Component

To account for the unpredictable nature of renewable energy and the gap between peak supply and peak use, it's crucial to discover ways to store generated energy for future use. To develop a Smart Grid component at the generation level, market mechanisms for renewable energy, distributed generation, environmental effect, and pollution must be considered. Energy storage technologies include pumped hydro, advanced batteries, flow batteries, compressed air, superconducting magnetic energy storage, supercapacitors, and flywheels [9].

3.6. Demand-side Management Component

The development of demand-side management (DSM) and energy efficiency alternatives aims to reduce operational costs from costly generators and defer capacity increase [9]. DSM solutions minimise emissions from fuel production, lower prices, and help to the dependability of generating. These choices affect the total utility load curve. Electrical power companies are required to maintain a consistent frequency. Adjust output levels using thermoelectric and pumped storage generation to balance demand and supply instantly. Increased solar power output may cause significant fluctuations in supply power owing to weather conditions. Imbalanced demand and supply can create system frequency fluctuations, significantly impacting user appliances and perhaps leading to power outages [9].

To address this challenge, optimum demand-supply control solutions are needed to manage not just traditional generators but also batteries and other storage devices. Fig.7 shows a sophisticated demand and supply planning and management system for electric power firms and transmission system operators.

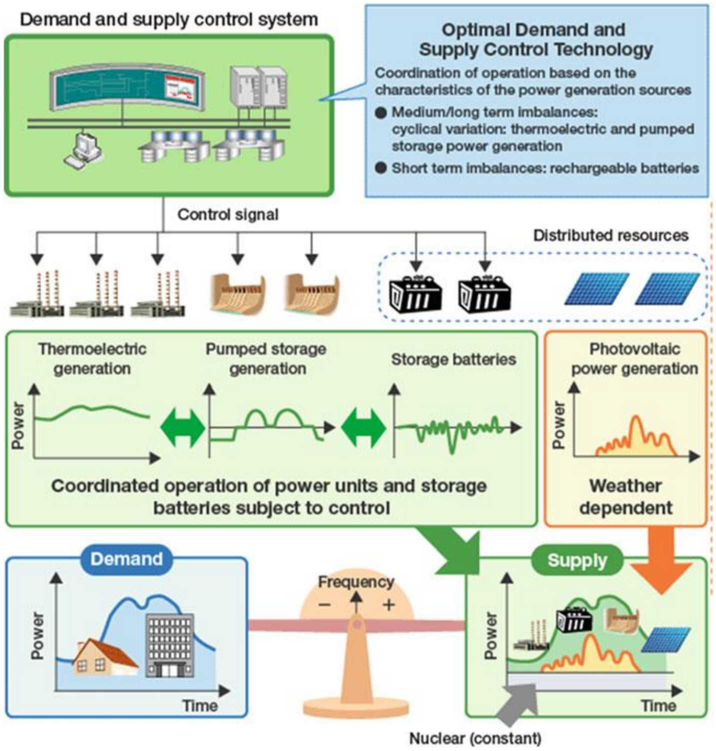


Fig.7. A demand and supply planning and management system for electric power providers and transmission system operators [6].

4. Features and Advancements in Smart Grid Technologies

Smart Grid is a new energy transportation system that combines innovative features and new technology, replacing traditional power frameworks [10]. The National Institute of Standards and Technology (NIST) which is a non-regulatory agency of the United States Department of Commerce's Smart System division is divided into seven zones as shown in Fig. 8, with focuses on assisting with help administration, changing establishments, documenting best practices, and achieving a higher assembly of interconnected frameworks and parts, including the smart grid framework [11],[12].

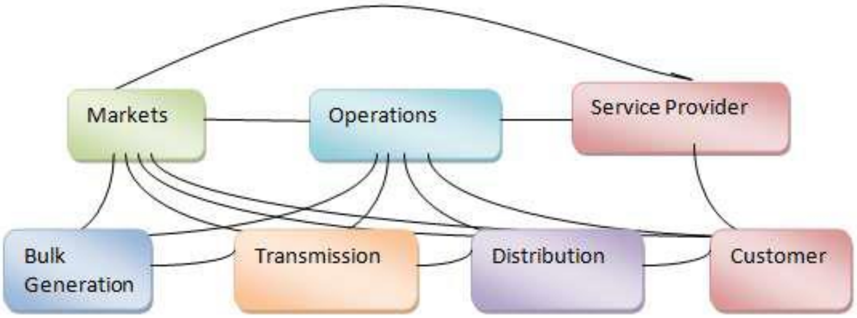


Fig. 8. NIST Smart grid consists of secure correspondence and electricity streams in seven smart grid zones [11],[12].

NETL(The National Energy Technology Laboratory (NETL) is a research and development facility operated by the United States Department of Energy (DOE)) has adopted eight mechanical solutions to improve power quality, economy, efficiency, condition, security, and security, as indicated below[13]:

- Advanced metering infrastructure (AMI)
- Consumer Side coordination (CSC)
- Electric vehicle charging systems (EV)
- Transmission line improvement appliance
- Distributed management side (DMS)
- Combination Renewable energy
- Information and communication technology (ICT)
- Wide-area monitoring and control.

Fig. 9 depicts several technological components put in the electrical system of Generation near customers. To meet consumer demand, the virtual energy sector is expanding to offer more options [14].

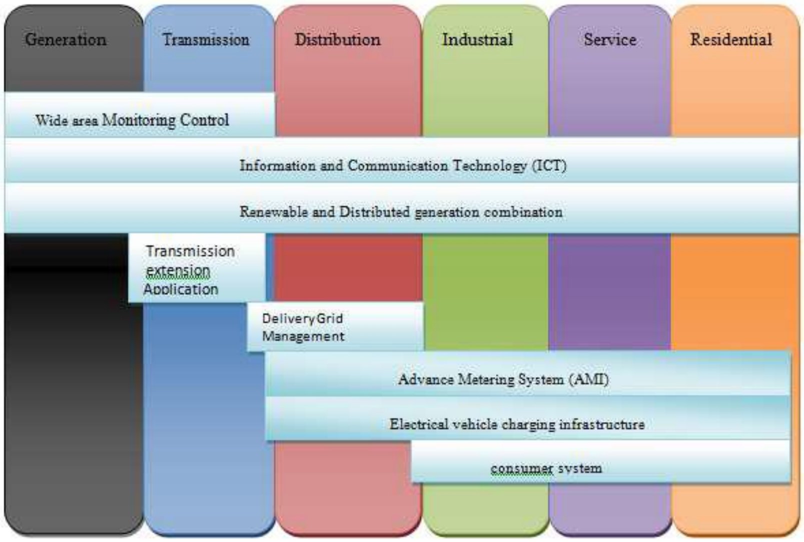


Fig. 9. Smart grid technology implementation in power systems[14] .

4.1. Advanced Metering Infrastructure (AMI)

AMI's two-way communication control provides customers and public services with real-time cost and energy consumption data. AMI identifies energy losses and the location of electrical theft. AMI offers customers data, decision-making tools, and a range of solutions that benefit them [15],[16].

Technology can increase public service operations and support the development of AMI data management for better customer monitoring. AMI connects networks, consumers, generation, and storage resources by integrating technologies like intelligent evaluation, starting zone systems, coordinated exchanges, data management applications, and institutionalized programming interfaces. Fig. 10 illustrates the impact of AMI on residential, commercial, and industrial progress [17].

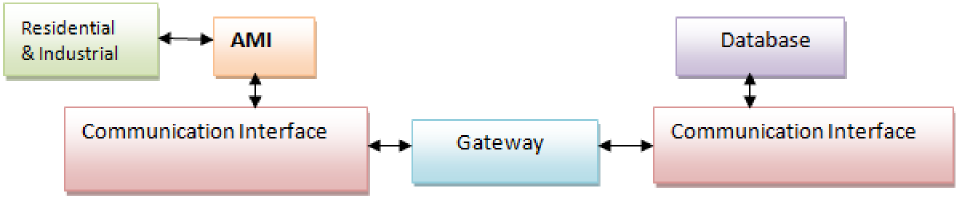


Fig. 10. The AMI Interface [17].

The implementation of AMI has communication risks, which can harm the national economy, general security, government conviction, public protection, and environmental reliability [18]. If there is a dispute between drivers and public services, and private customer rates have increased, the risk to the economy and trust in the administration may rise from low to high. To achieve intelligent network security goals, it's important to define system security prerequisites [19].

4.2. Consumer Side coordination (CSC)

Consumer-side coordination is being upgraded to monitor electrical power use at the user level, including industrial, tertiary, and residential sectors. Four points of view are committed to consumer-side cooperation [20],[21].

- Energy Management Systems.
- Energy Storage Devices
- Intelligent Electronic Devices.
- Distributed Generations.

Home monitoring using control cards, smart devices, and cargo storage can improve energy efficiency and reduce peak demand [22]. According to the research, clients reduce their energy use due to power grid needs, economic incentives from a discount market, or high retail sales rates. Energy management techniques, including manual consumer reactions, programmed devices, and internal controllers, are typically controlled by a utility program or system supervisor [23].

4.3. Electric Car Charging

The electric vehicle's loading frame can handle the charging requirement. Electric automobiles have four different charging functions. These are ideal for car storage, grid vehicles, and vehicle storage [24]. Cars can serve as versatile storage pieces by considering interest and dynamic value. Currently, the system is experiencing high demand due to fully charged electric automobiles. This has resulted in huge pressures on home storage devices to support domestic energy operations [25]. During peak demand and power outages, home storage devices charge electric vehicles on a regular basis for utility purposes. Electric automobiles can be charged by the electricity network during periods of low power demand and energy expenditure [26].

4.4. Transmission line improvement appliance

Transmission technologies aim to increase control, exchange, and reduce energy loss. Three important applications have surfaced here [27],[28]:

- Flexible AC Transmission Systems (FACTS)
- High voltage DC systems (HVDC)
- High-temperature superconductors (HTS)

4.5. Communication and Data exchange Technologies use in Smart grid

Successful implementation of SG(smart grid) requires effective communication between substation domains and sub-domains over various networks, including private and public, cable and wireless [29].This section outlines the communication infrastructure required for the inherent SG property, which is crucial for interoperability between equipment. Updating communication techniques and SG equipment requires preserving interoperability to meet future energy demands. Interoperability allows SGs to interact and develop quickly, cost-effectively, and with flexibility for all components.

Wireless communications provide greater flexibility for information collection, transmission, and processing compared to traditional telecommunications infrastructure. Various communication systems have been proposed, including ZigBee, Wireless Mesh, and Power Line Communication (PLC). ZigBee is a short-range wireless communication used in home area networks [30], while wireless mesh networks connect multiple devices as nodes in a larger network [31],and PLC is a low-cost wireline communication technique [32]. Here are some novel communication methods that have not yet been fully explored. Fig. 11 illustrates the different communication layers in SG.

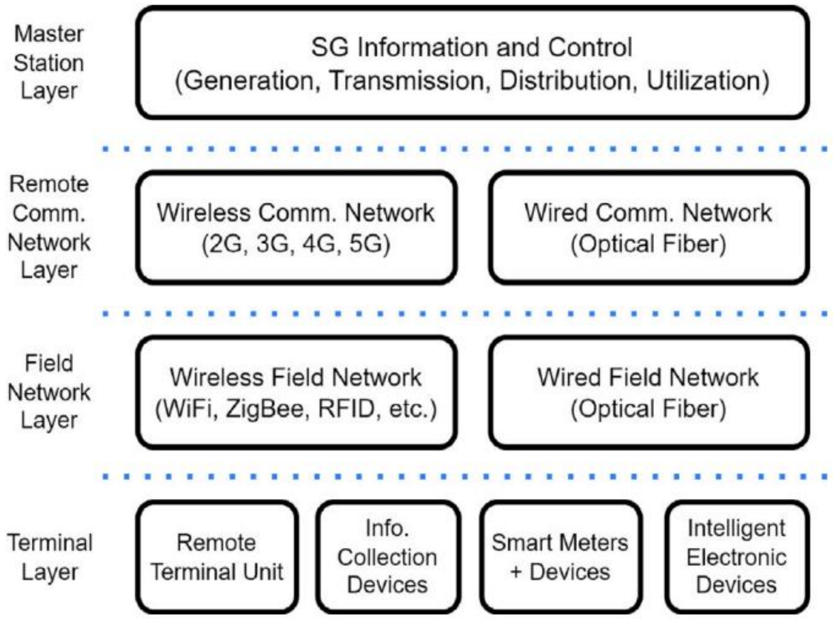


Fig. 11. SG communication layers [33].

4.5.1. Wireless sensor network (WSN)

Wireless sensor networks (WSNs) can create a stable power grid with self-healing capabilities, which is crucial for the adoption of smart grids [34]. WSN improvements now allow for embedded electric utility monitoring systems [35],[36] suggest that the SG could be used for fault sensing, remote monitoring, and WAMR. WSNs offer flexibility, rapid development, and low cost, making them suitable for application across the SG network [34].

4.5.2. SG Interoperability Platform (SGIP)

Kim et al. (2017a) [37] propose a novel SGIP communication approach that addresses interoperability difficulties by controlling data and communication, allowing for data-centric communication in SG. Implementing a single semantic model ensures data-driven interoperability by allowing systems to interact in the same language [37]. The SGIP design addresses multiple requirements, such as publish-subscribe and client-server communication, data object reconstruction, and adjustable QoS features for reliable communication [37]. NIST has established an SG interoperability panel (SGIP) to promote interoperability across smart sensors [38].

4.5.3. ZigBee

Zigbee wireless communication is notable for its low power consumption [39]. The IEEE 802.15.4-based specification is extensively used for high-level communication protocols for creating personal networks. Zigbee's design comprises of six layers: Application, Application Interface, Security, Network, Medium Access Control, and Physical [40]. Zigbee's widespread use in home automation, medical data collection, industrial control systems, meter reading, and light control systems makes it an ideal candidate for smart grid communication value addition. Energy profiling is a key feature of this communication standard, making it ideal for home systems worldwide [39].

Zigbee channel access is dynamic, utilizing both the Content-Based Method (Carrier-Sense Multiple Access with Collision Avoidance Mechanism) and the Content-Free Method (the coordinator assigns a specific time slot to each device (Guaranteed Time Slot (GTS)). ZigBee technology, together with other wireless and cable communication technologies, can help control peak and non-peak electricity demand on grids. Zigbee-integrated devices, such as smart meters, may communicate and control other devices that use the same technology. Zigbee has a range of 30-50 m and operates on the 2.4-915 MHz frequency. Despite its short range and low data rate, it can transfer up to 250 Kbps. It enables utilities to send and receive messages, making it an ideal option for smart grids [41].

4.5.4. Wireless Mesh

Wireless mesh is one of the fundamentals for developing smart grid infrastructures. It is safe and reliable for energy distribution networks [42]. Wireless mesh networks (WMNs) connect network infrastructures via wireless access points. WMN's unique feature is its decentralization and ability to send messages only to the next node, rather than the complete network from the start. Messages are routed via the network in an algorithmic order.

An effective and efficient technique. This could be automated with appropriate algorithms. Wireless mesh is a great complement to electricity utilities, particularly when processing output data. WMN improves efficiency and services and attracts more users to smart grid infrastructures by passing through mesh nodes, clients, and gateways. Signal attenuation can occur during wireless transmission, unlike conventional transmission when interference is minimal. In a smart grid system, information should flow from sensors and electrical appliances to smart meters to ensure smooth transmission. Wireless mesh networks can facilitate communication between smart meters and data centers [41]. Wireless mesh technology is beneficial for smart grid connectivity, but adoption can be time-consuming and costly due to the need for highly optimized equipment and limited availability in target locations [43].

Using wireless mesh technologies for smart grid deployment involves several considerations. It isn't a universal method. Smart grid implementation decisions are often influenced by factors like rural/urban, indoor/outdoor, and cabling. Theft is a post-deployment factor for communication technologies in smart grids, particularly for wireless mesh networks [44].Wireless mesh technology allows two ends to function independently as routers. When multiple nodes are present, WMN can look for alternative routes inside the active network in case of node absence. This functionality is useful in smart meter systems. Smart meters often have built-in radio subsystems that allow them to communicate with nearby meters. This WMN technique uses individual meters as network repeaters until data reaches the needed access point via the power grid.

SkyPilot networks and other carriers employ the WMN for smart grids due to its high availability [45]. Asus ZenWiFi AX6600 Tri-Band Mesh, Eero Pro 6E Tri-Band Mesh Wi-Fi 6E System, TP-Link Deco M5 Mesh Wi-Fi System, TP-Link Deco X20 AX1800 Mesh Wi-Fi 6 System, and Eero 6+ Dual-Band Mesh Wi-Fi 6 System are highly available and optimized wireless mesh systems suitable for smart grids [46].

4.5.5. Cellular network communication

Cellular network refers to the spread of transceivers or base transceiver stations throughout land areas. This research identifies Cellular Network Communication (CNC) as a suitable communication technology for smart grid applications, alongside Zigbee and wireless mesh. It includes GSM, GPRS, and 3G, among others. CNC offers high capacity, speed, valuable data, and voice functions [43]. It offers multimedia roaming and supports mobile cellular devices. They are the primary means of communication in sensitive business transactions and mission-critical services, making their use in smart grids highly appropriate. CNC enables flawless communication between wireless nodes [47].

Cellular communication methods, both established and emergent, are ideal for smart-meter communication, particularly for remote nodes. The unique functioning concept of cellular networks makes them ideal for smart grid applications. Clients can connect to PSTN via a non-cabled transmission method. Initially, cellular networks relied on electrical connections between nodes before the addition of switching devices and interconnected entities are described in Fig. 12.

The base station subsystem consists of individual cells with Base Station Transceivers (BST) that operate within the radio spectrum [47]. The cell houses each geographical region and transmits data via radio link. The base station controller (BSC) connects to a group of BSTs and then to a Mobile Switching Centre

(MSC) and PSTN. Smart grids use protocols to ease data transmission across multiple power systems and the overall grid [48]. Protocols manage message transmission between entities, minimizing operational costs without the need for dedicated communication substructures. Smart metering adoption could benefit from high-speed cellular networks (2G/ 3G/ 4G LTE). According to [49], CDMA, WCDMA, and UMTS technologies are employed in smart grid implementation, like Power-line communication (PLC) and other communication technologies that modulate and demodulate data into the power system.

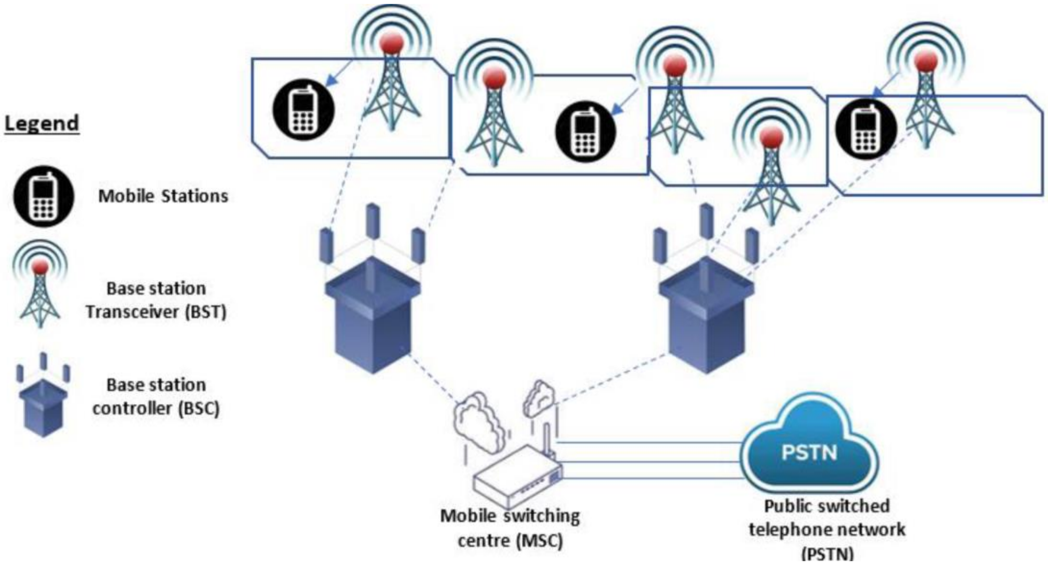


Fig. 12. Cellular system architecture [105].

4.5.6. WiMAX

This technique uses a spectrum to provide a network connection. It boasts fast data rates, enhanced security, ample capacity, and seamless communication [50]. Wireless communication technology is slow to adopt in energy activities due to factors such as poor data rates, interference, availability, and security concerns [51]. There have been several efforts to address wireless technical difficulties, particularly in smart grids. In a new era, [52] suggested a patch antenna with enhanced communication parameters and optimized performance, with a U-shaped design in the 4-4.5GHz frequency region. Using relevant resources, a microstrip antenna substrate with high gain and return loss efficiency was created. This technology has progressed continuously. Broadband and wireless technologies have seen significant advancements. WiMAX, also known as 802.16, enables real-time procedures with standard QoS. WiMAX setup offers great versatility and may be adapted to certain applications and goals. This improves its suitability for smart grids. The product supports both point-to-point and multipoint configurations and is interoperable with other electric products [50].

4.5.7. Bluetooth

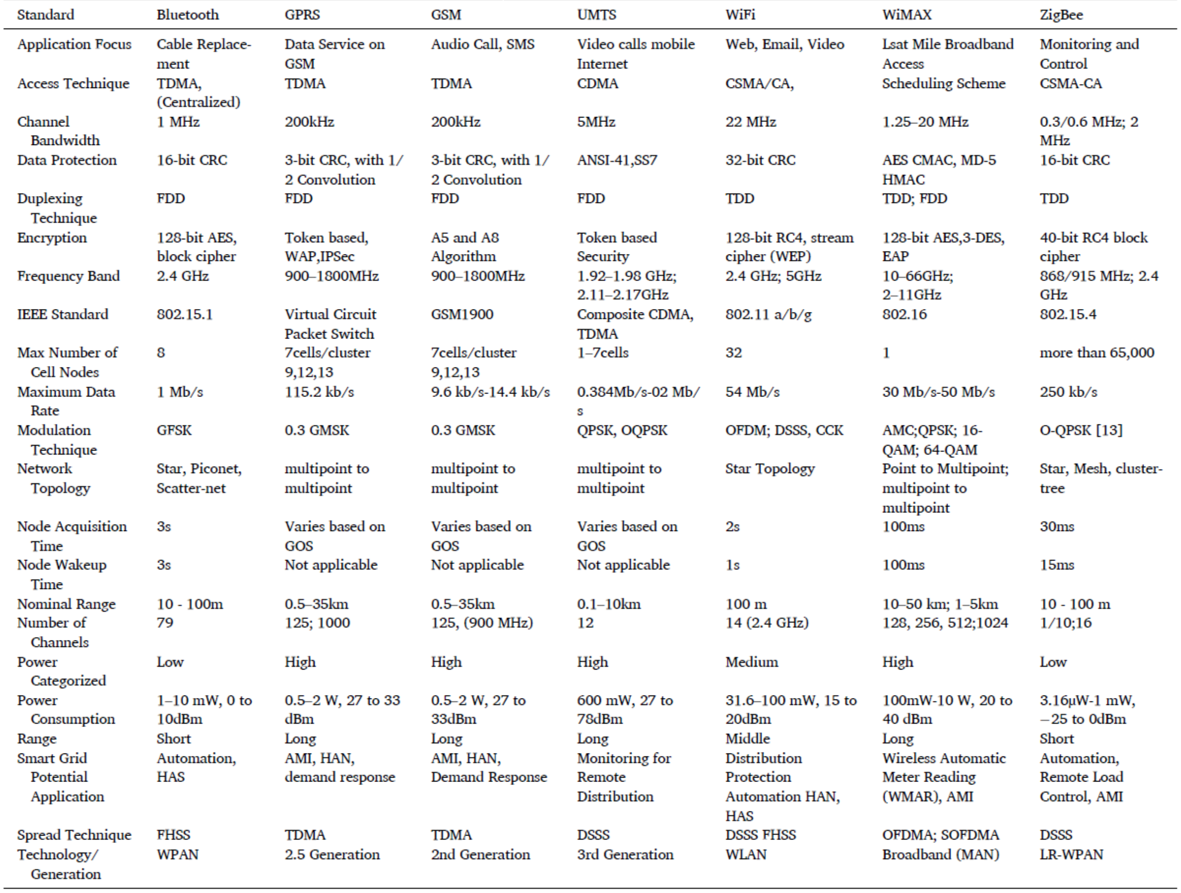
Bluetooth is one of the fastest growing technologies in the market. Bluetooth transmission is effective when parameters and settings are suitably configured. It is compatible with several wireless technologies. This technology automates basic power system functions and substation control by integrating data from various intelligent sources and electronically controlled equipment. Bluetooth technology improves smart grid AMI systems and service contributions. In the future, this technology will integrate solar and wind power into the grid as renewable distributed energy resources (DER).This work highlights the importance of wireless technology in enhancing smart grid applications. Bluetooth is a popular short-distance communication technology that is energy-efficient and easy to monitor [53].

This communication standard is used in the industry for short-distance communication between personal computers, desktops, and mobile devices. It's more energy-efficient and cost-effective than other communication devices. Likely to experience interference from other wireless devices running in the same 2.4 GHz radio band. Although it can only communicate within 30 ft, it plays an important part in smart grid applications due to its small range. They are often used in personal area networks [54].

4.5.8. WLAN

Wireless Local Area Network (WLAN) is an industry standard technology that connects computers and other devices to the internet [55]. This is a modified version of Ethernet technology that works in tandem. It transmits and receives data at rapid speeds via radio waves, eliminating the need for cables. WLAN presents numerous benefits for smart grids [56]. Previously, WLAN was not widely recognized in the energy sector because of worries about security, availability, interference, and data rates. However, these concerns have recently been addressed, particularly for smart grids [57],[58] and [55]. Researchers have improved WLAN technology to compete with other technologies in the power industry for dependability and efficiency, in addition to security. Table 1 provides further information on wireless technologies.

Table 1: Comparison of several wireless communication methods [59],[60].



Standard	Bluetooth	GPRS	GSM	UMTS	WiFi	WiMAX	ZigBee
Application Focus	Cable Replacement	Data Service on GSM	Audio Call, SMS	Video calls mobile Internet	Web, Email, Video	Lsat Mile Broadband Access	Monitoring and Control
Access Technique	TDMA, (Centralized)	TDMA	TDMA	CDMA	CSMA/CA,	Scheduling Scheme	CSMA-CA
Channel Bandwidth	1 MHz	200kHz	200kHz	5MHz	22 MHz	1.25–20 MHz	0.3/0.6 MHz; 2 MHz
Data Protection	16-bit CRC	3-bit CRC, with 1/2 Convolution	3-bit CRC, with 1/2 Convolution	ANSI-41,SS7	32-bit CRC	AES CMAC, MD-5 HMAC	16-bit CRC
Duplexing Technique	FDD	FDD	FDD	FDD	TDD	TDD; FDD	TDD
Encryption	128-bit AES, block cipher	Token based, WAP,IPSec	A5 and A8 Algorithm	Token based Security	128-bit RC4, stream cipher (WEP)	128-bit AES,3-DES, EAP	40-bit RC4 block cipher
Frequency Band	2.4 GHz	900–1800MHz	900–1800MHz	1.92–1.98 GHz; 2.11–2.17GHz	2.4 GHz; 5GHz	10–66GHz; 2–11GHz	868/915 MHz; 2.4 GHz
IEEE Standard	802.15.1	Virtual Circuit Packet Switch	GSM1900	Composite CDMA, TDMA	802.11 a/b/g	802.16	802.15.4
Max Number of Cell Nodes	8	7cells/cluster 9,12,13	7cells/cluster 9,12,13	1–7cells	32	1	more than 65,000
Maximum Data Rate	1 Mb/s	115.2 kb/s	9.6 kb/s-14.4 kb/s	0.384Mb/s-02 Mb/s	54 Mb/s	30 Mb/s-50 Mb/s	250 kb/s
Modulation Technique	GFSK	0.3 GMSK	0.3 GMSK	QPSK, OQPSK	OFDM; DSSS, CCK	AMC;QPSK; 16-QAM; 64-QAM	O-QPSK [13]
Network Topology	Star, Piconet, Scatter-net	multipoint to multipoint	multipoint to multipoint	multipoint to multipoint	Star Topology	Point to Multipoint; multipoint to multipoint	Star, Mesh, cluster-tree
Node Acquisition Time	3s	Varies based on GOS	Varies based on GOS	Varies based on GOS	2s	100ms	30ms
Node Wakeup Time	3s	Not applicable	Not applicable	Not applicable	1s	100ms	15ms
Nominal Range	10 - 100m	0.5–35km	0.5–35km	0.1–10km	100 m	10–50 km; 1–5km	10 - 100 m
Number of Channels	79	125; 1000	125, (900 MHz)	12	14 (2.4 GHz)	128, 256, 512;1024	1/10;16
Power Categorized	Low	High	High	High	Medium	High	Low
Power Consumption	1–10 mW, 0 to 10dBm	0.5–2 W, 27 to 33 dBm	0.5–2 W, 27 to 33dBm	600 mW, 27 to 78dBm	31.6–100 mW, 15 to 20dBm	100mW-10 W, 20 to 40 dBm	3.16μW-1 mW, −25 to 0dBm
Range	Short	Long	Long	Long	Middle	Long	Short
Smart Grid Potential Application	Automation, HAS	AMI, HAN, demand response	AMI, HAN, Demand Response	Monitoring for Remote Distribution	Distribution Protection Automation HAN, HAS	Wireless Automatic Meter Reading (WMAR), AMI	Automation, Remote Load Control, AMI
Spread Technique	FHSS	TDMA	TDMA	DSSS	DSSS FHSS	OFDMA; SOFDMA	DSSS
Technology/ Generation	WPAN	2.5 Generation	2nd Generation	3rd Generation	WLAN	Broadband (MAN)	LR-WPAN

4.5.9. Power line communication

Power line communication PLC technology uses existing power connections to transmit data signals quickly between devices [61]. PLC technology is more cost-effective than wireless technology due to the availability of existing lines [62]. It is the most effective communication mechanism for metering power due to its strong connection with the meter [63].

The PLC communicates data from smart meters to a data concentrator [61]. In the US, PLC was used to power street lighting in New York [64]. This PLC smart metering project has been ranked as the most effective to date [65]. This implementation has been replicated in other PLC smart metering installations globally [68]. In a PLC network, smart meters link to power lines [66],[67] that connect to a data concentrator. Data is then transmitted to the data center via cellular network technology.

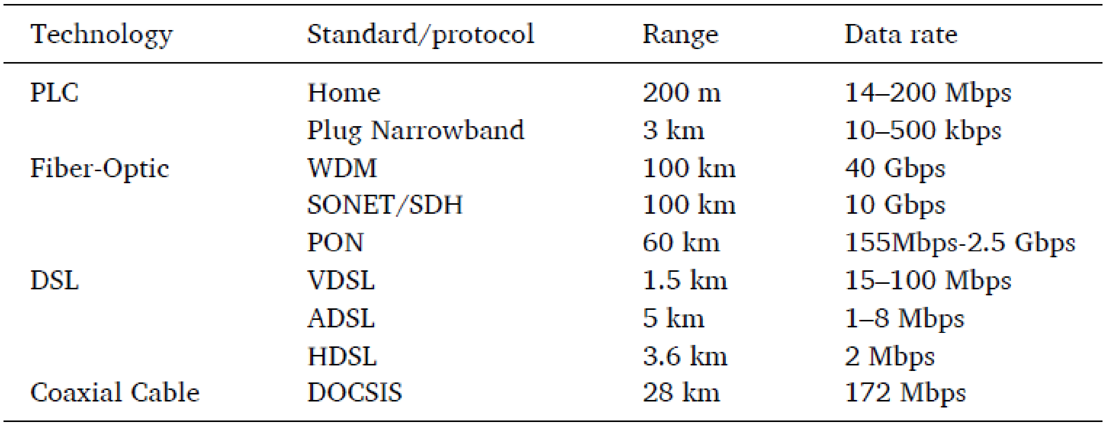
4.5.10. Digital subscriber lines

Digital Subscriber Lines DSL is a high-speed digital data transmission method that uses voice telephone networks. DSL’s existing basic infrastructure helps reduce installation costs. Many companies use DSL technology for smart installations. This technology is being used in several global initiatives for smart grid solutions [68]. The technology involves installing a communication box at the energy consumer's premises and transmitting energy use data to the utility provider via DSL [61]. The distance between the subscriber and the telephone exchange impacts DSL technology [69].

4.5.11. Fiber Optic

Fiber optics has played a crucial role in information transfer for decades. The unique application of this substance has transformed the telecommunications framework. The method uses light waves instead of electricity to prevent interference and signal degradation/noise when transmitting data [70]. This cable medium allows for rapid transmission of large amounts of data across lengthy distances of over 100 kilometers. Installation is simple and includes a moisture-resistant plastic cover. Fiber optics can be multimode or single mode. These cables play significant roles in smart grids, like coaxial and twisted pair cables in the wired communication family [71]. They are also utilized in medicine and operations. Fibers are costly yet offer several benefits across multiple platforms. Table 2 provides information on several wired communication systems.

Table 2: Several wired communication systems [72].



Technology	Standard/protocol	Range	Data rate
PLC	Home	200 m	14–200 Mbps
	Plug Narrowband	3 km	10–500 kbps
Fiber-Optic	WDM	100 km	40 Gbps
	SONET/SDH	100 km	10 Gbps
	PON	60 km	155Mbps-2.5 Gbps
DSL	VDSL	1.5 km	15–100 Mbps
	ADSL	5 km	1–8 Mbps
	HDSL	3.6 km	2 Mbps
Coaxial Cable	DOCSIS	28 km	172 Mbps

5. Challenges and solutions in smart grid technology

As a novel system with a significant amount of innovative autonomous execution, the smart grid faces several obstacles. Internet-connected smart grids, sometimes referred to as Internet of Energy (IoE), are becoming increasingly popular as an innovative method to guarantee the supply of energy from any location and at any time. The primary objective of these improvements is to establish a sustainable and dependable energy society. Nevertheless, the process of incorporating a growing array of diverse elements and addressing issues related to security and transparency may prove to be challenging [73].

5.1. Grid Infrastructure's State Awareness

Because of the vulnerability of the electrical system, data must be available in a fast and reliable manner. Compromises in information availability can have serious ramifications for power supply strategies. Synchro phasor networks gather and transmit measurement data, including voltage, current, frequency, overloads, synchronization losses, and time, via PMUs and PDCs. The communication architecture's centralized nature can lead to a Single Point of Failure (SPoF) issue, as several localized PDCs transmit data to a single trusted control center. This also leads to increased control complexity as the number of components increases. Additionally, the grid's instability is exacerbated by its hierarchical construction, resulting in slow processes. Furthermore, DERs often operate at full capacity, pumping all available electricity into the grid to improve efficiency, without considering the system's status. This can cause erratic voltage behavior on distribution feeders [74].

Regulating DER power output, either by active or reactive power modification, is a typical method for preventing grid instability. Managing power-producing technology can be problematic due to regulatory limits and the need for oversight by a trusted central authority, such as the Distribution System Operator (DSO). Grid equipment failures or malfunctions can have a substantial influence on system stability and safety. Currently, equipment maintenance includes technicians diagnosing and repairing issues in the field, which is time-consuming and wasteful. Some research proposes a trustworthy central node to monitor equipment upgrades and maintenance. However, if this central node is attacked, all data could be lost. New diagnostic and maintenance procedures for smart grids are urgently needed. Inadequate engagement and coordination among stakeholders are a serious concern in modern smart grids. Energy suppliers often analyze state estimation and stability using data from producers and customers. Insufficient information can lead to inaccurate estimations, causing resource distribution issues, poor real-time performance, higher distribution losses, and power outages [73].

5.2. Secure data interchange, aggregation, and privacy

Integrating IoT devices into the power grid may bring concerns, including data mismanagement and cybersecurity threats. The existing SG data management system confronts issues related to data confidentiality, integrity, compliance control, common scope, aggregation, and management efficiency [75]. Confidentiality protects data and user information from unauthorized access, while data integrity ensures accuracy [76]. Specifically, if the data transferred and exchanged between PMU and PDC is hacked, the control center's decision-making process may suffer. Furthermore, smart meters that collect electricity usage statistics and requests may mistakenly leak users' personal information and future activity plans [76]. A criminal could use power demands to predict a user's absence from home and then commit theft. Anonymization is a commonly used method for concealing users' identity. Secure information processing requires a reputable third party to manage consumers' data. Using a pseudonym is a popular method for maintaining user anonymity. Registering a pseudonym often involves complicated encryption procedures. Adversaries can relate a user's pseudonym to sensitive information by analyzing quasi-identifiers like age and gender [76].

Data security compliance requires extensive inspections by numerous departments, resulting in lengthy business operations and inefficient data consumption. This issue also affects the aggregation of large-scale multi-party data from many smart grid domains. Using a hierarchical data management technique with data aggregation leads to longer collecting and processing times, as well as information distortion [73]. Furthermore, dependable central nodes oversee storing energy data on the power grid. However, centralized storage has security problems, such as single-point failures and the risk of malicious data tampering. Creating a secure and dependable decentralized data storage system is critical [75].

5.3. Decentralizing grid management and operation

Decentralization should include not only data storage, but also operation and control. The electrical system was not intended to handle significant energy consumption and load dynamics from electric vehicles. DSOs must rely on adaptive DERs, including flexible loads, controlled generation, and storage, to maintain grid balance. Electric utility suppliers face challenges in providing cost-effective, environmentally friendly, and technologically advanced solutions. As a result, they often modify control settings under different working conditions. DSOs require new energy management structures that encourage collaboration among wholesale market participants and consumers. This collaboration allows for easy integration of smart grid Distribution Management Systems (DMS) and Distributed Energy Resources Management Systems (DERMS), resulting in demand-side flexibility and decentralized operation [77].

Transactive energy combines demand-side management, energy markets, and system operations, enabling decentralization, microgrids, and sustainable energy (source: [78]). The current energy trading market involves manual processing by third-party auditors, including agents, trading agencies, brokers, and banks. This results in high time complexity due to several participants. Research in transactive energy often focuses on aligning wholesale and retail markets through trading models. Retail markets' stagnant pricing for prosumers is driving this trend. However, registration and authentication with a centralized server make it challenging for prosumers to participate in trade activities [73].

5.4. Blockchain as Solution

Blockchain technology holds the potential to transform smart grid applications. The tiers will help categories blockchain-based smart grid systems.

5.4.1. Grid infrastructure status awareness

Blockchain technology synchronies data from several sources and facilitates communication between domains and stakeholders. Blockchain's open ledger allows for improved data availability and dependability in smart grids [79]. Bhattacharjee et al. [80] found that integrating blockchain with a smart grid's synchro phasor network improves the decentralized communication architecture. The relationship between the number of Phasor Measurement Units (PMUs) and the time needed to build a Merkle tree was investigated. Surprisingly, even with 300 PMUs, the time required was approximately 1.5 milliseconds. This proves the viability of the proposed blockchain infrastructure for real-time measurement. The study found a correlation between the number of PMUs and the number of hashes required to create a Merkle tree root hash, indicating lower computation and communication complexity. Furthermore, the cost of hash verification is low, with actual times of 0.0020 and 0.0040 milliseconds for 50 and 300 PMUs respectively. To achieve more effective and secure equipment status monitoring, Zhang and Fan [81] devised a solution that integrates blockchain technology and IoT devices. The blockchain registers diagnostic nodes, which send diagnostic requests to the Ethereum consortium network when power protection devices or electrical terminals fail or behave abnormally. Original vendor and non-original supplier nodes submit bids for diagnosing the node, and the diagnostic smart contract determines the winner. Because of the transparency of blockchain, these interactions may be saved and audited on the Ethereum network. This decentralized technique decreases network congestion and prevents unwanted modification of important data.

In [82], a similar blockchain-based approach was used to localize faults in SGs, particularly those with a high DER penetration and frequent high-impedance faults. According to the research, the blockchain architecture for grid situational awareness typically consists of three major components. 1).The member nodes represent various PMUs, PDCs, generating, and distribution systems. Each node collaborates by sharing relevant data across the communication network. 2).A dispersed peer-to-peer network connecting the member nodes. 3).A distributed, secure, and accurate ledger that records the grid's current state and history. The shared ledger could contain synchro phasor data, measurements for equipment diagnosis, switch statuses, generation and consumption quantities, violations, and timestamps [79],[81]. Section 4.2 provides more information on the consensus processes and authentication approaches used for transaction validation. The Merkel tree-based technique is commonly used for consensus execution as it converges quickly and maintains data integrity [79].

5.4.2. Secure data exchange, aggregation and privacy

Implementing protection architectures like blockchains can improve communication between system control and physical grid infrastructure, reducing cyberattacks like Man-In-The-Middle (MITM) and Denial of Service (DoS) and creating a secure platform [83]. Blockchain technology can help aggregators like Virtual Power Plants (VPP) improve multi-domain data aggregation while maintaining privacy and sustaining stakeholder interactions [84].

Yang and Wang created an IoT-based blockchain to facilitate secure data transmission between users [85]. The consensus mechanism was improved by implementing a leader selection approach and message aggregation utilizing a modified Practical Byzantine Fault Tolerance (PBFT). The leader selection process rotates validators to become the consensus leader, ensuring transactions have rapid finality and preventing single-point failures in classical PBFT. PBFT is more resilient to IoT network outages and message delays due to its asynchronous nature. The leader asks confirmation messages from validators and aggregates them into a single message to reduce communication complexity, maintain network bandwidth, and speed up consensus. Blockchain validation is effective for IoT devices that use less than 50% of their CPU.

Guan et al. [86] demonstrate a blockchain-based architecture for efficient and privacy-preserving aggregation mechanisms. Users are organized into private blockchain groups or neighborhood area networks (NANs) based on their electricity use. Each user may use many pseudonyms to obscure the connection between their genuine identity and pseudonym.

The Key Management Centre (KMC) creates a bloom filter for each group to improve authentication time. Zero-knowledge proofs can establish the authenticity of user pseudonyms. To ensure reliable data aggregation, a user-selected mining node is chosen for each time. This strategy is more computationally efficient than standard authentication systems and other data aggregation methods, according to security evaluations and performance assessments. Blockchain technology has been used in works [87, 84] to increase grid data security, open exchange, and asset management efficiency. Blockchain’s distributed smart contracts provide unified data management across many energy domains, creating a decentralized and autonomous system for data upload, aggregation, and storage. Furthermore, the consensus between DERs and aggregators allows for trusted collaboration [84].

Liang et al. [87] proposes a data security sandbox with homomorphic encryption to prevent data leaking and unauthorized access. Blockchain, being a distributed platform, ensures secure data sharing and facilitates data administration. The authors proposed a three-layered data asset management design. The fundamental resource layer includes the smart grid's systems. The unified data interchange layer enables unified data access and monitoring. The data middle layer serves as a resource convergence point for smart grid stakeholders, processing and aggregating data assets with big data technology. To ensure data privacy and authentication, a data side chain was created, while the directory blockchain shared business processes, rules, and behaviors [87].

5.4.3. Decentralizing grid management and operation

Blockchain technology enables safe, decentralized operations by using participant computer resources [88]. Smart contracts enable secure operational control based on distributed ledger measures, eliminating the need for a trusted third-party operator. Blockchain technology facilitates transparency among stakeholders, enhances real-time performance, optimizes resource management and controls, and improves renewable energy efficiency [89].

Blockchain technology was used in microgrids to decentralize load requests [90]. The authors created an autonomous and distributed power dispatching solution using Ethereum smart contracts. To overcome the processing limits of smart contracts, Luo et al. [90] distributed dispatching operations across two smart contracts and optimized the process through coordination. Implementing distributed power dispatching can significantly reduce generation costs. Blockchain technology is compatible with the distributed control architecture of virtual power plants (VPP), allowing for more efficient power market trading and operation. Li et al. [91] created a virtual power plant control model that integrates two blockchains: one technical and one commercial. The technological blockchain connects the SCADA system to Ethereum, enabling stable power scheduling, transmission, and balancing. The commercial blockchain offers energy pricing, transactions, and contracts. The blockchain methodology accessed 17.6 MW more renewable grid-connected power for the same total power supply compared to the traditional method. Additionally, compared to standard control methods, this strategy reduces both active power loss and generation costs. Danzi et al. [92] advocated using smart contracts to mitigate grid congestion caused by the growth of DERs. The blockchain is utilized to create a smart contract that assures equitable rotation of DER involvement in microgrid regulations. The study found that increasing the number of DERs reduces communication costs in the blockchain-based system by reducing the number of blocks they create during the control period.

Blockchain technology was used to implement incentive systems for prosumers to share energy with the grid. The peers that contribute the most are rewarded with virtual currency. This is accomplished by tracking transaction history from blockchain ledgers. Smart contracts can be used to define linked rewards or penalties, as well as regulations for demand response (DR) programs. Blockchain technology enables secure and automated bids, discussions, and payment processes without requiring human interaction [93]. Furthermore, a secure, blockchain-based credit system allows consumers to acquire the local energy required without having actual possession of virtual cash at the time. In [94], supervisory nodes administer the credit-based mechanism, which evaluates each node's request for credit token release.

Release them if the requesting node meets the stated requirement. Pop2018Sensors [95] provided additional options for stakeholders in the peer-to-peer energy sector. This technique involves self-enforcing smart contracts that compute predicted modifications for each DR event and impose energy flexibility at the consumer level by registering their baseline profile. This technique-built confidence among market players and efficiently addressed energy balance discrepancies. The energy demand profile of all DEPs was changed by 7% to align with peak energy production projections. According to the literature, decentralized grid management architecture consists of three key components: (1) Energy devices consist of energy buyers, sellers, and consumers. Each node chooses its duty based on its present energy state and flexibility. (2) Super nodes have the authority to pick specific edge devices for consensus. (3) Real-time energy exchange recording with smart meters. Once registered in the blockchain, each energy node becomes a genuine entity. Each node is assigned an identity, public and private keys, a certificate for unique identification, and a wallet address [95].

6. Future Trends and Directions

This section examines the capacity of emerging technologies to bring about significant changes in smart grid networks. Artificial intelligence (AI) and machine learning (ML) are improving grid management by utilizing sophisticated prediction techniques and automating decision-making processes. The advent of blockchain technology is fundamentally transforming the process of purchasing and selling electricity and ensuring security by means of decentralized and transparent services. Emerging technologies such as quantum computing and improved grid sensors provide significant advancements in the performance and reliability of electrical grids. These advancements will drive the progress of intelligent power networks, enhancing their efficiency, safety, and durability.

6.1. Investment in SG infrastructure

Several countries have used smart grid infrastructure to cut carbon emissions. These nations are actively engaging in projects to assess the network's feasibility. Construction of SG infrastructure has already started in Australia, South Korea, and Japan. The biggest worry is the high initial investment and continuous maintenance costs for the network. Before making a big infrastructure project, it's important to do a thorough financial review [96].

6.2. Restructuring the Business Model

The implementation of the new smart grid has significantly impacted the organization's model. New technologies have shifted customer perspectives and enabled a decentralized power supply network. According to Pal et al. (2021), company procedures are always developing. Implementing new protocols is vital for properly communicating benefits to clients. Implement the utility business model at the distribution level for smooth integration of load management and power generating [97].

6.3. Attacks on Cybernetics

The smart grid system consists of a large part of IoT-enabled transformers and other physical assets including AMI. As such, cyberattacks aimed at the smart grid seriously jeopardies the infrastructure and correct operation of these resources. The need to prevent cyberattacks gets even more crucial as IoT enabled SG applications are developed (Li et al., 2022b). Under federal legislation, then, rigorous adherence to accepted rules of practice like IEEE 802.15, Security for IoT consumers, and the Electrical Equipment Safety System is absolutely vital [98].

6.3.1. Machine learning-based classification and detection

Detection and categorization systems are one way SG can help to lessen the effects of destructive cyberattacks. Generally, the classification and detection of flaws in any system is vital to remedy the fault; hence, where in learning what these faults are and how they arise, we can use self-healing techniques. In the framework of SGs, these kinds of flaws might constitute cyberattacks, endangering accounting of distributor energy or consumer integrity. Since SGs are quite complicated nonlinear systems, they can also emerge from environmental or error sources. Using machine learning is now the best way to spot ever complex attacks and natural errors. Deep or convolutional neural networks are shown using data to offer accurate and quick diagnosis of defects and cyberattacks by means of machine learning methods. Deep learning-based techniques were suggested by He et al. (2017) [99] as a real-time detection system. By means of a historical examination of the measurement data, deep learning approaches identify the behavioral patterns of the assaults and thereby effectively incorporate the disclosed features for real-time FDI attack detection .

The durability of their detection approach to the several values of attacked measurements, detection thresholds of the state vector estimator (SVE), and degree of environmental noise levels (He et al., 2017) [99] is shown by their simulation findings. Furthermore, shown is the capacity of the used strategy to produce high detection accuracy in the face of the sporadic operation failures. Based on a new dimensionality reduction technique and a Gaussian mixture model, Shi et al. (2021) [100] put up a strategy targeted at statistical FDI attack detection. Their method consists in two phases: a dimensionality reduction approach in the first phase and a semi-supervised learning process grounded on the Gaussian mixture model in the second (Shi et al., 2021) [100]. The results of the simulations from the testing show that the suggested system achieved the required discriminating performance and highly detected the FDI attacks with great accuracy (Shi et al., 2021) [100].

Under the action of cognitive risk control (CRC), Oozeer and Haykin [101]shown how the entropic state and reinforcement learning was able to recognize FDI attacks and push them to a manageable state. Originally suggested for usage in smart grids in Oozeer and Haykin (2019a) [101] , the entropic state was further developed by the same authors in Oozeer and Haykin (2019b) [102]. The objective of a cognitive dynamic system (CDS) is to minimize the quantity of uncertain information in the preceptor and simultaneously control the state. The latter is carried out by dynamically optimizing the estimation process (Oozeer and Haykin, 2019a) [101], hence minimizing this entropic condition. Having two main uses—to indicate the health of the SG from cycle-to-cycle (Oozeer and Haykin, 2019a) [101] and to be used to identify FDI attacks, the authors present the entropic states as a "new metric" for the SG. By means of task-switching control, the cognitive dynamic system (CDS) was able to enable a new executive with an alternative set of activities, so augmenting the system configuration to bring the risk to a tolerable condition during an attack (Oozeer and Haykin, 2019a) [101]. The entropic state represents the information gap, quantifying uncertainty and in the case of Oozeer and Haykin (2019b) [102], can be utilized to detect an attack. This CRC technique has been applied to various systems, such as vehicle-to vehicle (V2V) communication systems (Feng and Haykin, 2019) [103], and the CDS method in control systems is a rising research field. Furthermore, applicable for availability attack prevention on several levels, including in study by Jokar and Leung (2018) [104] who presented a detection and prevention approach based on ZigBee, are machine learning based techniques.

6.3.2. Blockchain

Systems have been coupled with the internet to increase SGs' distributed character and scalability. SG components can virtually instantly transmit and exchange information across great distances using wireless frameworks and the internet, therefore enabling people to obtain energy from anywhere. But the quantity of connections home, gadget, car, etc. Will likewise expand exponentially as energy consumers and distributors increase in numbers. For SG technology, where keeping control over a constantly expanding centralized network would need a range of advanced communication and information infrastructure, this presents a challenge (Mollah et al., 201) [106]. Large internet-based networks' centralization also calls for advanced security mechanisms where the compromising of the central node denotes the compromising of all the data in the network. By means of distributed command nodes, one can minimize the negative effects of a big, centralized network and get more effective operation. But if the number of nodes and people connected to them rises (Mollah et al., 2021) [106] and more creative ideas are needed, this can complicate security even more. Researchers are now looking at Blockchain technology to help them attain data security in a distributed SG.

Blockchain technology is rising in importance as a means of distributed data decentralizing tool. Whereas the distributed architecture is peer-to-peer and divides tasks among several entities, the centralized system requests resources and performs activities from a single server. Most often used in cryptocurrencies, Blockchain is best understood as a distributed ledger with growing many securely linked records called blocks (Kumari et al., 2020) [107]. Security is applied inside the block links using cryptographic hashes; succeeding blocks include data on transactions and time in addition to the cryptographic hash of the one before them. The associated information between connected blocks creates an irreversible data chain by means of cascading effect. Peer-to-peer (P2P), blockchain networks use their decentralization to provide more security and efficiency over data. Blockchain can vary in its permissions (Kumari et al., 2020) [107], where private Blockchain is more desirable against cyberattacks for safe data transfer in SG applications. Mostly for data security in AMI, decentralized energy trading, monitoring and control, and EV charging, Mollah et al. (2021) [106] compile a thorough survey on blockchain implementation in SG.

Kumari et al. (2020) [107] helps to address this by enabling effective demand response management using blockchain-based safe energy trading. Raising energy needs and the inherent weaknesses of the present centralized energy trading system motivated their approach to help address this problem. Using blockchain technology, where they assess the performance of their framework depending on computation time and communication costs, writers decentralize and secure this system. Compared to a conventional centralized structure, results showed that quality of service had been much raised. Mengelkamp et al. (2018) [108] also investigates this use of blockchain as well as Bansal et al. for electric vehicles (Bansal et al., 2019) [109].Gao et al. use blockchain to improve customer awareness of their energy consumption and mitigate compromised data over wireless networks, therefore helping with energy monitoring (Gao et al., 2018) [110]. Using a novel block structure whereby threading side blocks from parent blocks identifies customers and their needs, they define the framework of their sovereign blockchain method.

Every block on the chain is under observation such that the system is triggered when attackers compromise the framework of data access. Their platform is shown to be robust while preserving complete consumer control and immutability over data. Research by Kumar et al. (2023) [111] uses blockchain alongside digital twins and deep learning for SG operation and security. While their deep learning framework improves attack detection with their self-attention mechanism and SoftMax classifier, their blockchain based authentication approach boasts the capacity to resist a great volume of attacks. Their fresh approach shows improved efficiency than traditional techniques. Further SG studies on blockchain deployment for data security inside the system consist of Faheem et al., 2024 [112]; Mahmood et al., 2023 [113].

6.4. AI Technology

Predictive analysis can be given by using artificial intelligence technologies [114]. AI-powered smart contracts can enable the grids to control and spot P2P transactions and manage hostile purposes. Blockchain-based smart contracts including artificial intelligence models may handle transactions including stock purchases, reorders, payments, and dispute settlement as well as suggest which delivery method would be most ecologically friendly and help to resolve conflicts. The AI/machine learning (ML) dependent predictive analysis could have to be used through SCs to modify the variance between the demand and supply of energy. Blockchain-based SGES networks will thus gain from a new degree of intelligence thanks to the remarkable speed and power of artificial intelligence to read, understand, and correlate data in detail. In this sense, the use of artificial intelligence in the design of Blockchain (BCn) smart contracts could function as the "brain" to reach a completely self-operated and distributed framework [115].

6.5. Network Slicing Technology

One can think of network slicing as a solution for connectivity problems. In this sense, the 5G network must be split into conceptually isolated networks ready for numerous network operations coupled with unique service level agreements (SLAs) [116]. For the SGES, the 5G network slicing would offer smart data management, control of the distribution network, and IoT device supervision. Using smart contracts, the BCn network can help to build confidence among the members of different network slices [117],[118],[119]. Once more, the 6G wireless technology must be applied to guarantee the flawless connection of devices connected to different networks so that significant advancement of interconnection can be guaranteed [120],[121]. This helps to retain the sensitivity of data as well. The cooperation of 6G technology with BCn scheme will solve current connectivity problems.

6.6. Big Data

Smart grid depends on the data it gets completely. It serves as back bone for the grid, not only its eyes. Large volumes of data are gathered from power generation, transmission, transformation, and power use for a dependable and effective operation of a smart grid [122]. The grid bases all its decisions on it. It also is very important for the smart grid's autonomous capacity. Big data in smart grid technology presents many difficulties from storage to its visualization and security. Researchers have also concentrated on data combining information and useful applications. Fig. 13 [123] shows a summary of data flow among smart grid components. Data collected from several sensors, wireless transmission and communications accumulates in great volume. Various algorithms use all the generated data to forecast and will also assist in identifying the trend of power consumption. This will eventually help to create a clever energy management system. Energy big data consists not only of data obtained from meters but also of a great volume of data on the environment and weather. This data lacks "4Vs" (volume, velocity, variety and value) and "3Es" (energy, exchange and empathy) [124].

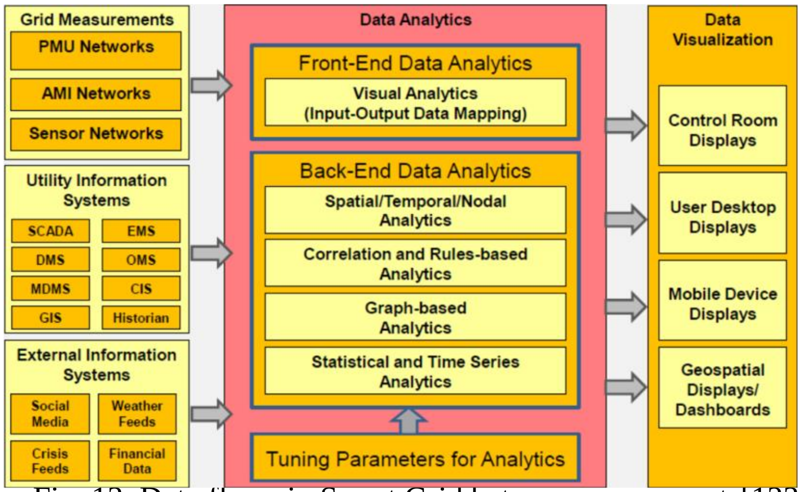


Fig. 13. Data flows in Smart Grid between components[123] .

7. Conclusion

This review paper addresses the possibilities of smart grid technology in energy management and distribution. Key components like Advanced Metering Infrastructure and Distribution Automation improve electrical grid reliability and efficiency. Energy Management Systems and communication networks promote renewable energy integration and demand response programs. However, difficulties like cybersecurity risks, interoperability issues, and regulatory impediments need to be solved. Emerging technologies like Artificial Intelligence, Machine Learning, and blockchain can further expand smart grid capabilities, leading to a more sustainable, resilient, and efficient energy infrastructure.

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