Smart Grid Architecture, Functionalities and Developments

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Abstract

A smart grid is a digitized, intelligent energy network used to deliver energy between sources and consumers in a way that combines information, telecommunications, and power technologies using a two-way communication channel between the service provider and customers. This enables an efficient and reliable exchange of electricity and data between users and the grid operator and electricity sources. The architecture of a smart grid consists of components like energy storage, smart meters, smart substations, phasor measurement units, distributed energy generators and energy sources, and communication systems. Recent developments in smart grid systems include on-grid smart chargers for electric vehicles, innovative power converter topologies, AI-based electricity theft detection in power grids, and others. The integration with existing systems is a major challenge facing renewable energy planning and management because of the intermittence of the resources and uncertainties of customer demand. A smart grid is a digital, modernized electrical network that employs a two-way communication connecting power plants, power lines, and electricity users. It also employs computer-based intelligence and remote control to the conventional grid saving energy, improve reliability and reduce costs. The smart grid is designed to maintain stable grid operation, the power system efficiency, deploy the reliability, and balance power generation and supply. This paper presents a general overview of the smart grids, attributes of the SG, its architecture, and developments. A smart grid is a modern form of the electrical grid that employs two-way communication, digital sensors, and automated in the management of power generation, transmission, and consumption. The smart grid is designed to send power and data in the back-and-forth manner. Tit is a dynamic system that significantly improves reliability, integrates renewable energy sources, and improve energy efficiency. The smart grid is much automated from can integrated the main supply with distributed generation (DG) most of which are renewable sources, the energy storage systems (ESSs), and advanced metering infrastructure. The smart grid represents an advanced digital system because it employs high technology devices in its design and operations.

Key words: Smart grid design; smart grid maintenance; smart grid operations;

I. INTRODUCTION

A smart grid employs digital technology to improve the power system reliability, security, and efficiency from large generation, to delivery of electricity to consumers and often incorporates a large number of distributed-generation and storage resources. The smart grids also integrate information and communication technologies hence the grid infrastructure contains advanced sensors, computers, and communication devices[1-3].

As opposed to the traditional grids, the power flow power flow and information is bidirectional. The operator of the smart grid can monitor the system from supply to user, while in the traditional grid, the communication fails between suppliers and consumers. The use of smart grids enhances the reliability, availability, resilience, stability, while at the same time provides safety features for protection of the power system, which is lacking in the traditional grids because of limited instrumentation making it hard to detected and reduced faults. SG operate as digital system, while TG operate as electromechanical system. The smart grid is

equipped with many of features like elf diagnosis, self-healing, controllability, computational ability, incorporation of RER, and converts consumers to prosumer who are active participants [4, 5].

The operation of Smart Grids involves the use of hardware, software, and technologies that facilitate the identification of power imbalances and enable instant correction to restore quality, increase reliability, safety and reduce energy costs[6]. These components must communicate with each other and work harmoniously together by means of modern computer software[7]. An electricity or power grid is a network of infrastructure for delivery of electricity from power stations to consumers[8, 9]. When such a grid is made intelligent through addition of automated monitoring and control devices with two-way communication capability, it is converted to a smart grid[10]. Therefore, a smart grid is a concept for conventional power grids that are equipped with the latest and automated features that enhance their reliability and sustainability in delivery of electric power. Smart grids have ability to store data, process data and information, communicate, make critical decisions and execute functions based on to the prevailing situation[7]. Therefore, the conventional grids just transmit and distribute power to consumers from generating centers, but smart grids can accommodate reverse flow of power, information, and commands[7, 9].

The term smart grid was used in the year 2005 for the first time in by Amin and Wollenberg in their paper entitled “Towards a Smart grid”. Amin and Wollenberg proposed practical methods, technologies and tools that allow electricity grids and other infrastructures to self-regulate, and automatically reconfiguration in the event of disturbances, failures, and threats[11]. Although Amin and Wollenberg did not provide a formal definition of smart grid, it is implied in the paper that a smart grid is a network that makes use of modern computer and communication technology to realise a grid that can manage failures[11, 12]. The use of smart grids leads to better integration of fluctuating renewable energy, create environment for involving the consumer in active operation through application of incentives that enable flexible demand, and provision of effective two-way information and communication systems[9, 12].

The smart grid can be viewed as a combination of new technological developments and a more demanding business environment. According to the Smart Grids European Technology Platform, a Smart grid is defined as “an electricity network which intelligently integrate all users actions i.e. consumers, generators and prosumers whose objective is to efficiently deliver sustainable, economic and secure electricity. The US department of energy defines a smart grid as a grid that applies digital technology to improve power system reliability, efficiency and security right from power generation, through the delivery systems to power consumers with growing use of distributed-generation and energy storage resources[11, 13].The smart grid is the state-of the-art concept and infrastructure defined within the limitations of electric power sector, particularly with regard to the integration of fluctuating renewable energy within the power sector[10, 12, 14].

The smart grid development has been an evolutionary process that took place over time in a process referred to as “smartening the grid” or “modernizing the grid”. The deployment of smart grid technologies is enabler to the delivery of clean, economic and reliable electric power to end users in a secure, reliable, clean, economic manner[15, 16]. The International Energy Agency (IEA) defines a smart grid as an electricity network which applies digital technology as well as other advanced technologies to manage, monitor, and control the transport transportation of electricity from power plants to end-users. The Smart grids co-ordinates the ability and capability of power system stakeholder and equipment like power plants, utility companies, consumers or end-users and stakeholders of the electricity market to enable efficient operations, minimize costs and minimize the environmental impacts as it maximizes power system reliability, stability and resilience[16].

The European Commission (EC) defines a smart grid as an energy network that monitors, energy flows and adjusts to supply and demand changes automatically. Smart grids incorporate smart metering system and provide real-time information, to both consumers and suppliers in a two-way

communication[11]. With smart meters, consumers are able to adjust their consumption in line with energy prices throughout the day, thus reduces energy bills by ensuring more consumption is done when process are low[16].

According to the United States Office of Electricity Delivery & Energy Reliability (USA OE) as cited in [16], a "Smart grid" is a class of technology used by power utility companies to deliver using computer-based remote control and automation. The systems use a two-way communication technology and computer capability. Smart grids are applied in electricity networks, right from power plants, wind farms, to the users in homes, industry, and businesses. Which leads to improved energy efficiency on the grid and users. According to the International Electrotechnical Commission (IEC), a smart grid refers to a concept of modernizing the power grid. By addition of Smart Grid technologies makes the grid more flexible, more interactive and the grid gets ability to give real time feedback. It intelligently integrates the interests and actions of all grid users namely generators, consumers, and prosumers to efficiently deliver power that is sustainable, secure, and economical. Through innovative products and services with intelligent monitoring, communication, control, and self-healing facilities, a smart grid makes it efficient and economical to connect different power plant technology and sizes of generators, allows consumers to be active participants and play a role in system optimization, provides useful data and information and choice of power supply, which reduces environmental impact the entire power system leading to safe, reliable and secure electricity supply[16]. On the part of the Japan Smart Community Alliance (JSCA) which represents the views of the Smart Communities, a smart grid promotes greater use of renewable energy and idle energy resources and local generation of heat energy for local consumption. Therefore, smart grids contribute to energy self-sufficiency leading to reduced greenhouse gas emissions. They also provide a stable power supply and optimize overall grid operations from power generation to the end use[16]

II. SMART GRID ARCHITECTURE AND HARDWARE

The domains that constitute the smart grid architecture are the Generation, transmission, distribution, end-users, operations, energy market, demand response, and energy market domains. The architecture of the smart grid showing these domains is shown in figure 1.

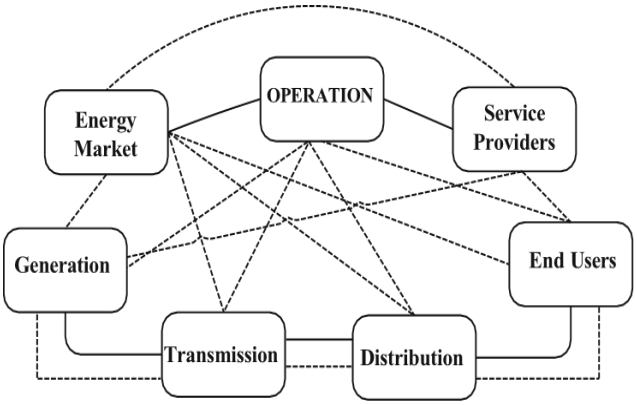

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Figure 1: The Smart grid architecture domains

From figure 1, it is noted that the following are key elements of smart grids architecture and their

A. Functions

The functions of key elements/ features of the smart grid are summarized in table 1

Table 1: Elements of smart grid architecture [4]

	Element/player	Function/contribution
1	Operations	The operations domain controls power flow between generation, transmission, distribution, end user, and the market. The main objective of transmission and distribution operations is to attain reliability, efficiency, and smoothness
2	Service Provider	Services like installation, maintenance, billing, and customer complain management, are provided for both distributors and consumers. Specific services include such as account management, end-user account maintenance, end-user account maintenance, managing customer relationships, monitoring

		and controlling home energy use, etc.
3	Markets	The smart grid market has evolved with key issues to the success of the power market being: • The communication infrastructure for integration of generation, transmission, distribution, end-users, service providers, and market. • interoperability between the supply and consumers. • Supporting regulatory policies for seamless operation of the storage and DER aggregators. • Extending pricing signals to each end-user.
4	Generation	Various types of generating technologies for power generation like coal, diesel, nuclear, biomass, hydro, wind, solar, geothermal, RESs, and a new requirements of generation domain like GHG emission controls, electric vehicles, batteries, and increased RESs
5	Transmission	The role of the transmission grids transfer power from power plants to the distribution networks through substations normally operated by Regional Transmission Operators (RTO) to balance demand and supply. In Smart Grid, interfacing of communication will be between the transmission network and generating units, electricity market, distribution system. Monitored in real-time, controlled on power flow and voltage, and optimal utilization of the transmission network are the important tasks of the system operator
6	Distribution	The smart distribution system connects IEDs to SM and manages a bi-directional wired/wireless using the communication channel. The smart distribution systems play an important role in future distribution systems through control DERs by coordinating with the distribution systems to ensure stability and power quality
7	End Users or Customer	The customers in a smart grid system are classified into three main categories: namely the home/building, industrial and commercial. Smart grid customers participate through demand response, peak-load shaving, emergency response, and valley-filling which facilitate a better operation of the distribution system.

The smart grid architecture is a highly distributed and hierarchical network utilizing intelligent sensing devices for data collection about each grid component which enabled informed operational decision making. The main components of a smart grid include are shown in figure 2:

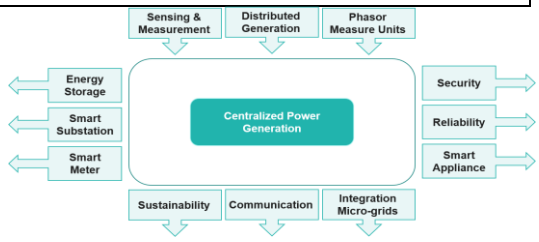


Figure 2: Components Architecture of Smart Grid System environment

Figure 2 shows the main components of the smart grid architecture which include energy storage, smart substations, smart meters, smart appliances, microgrid integration, communication, sustainability. Phasor measuring units, power plants, distributed generation function.

B. Functions of devices

The function of the function of the devices and systems are summarized in table 2.

Table 2: Smart grid systems and devices and their functions

	System	Functions
1	Energy Storage	Energy storage is an integral part of smart grids, while suitable scaling and optimized operation of energy storage devices leads to effective management of peak power demand, and higher penetration of renewable energy at improved power quality, and other benefits. Typical energy storage systems for smart grids include electrostatic energy storage like capacitors, super-capacitors, and magnetic/current energy storage. Mechanical energy storage like flywheels, compressed air, and hydro-pump energy storage, are examples of chemical energy storage. Chemical conventional batteries, fuel cells, solar fuels, metal-air batteries, and thermochemical reversible processes Thermal (sensible, latent, and thermochemical) energy storage.
2	Smart Meter:	Smart meters use a two-way secure communication network to transmit data to the service provider automatically and they have built-in display screen which shows the real-time energy consumption and cost.
3	Smart Substation	Smart substations support advanced functions like real-time automatic control of power grids, intelligent regulation, online analysis, and decision-making and interact with adjacent substations to enhance power dispatching and are responsible for collecting, measuring, controlling, protecting, computing, and monitoring information.
4	Distributed Generation	Smart grids help lower prices, improve dependability, reduce emissions, and extend generation options with electricity generation taking place near demand side which effectively reduces transmission costs and t losses, and hence higher power system efficiency.
5	Phasor Measurement Units:	Phasor measurement units (PMUs) or synchro phasors measure voltages and currents at predetermined locations in the utility grid and synchronize with the global positioning system (GPS) radio clock to offer a revolutionary method for managing power flow in the utility grid, which enhances security and improves transmission
6	Sensing and Measurement:	Advanced sensing and measurement technologies are employed to collect and process /manipulate data to improve the management of the power system by analyzing and monitoring equipment status, prevent theft, and provide strategy support and generate an energy bill estimates
7	Smart Appliance	Smart appliances like fridges, washing machines, toasters, dishwashers, and electric vehicles make use of cutting-edge computer and communication technology to complete tasks quickly, efficiently, and effectively.

8	Security:	The smart grid system proactively identifies anomalies and help reduce e attack surface of the smart grid and hence avoid both intended and unintended consequences. The security coverage extends to critical aspects like control of user data confidentiality, addressing basic grid faults, and mitigating cyber-attacks.
9	Reliability:	Smart grids improve reliability by identifying any fault and allowing the system to self-heal. Smart Grids address grid reliability issues because of their ability to monitor and retain all data as well as estimate service reliability.

The main components that convert a traditional grid to a smart grid are the two-way communicable sensors which monitor and control electricity flows in real time mode, the information technology systems that processes data captured and give commands and alerts. As a human body analogy, the smart grid system can be presented with the brain which carries carry data of two-way communication and nerves of the nervous system which convey the frequency while the muscle delivers the energy[8]. Figure 2 shows the main elements of a smart grid architecture.

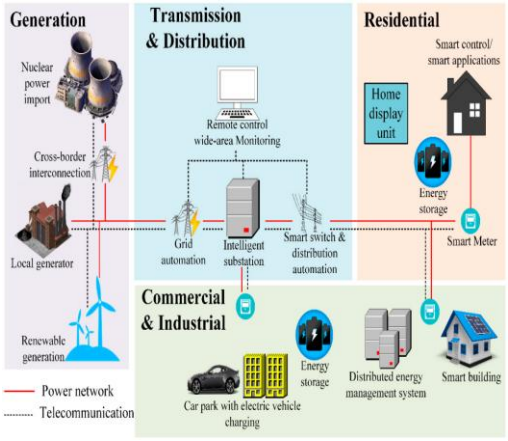


Figure 2: Elements and stakeholders of smart grids

Figure 2 shows the main elements that make up the smart grid system. They include central and decentralized stations, renewable and nonrenewable energy power plants, grid automation infrastructure, the intelligent substations, smart switches and distribution automation, car parks with electric charging stations, energy storage facilities, smart buildings, end user energy storage, among others. The elements are spread over the generation, transmission and distribution and end user or demand side sections of the power grid system. These facilities enable smart grids to create new opportunities and capabilities in a rapidly changing operating environment. The smart grids can intelligently manage the continuous grid parameter fluctuations by applications of digital technologies and the Internet of Things. The grid intelligence is used to create grid reliability, cost-efficiency, flexibility as well as system safety is maintained. They also enable customers to control both consumption and generation as opposed to the traditional or conventional grid [17].

C. Supervisory Control and Data Acquisition System (SCADA)

This is an Extra High Voltage (EHV) transmission network (110kV and above) that is traditionally smart or intelligent equipped with automation and real-time communication systems for system operations. The monitoring and control of power flows in real time at dispatch centers or at load control centers of Extra High Voltage (EHV) systems is done by the Supervisory Control and Data Acquisition (SCADA) and the Energy Management System (EMS). A dedicated communication system between the control center, power plants the EHV substations facilitates the operation of SCADA / EMS. It is from the control centers that operators are able to control power generation and load at system substations[8].

SCADA allows a user gather data from distant fields and send control commands to same distant fields. It provides a visual management interface for the power system operators for remote control and configuration of the power network. Although some utilities developed many different control systems for grid management, most of the utilities rely on SCADA systems to supervise their power

infrastructure[18]. The Supervisory Control and data Acquisition System (SCADA) operates by collecting information related to grid operation from various sensors located at various points and send data to the master computer for real time analysis[8].

D. The Energy Management System

Energy Management System (EMS) is used by grid operators as a tool for monitoring, controlling and optimization of power generation and transmission systems. The main functions of the energy management system include real time network analysis and contingency analysis, Study power flow, power factor, security enhancement. The EMS enables real-time functions which the plant operator to monitor, analyze and control power generation functions on real time basis. It also enables automatic generation control. The energy management system also sets economic dispatch and directs the dispatcher to set economic base point for the generator units selected.

Other functions performed by the energy management system of the smart grids include monitoring of the reserve and establishing sinning reserve, regulating reserve and operating reserve levels. The energy management system also computes the production costs, forecasts load, schedules transactions. The smart grids advanced functionalities include grid reliability enhancement, increasing grid capacity, advanced contingency awareness operations and cost management. Besides the technical capacity and requirements, a smart grid should meet the regulatory requirements[8]. Therefore, overall energy management system in a smart grid enhances reliability, increases efficiency and compliance with standards.

There are several various bio-inspired approaches are used for smart Energy Management Systems strategies. Common systems are Home Energy Management Systems (HEMS), Building Energy Management Systems (BEMS). Bio-inspired computing, is divided into two groups[19]namely evolutionary computing, which involves the incremental development of living organisms in reaction to environmental conditions, and swarm intelligence, which is focused on agents' collective and social behaviors in a system. These algorithms can be used in design, planning, and control issues in smart energy management systems for homes, buildings, and smart grids with traditional/conventional as well as renewable energy sources and as well as stored energy sources [20]. Generally, the purpose of EMS is to minimize energy consumption through device scheduling within specified time horizons [21]. The energy management systems perform several functions as presented in figure 3 below.

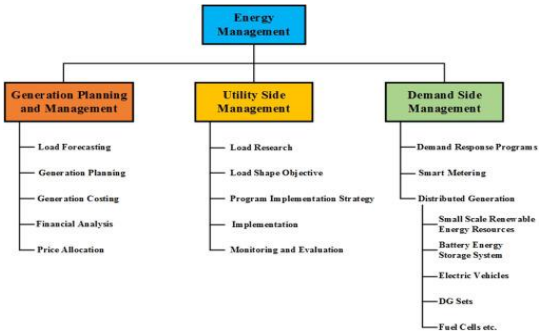


Figure 3: Functional view of energy management system in a smart grid.

From figure 3, it is noted that the energy management system in a smart grid has three main functions, namely demand side management, utility side management and generation planning and management.

The planning and execution of grid activities must be done by means of interoperability. The National Institute of Standards and Technology (NIST) established the smart grid interoperability (SGIP) whose responsibility was to develop and maintain the standards for smart grids and related components necessary for efficient operation. SGIP also provides a platform for all the stakeholders of power grid like the markets, customers, service providers, the power system, generation, transmission, and distribution network to cooperate and work together. Grids and end users must play their roles effectively for implementation of energy management. The energy management system is made more realistic for smart grids due to technologies like communication , advanced metering infrastructure (AMI) and cyber security which facilitate self-decision capabilities for the power grid[7]

E. Smart Meters and Advanced Metering Infrastructure (AMI)

Smart metering can revolutionize access and control of energy consumption. A meter is said to be smart if it has capabilities like real-time monitoring; local and remote data accessibility; remote meter controllability, energy cut off; interaction with other meters like gas meters, water meters; quality monitoring of power and device self-analysis; and interaction with the internet of things (IoTs) [22]. In studies on ICT linked energy saving by [22, 23] it was estimated that between 0.23 and 3.3% of the European CO2 reduction target to reduce global warming to the 1.5 °C minimal realistic warming goal by 2100 can be attributed to the use of ICT in the energy sector. Smart meters make it possible to read in real time rates and pricing policies, which facilitate demand response and demand side management programs. Hence smart meters enable realization of energy efficiency, increase system reliability, and yield significant economic savings to both customers and utilities. [22, 23]. Smart meters constitute an import element of the smart metering system.

Advanced Metering Infrastructure (AMI) is also called Smart Metering and comprises of equipment or devices like Smart Meters, Data Concentrator Units (DCUs) also referred to as gateways, routers or access points, Meter Data Management System (MDMS), Home Area Network (HAN), Head End System (HES), communicating over bi-directional Wide Area Network (WAN), Neighborhood Area Network (NAN) or Field Area Network (FAN) and Multiple smart meters used to connect to the DCU/gateway/router/access point to send aggregated data to the head end system (HES). Smart meters can communicate with the HES directly via appropriate wide area networks (WAN) technologies like the GPRS sim cards placed in the smart meters to send data to head end systems (HES) on the servers in the control room[8].

The role of the MDMS (The Meter Data Management System) is to collect data from the head end system (HES), process and share with the billing system as well as other information technology (IT) applications. The home area network (HAN) can incorporate common appliances like fridges, television sets, radios, heaters, dryers, washing machines, air conditioners, water heaters among others. It is the inclusion of a two-way machine to machine (M2M) communication module in a meter as well as a remotely operated connect and disconnect switch that makes a meter smart. The smart meter is always at the heart of the advanced metering infrastructure (AMI). The smart meter electronically records electricity consumption normally on hourly intervals or less and communicates with the utility on regular basis for monitoring and billing. Smart meters facilitate a two-way communication between computer systems/computers at the utility control centers and the meter[15]. They are equipped with real-time or near real-time sensors, power quality monitoring features and outage notification capabilities[8]. This capability helps in cutting down outages through quick response in case power failure or intermittence in supply where supply comes from variable renewables or outages caused by extraneous factors to the conventional power supply sources.

The smart meters are the backbone in the development of smart grids. smart meters make billing free from manual intervention unlike the traditional billing system where an individual must move from house to house to note down the readings from energy meters normally once a month. With smart meters, billing can be done for multiple consumers any time desired[15].

F. Wide Area Monitoring System (WAMS)

A smart grid deploys Phasor Measurement Units (PMU) which facilitate faster and more accurate measurement of the grid equipment. For real-time wide area monitoring applications, the latency requirements are high in the range of 100 milliseconds to 5 seconds. This requires a fast communication system to handle these huge amounts of data from the phaser measurement Units (PMUs). Smart grids are meant to exploit high data throughput measured in real-time. The main differences in functionalities between PMUs and SCADA is that SCADA data is collected in 1- 5 seconds, but PMU data is captured in milliseconds. Additionally, SCADA data does not have timestamps, while PMU data is accurate time stamped. Operationally SCADA works like an X-Ray, but PMU Data is like an MRI scan of the electricity grid[8].

G. Distribution Automation (DA)

Distributed Automation (DA) refers to the different computerized control strategies meant to upgrade implementation of energy dispersion by enabling specific gadgets to detect operational states of surrounding lattice then influence necessary changes in line with enhanced general energy to streamline operations. With no smart grid configuration, lattice must physically recognize and break down the energy system physically and either remotely enact gadgets or dispatch an expert to intervene[8]. The distribution automation related sensors and interchanges can recognize faulty gadgets and enable the power to utility to take early action. It is through distribution automation that the network is made more proficient and solid. Renewable Energy (RE) is empowered by distribution automation systems by appropriate change of controls to suit fluctuation, control inclining and bi-directional power streams[24].

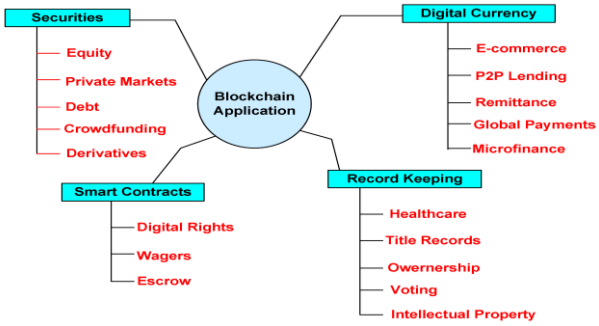
H. Substation Automation

Through automation of substations, it is possible for the utility company to remotely monitor, control, coordinate and operate power distribution components at substations. This will cut down interruptions and downtime caused by equipment failures, strikes from lightning, accidents and natural catastrophes, surges or power disturbances and substation outages. The equipment or components of substations are made digital (or numeric) with related communication systems to facilitate remote operation[8].

i. Block Chain Technology

. Block chain refers to a distributed network, which maintains an immutable database proposed by Satoshi Nakamoto and first implemented in the bitcoin as a technology that enables a community to maintain trust[25, 26]. The block chain technology has potential to transform applications through creation of trust and facilitate decentralization. The technology was considered as a cryptocurrency at the beginning of its application in digital currency although it was just the backbone cryptocurrencies. In a decentralized network, the block chain is distributed ledger for the transactions taking place. Although many researchers were initially skeptical about the block chain technology, it is the popularity of Bitcoin that changed the negative perception [26, 27]. The various applications of the block Chain technology are demonstrated in figure 4.

From figure 4, it is noted that the block chain technology has wide applications in fields like securities which include debt, equity, crowdfunding and derivatives; smart contracts like wagers,



escrow and digital rights; record keeping in health care, voting, intellectual property, title records etc.; and digital currency applications like microfinance, global payments, and ecommerce.

The block chain consists of blocks of transactions that are linked together in a chain. The client/server architecture is applied in the traditional client/server systems and have various administrators who are in charge of the systems. The block chain as a distributed, decentralized peer-to-peer (P2P) network has every network participant with ability to control the network. The block chain network has connected computers or nodes, while the blocks in the chain need the network's approval to be changed. The nodes in the network have a copy of digital ledger[27] and the blocks are ordered in a time-sequential manner, with a hash function being used to secure and link them. Unlike in bitcoin where transactions change of ownership of the money, the transactions in smart grid block chains are of electricity. A hash function refers to a mathematical one-way function with a fixed output, for ant given input with a significant change in output being realized for any slight change in the input [25]

Block chain refers to a secure, transparent, and decentralized, means of recording and sharing data, without relying on third-parties or intermediaries. An example of a block chain application is the digital currency, Bitcoin. Other applications of block chain technology include making supply

chains traceable, combating voter fraud, and securing sensitive data like medical data[28]. In smart grids the block chain technology is made up of distributed information and communication technology that supports decentralized structure of local energy markets and facilitate direct interaction between users[29]. In a block chain-based local energy market prosumers who are both consumers and producers in a system can trade electricity without intermediaries. The market place is represented by a smart contract which accepts orders from all participants of a block chain and performs a merit-order mechanism for efficient allocation[29].

Through the block chain technology, smart grids integrate digital sensing and communication devices which t track energy usage on real-time basis, control the usage of smart equipment, and establish a two-way communication between the power utilities and various users and devices. Development of smart grids have shifted attention to energy management systems (EMS) for smart homes like HEMS (Home energy management systems), Building energy management systems (BEMS) among others [30]. Therefore smart grids have created extra opportunities of optimal energy generation and consumption through various energy management systems [21, 30].

The community or stakeholders in the smart grid can maintain transactions in the system by integration of block chain into the smart grid. Smart grid transactions are doe with smart contracts with transactions history being stored in the block chain and duplicated to all full nodes. The block chain restricts change of which ensures that a smart contract between a generator and a consumer is executed always this providing certainty that a power producer will always deliver the electricity. The provided by the block chain also provides traceability needed for audit or solving a transaction dispute [25]. The main challenges facing block chain technology is expertise and. high initial cost of the infrastructure costs. Concerns over privacy and security the deployment of block chain technology. Other issues with block chain technology are scalability and legal requirements in some countries [27].

III. COMMUNICATION IN SMART GRIDS

A power system has got three key domains, namely: power generation, transmission, and distribution. The main elements of a conventional power generation scheme are a synchronous generator often with a 3-phase electrical energy produced by prime like steam, gas, hydro turbines. Voltage is stepped up and down in the transmission and distribution substations. Distributed energy systems like wind, solar, marine etc. are interfaced with power electronic devices to meet load requirements while customer premises consist of loads which are modelled based on their active and reactive power requirements[31].

The smart grid has a communication layer whose primary purpose is to interoperate between manual control and multiple automatic controllers, sensors, and actuators in the physical layer of the grid. A smart grid needs a scalable, secure and robust, communication infrastructure for design and secure operation. The sending, control and communication standards of electricity systems ought to be robust enough to meet the latency and overcome the bandwidth challenges for communication systems. Major communication technologies include IEEE specified Zigbee, WiMAX and wireless LAN technologies, GSM 3G/4G cellular and DASH7. These communication technologies are used in smart grid domains station substation automation, home area automation, vehicle to grid communication and metering infrastructure. A fundamental research challenge is standardization and interoperability of the communication standards for smart grids[31]. The most common standard of power systems communication in power systems and smart grids is the power line communication (PLC) which is commonly utilized in high, medium and low voltage power networks. The presence of noise and vibration and interference in the network makes reliable operation of wireless sensor network's very challenging in the industry 4.0 paradigm, used in the smart grid context. Therefore there is need to have a robust communication network for successful operation of wireless sensor networks (WSNs) in smart grids. Solutions include use of a dynamic clustering which is based on optimized protocol which improves the system's reliability by reducing the excessive packet retransmitted in the communication networks of smart grids smart grid [31]. Figure

5 shows the structure of the communication layer of the smart grid.

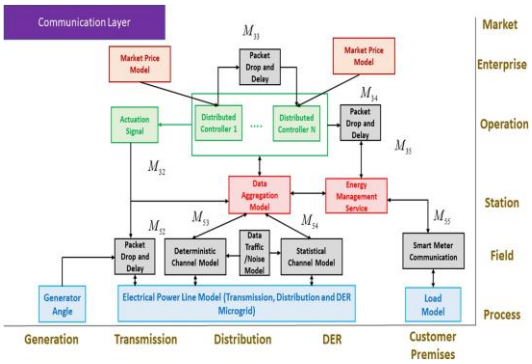


Fig. 5. The communication layers

Figure 5 shows the communication layer where grey illustrates the communication layer, blue sit the component layer, red is information layer, green represents the functional layer while brown represents the business layer.

In order to mitigate the uncertainty and noise in networked systems, it is necessary to have a control strategy that ensures optimal system performance [31]. It is the role of the information layer to facilitate data exchange and storage for smart grid protection and control applications. Smart grids need revolutionary ICT technologies to achieve robustness and reliability under a highly dynamic network of many players. Automation architecture is provided by standards - IEC 61850 and IEC 61499 which support multi-agent intelligence and distributed automation simulation. Software like SimPowerSystems in Matlab can be used for validation of custom-designed user datagram protocol (UDP) socket. The optimal efficiency of the multi-agent network, is critical to achieve a robust operability between them under various operational network topologies . Market algorithms are used to maintain a balance between supply and demand which in some typical applications use PowerMatcher software[31].

To ensure end-users privacy and security, the information exchange in power systems should not be accessed through local gateways. Data privacy is preserved through end to end encryption whose limitation is that it increases the data size causing unacceptable communication overhead. A typology in which data aggregation is performed at multiple levels based on the hierarchy and frequency has indicated to be helpful for load allocation and power generation administration application. Security architecture can be defined by application of multiple gateways at customer premises which provide communication and cryptographic abilities amongst themselves and external entities. This enables privacy preservation in the network. Homomorphic encryption can be used in smart meters for demand response schemes which secures users' session using adaptive key evolution[31].

IV. CHARACTERISTICS AND FUNCTIONS OF SMART GRIDS

The electrical grid spans kilometers of terrain supplying power to industries, businesses, homes by connecting electricity customers to power generating stations. The grid in arguably the biggest stationary machine ever assembled by mankind [32]. One of the greatest challenges facing the traditional grid is the risk of impaired consistency and security of power supply load when renewable electricity is disrupted. It is important improve the capacity of the transmission and distribution structure to accommodate growing distributed energy resources [10, 32]. Modernization of the grid is a development guided by finances, universal rules and technological advances in ICT. Currently, desirable grid improvements should ensure supply of green and sustainable energy and electricity. The smart grid which is an improved grid works with a two-way power flow [9, 14, 32]

Smart grids can be used to address the growing social, economic and environmental challenges encountered in the delivery of energy resources and generated electricity. This is achieved through increased awareness of the operation of the system and informed participation by in smart grids which improves end-use efficiency while optimizing utility of network assets, and increased resilience of the grid [9, 33]. The use of smart grids will also enable efficient integration of variable renewables and electric vehicles and provision of new grid services new products. Smart grids co-ordinate the abilities and needs of all generators, grid operators, consumers, and stakeholders of the electric power market. This coordination function increases system efficiency, reduces costs, wastage and environmental impacts and maximize system

reliability, stability and resilience. These optimizations by the smart grids is achieved by applying digital and other advanced technologies in monitoring and management of electricity transmission and distribution to meet the variable power demands of consumers. Therefore successful deployment and use of smart grids will enable the global community realize shared goals securing energy security, economic growth and development and mitigation of climate change [33, 34].

The Smart grid technologies and their applications prescribe power system that is significantly different from common or traditional power system[35]. The basic characteristics of smart grids that define the new model of the grid are;

They are equipped with extensive metering, control and communications

This enables effective metering of individual customers and grid equipment like switches, transformers, capacity banks, voltage regulators, and others across the distribution system and have ability to relay the information back to utility through the communication system [35, 36].

Two-way communication

Smart grids are equipped with Two-Way Customer Communication and Power Flows as opposed to the one direction flow to the customer alone in the traditional system and but the feedback of information is in the opposite direction to the utility often on monthly basis. The smart grid supports frequent and on-demand two-way flow of both power supply and information [35, 37-40].

Stakeholder Participation and engagement

Stakeholders in a grid environment like the customers can participate actively in the grid operations. Customers can supply own produced power from local resources like cogeneration, wind, solar and biogas and they can respond to signals from the utility to reduce peak power consumption when the system is under stressed[35]. Therefore, Smart grids can accommodate new energy or electricity products, services, and new energy markets and segments[34], since they can accommodate different conversion or generation technologies, sizes, characteristics, and storage options.

Better system control

Smart grids facilitate increased distribution system infrastructure control by the utility operator through the services and products like demand response and self-healing abilities [35]. This enhances system resilience and stability to deliver smooth power and services to stakeholder.

Integration of coordination

The Smart grids create synergy and harmony in the system by coordinating and integrating advanced metering, control, communications, customer service and strategies, leverage technologies and programs to realize across the utility system objectives like reliability, efficiency, safety and economy[35].

High system reliability and resilience

The Smart grids facilitate optimal asset assets and enhanced operational efficiency. This is further enhanced through operational resilience against physical and cyber-attacks to the power system. Therefore, Smart grids Smart grids facilitate power quality requirements for 21st century energy requirements.

Therefore, smartening of the grid equips it with the digital technology and capacity to improve its resiliency, reliability, economic efficiency, energy efficiency, and flexibility of the power system.

V. THE EVOLUTION OF THE GRID

Electrification history began in the 19th century in an arrangement where it was generated of specific load application. With proliferation of power stations at places far from the load centers, electricity transmission and distribution became necessary after Thomas Edison developed the first stable and domestic bulb in 1881, that led to the creation of the first commercial power plant in the US at Pearl Street Station, in lower Manhattan in the year 1882 that produced 600 kW of direct current. In the UK, the first commercial power station was the Pearl Street Station, within the Surrey town of Godalming in 1881, where Thomas Edison helped in the development of the world's first public electric supply system that supplied city lightening. It is the development of Edison's power station that inspired Nikola Tesla, to develop the first Alternative Current (AC) electric system used to light the World's Columbian Exposition Fair

in Chicago in 1893 that marked the beginning to the shift from DC to AC power system at the beginning of the 20th century. The industrial revolution and technological inventions in power generation and transmission influenced the gradual growth in electricity grids[41].

Several disasters and challenges influenced the shift to the smart grid from the traditional grid especially widespread blackouts that hit the US over many years for example in August 2003, NE blackout affected 50 million with loss of 62,000 MW power. This influenced the 109th U.S. Congress to approve what came to be called "The 2005 Energy Independence and Security Act (EISA)" which gave tax incentives and subsidies for integration of renewable energy and energy efficiency technologies in power grids. Additionally, in the 110th U.S. Congress, the Smart Grid initiative was initiated as an official policy to modernize the electricity grid of the United States of America and formalized in the 2007 EISA [41]

The section 1305 of the EISA 2007 made provisions for National Institute of Standards and Technology (NIST) whose primary responsibility was to coordinate in the development of a framework including model standards and protocols for management of information for realization of interoperability of smart grid devices and system which is critical to avoid premature obsolescence of the infrastructure. The National Institute of Standards and Technology (NIST) proposed three-phase plan to accelerate development of initial set of standards to promote development and deployment of the Smart Grid namely; creation of the "Framework and Roadmap for Smart Grid Interoperability Standards, release 1.0", January 2010 as the first phase followed in the second phase by Creation of the Smart Grid Interoperability Panel (SGIP), whose role was to develop additional standards and finally the third phase whose objective was to create a robust framework for conformity and certification of the Smart Grid devices and systems[2].

Literature does not state any specific start of Smart Grid. However, the concept started to evolve with the beginning of distribution systems of electrical networks. Distribution systems needed facilities and capabilities like control, monitoring, pricing, as well as transmission and distribution services. The smart grid implementation is however associated with the installation of smart meter. As early as the 1970s and 80s, smart meters were used to send data and information to the grid from consumers. Very important and fundamental need for smart grids today is reliability and efficiency of power transmission and distribution. The desire today is that grids and network systems should not be a barrier or limit to transmission and distribution and should promote generation and evacuation of clean and sustainable energy to minimize greenhouse gas emissions and hence the carbon footprint of grid electricity[7].

Today, the smart grid technology remains an evolving technology resulting from in development in automation, information technology, system control, and Internet of things (IoT). Real-time monitoring and control of power flow from power plants to end users is realized on real-time basis with use of smart grids[8]. The grid is made smart by integration of block chain technology and the traditional electric grid. The block chain technology facilitates decentralization of the grid network operations making central authority in grid control, distribution, and management of the electricity system unnecessary. Transactions and operations on the grid network are stored on the public ledgers of a block chain. Smart grids technology facilitates buying and selling energy across the network through a computer program by validation and verification of pre-determined transaction clauses. This implies that block chain technology enables real-time energy markets and preservation of identity transactions at lower costs [42].

The National Institute of Standards and Technology (NIST) first developed a conceptual model for the smart grid that set-in motion research and development of smart grid technology. The NIST model has seven domains of the smart grid namely bulk generations, distribution, transmissions, markets, consumers, operations, and power system service providers. The stakeholders of smart grids interact in a two-way direction by using several both wired and wireless communication protocols. The communication protocols include use of Zigbee, WiFi, Homeplug, power line carrier, GPRS, WiMax, LET, Lease line, and Fibers. Many software

packages were also developed to accommodate the new grid operation, management and maintenance like distribution management system (DMS), outage management system, geographic information systems (GIS), customer information systems (CIS), and supervisory control and data acquisition system (SCADA)[43].

VI. SUMMARY AND DISCUSSIONS

The global transformation of the power grid is still work in progress with a few countries already implementing it while many others are still using the traditional grid. The traditional grids delivers power in one direction flowing from the power plants to the user. Further development in technology and adoption is hinged upon the activities address the technical, business, and institutional challenges to the development of the smart grids. Smartening can be initiated at various levels like city level, regional, country, or national level, continental or on global scale. All types of electricity systems can be upgraded or improved or optimized but first is to identify key drivers that motivate investment or the transformation[15, 16].

Electricity is employed to power many things globally almost unnoticed except when we have an outage and lights go off and machines cannot move in factories and commercial enterprises As more and more people use electricity due to electrification and changes in lifestyles due to modernization, old electricity grids fail to keep up to the pressure and expectations thus give way to the smart grid as the answer to many question around electricity generation, transmission, distribution and final use. The smart grid is s a more efficient way to produce, transmit, and use electricity being more flexible, faster, more reliable and intelligent compared to the traditional grid. It is a modern electricity network that employs digital technology to monitor and control electricity flows in real time[1, 2, 5]. Utilities and users can send and receive information about electricity use.This makes electricity more reliable. Utilities can identify issues more quickly, and users can see how much electricity they are using. Power is utilised more efficiently. In India, where homes, offices, and industries are consuming more electricity than ever, adopting smart grid solutions is increasingly important.

A Smart Grid integrates electricity systems with digital technology and has three main layers.

i.) The first layer is the power layer.

This includes electricity generation, transmission lines, substations, and distribution networks. Renewable energy, like solar and wind, is also included in this layer.

ii.) The second layer is the communication layer.

This lets devices share information in real time. Smart meters, sensors, and control systems provide updates on electricity use, problems, and performance.

iii.) The third layer is the application layer

It is in this layer that data is used to make decisions e.g. utilities can plan electricity use, fix problems quickly, and balance the electricity demand and supply while people can use this information to manage electricity use.

Together, these layers form smart grid solutions that make the system faster, safer, and smarter.

A. Smart grid architecture Versus Conventional Power Systems

The key domains of power systems are power generation, transmission, and distribution while the main elements of the traditional power generation scheme are a synchronous generator in a 3-phase electrical energy generated in centralized power stations. On the other hand, distributed energy systems are interfaced with power electronic devices needed to meet varying load requirements of users[31].

For smart grids, there is need for a communication layer to interoperate between manual control and multiple sensors, automatic controllers, and actuators in the physical layer of the grid. Communication in electricity systems ought to be robust to meet the latency and overcome the bandwidth challenges. Commonly used communication technologies are IEEE specified Zigbee, WiMAX and wireless LAN technologies, GSM 3G/4G

cellular and DASH7[31]. The power line communication (PLC) is the most common standard communication in power systems and smart grids applied low, medium and high voltage electricity networks. Smart grids need a robust communication network for successful operation of wireless sensor networks (WSNs). Data exchange and storage for smart grid protection and control applications is facilitated by the information layer of smart grid. The smart grid automation architecture can be provided by standards - IEC 61850 and IEC 61499 which support multi-agent intelligence and distributed automation simulation while software like SimPowerSystems in Matlab can be applied to validate custom-designed user datagram protocol (UDP) socket. Market algorithms can be applied to maintain a balance between demand and supply where in some typical applications use Power Matcher software is applied[31]. Application of multiple gateways at customer levels can define security architecture that provides communication and cryptographic abilities amongst themselves and external entities whose benefit is to preserve privacy in the network. Homomorphic encryption can be used for demand response schemes [31].

B. The main components of the smart grid architecture are summarized in table 3 below.

Table 3. Summary of architecture [16]

	Element s	Construction	Applications
1	Supervisory Control and Data Acquisition System (SCADA)	This is an Extra High Voltage (EHV) transmission network (110kV and above) that is traditionally smart or intelligent equipped with automation and real-time communication systems for system operations.	SCADA operates by collecting information related to grid operation from various sensors located at various points and send data to the master computer for real time analysis. SCADA with the EMS monitor and control of power flows in real time at dispatch centers or at load control centers of Extra High Voltage (EHV).
2	The Energy Management System	Energy Management System (EMS) is used by grid operators as a tool for monitoring, controlling and optimization of power generation and transmission systems. It facilitates real time network and contingency analysis.	The EMS enables real-time functions which enable the plant operator to monitor, analyze and control power generation functions on real time basis. It enables automatic generation control, sets economic dispatch and directs the dispatcher to set economic base point for the generator units selected, monitoring of the reserve and establishing spinning reserve, regulating reserve and operating reserve levels.
3	Wide Area Monitoring System (WAMS)	The system deploys Phasor Measurement Units (PMU) used for faster and more accurate measurement of the grid equipment. Additionally, SCADA data does not have timestamps, while PMU data is accurate time stamped. Operationally SCADA works like an X-Ray, but PMU Data is like an MRI scan of the electricity grid	This requires a fast communication system to handle these huge amounts of data from the phasor measurement Units (PMUs). For real-time wide area monitoring applications, the latency requirements are high in the range of 100 milliseconds to 5 seconds. The main differences in functionalities between PMUs and SCADA is that in SCADA data is collected in 1-5 seconds, but PMU data is captured in milliseconds.
4	Distribution automation (DA)	The DA involves computerized control strategies used to upgrade implementation of energy dispersion. The lattice	The distribution automation (DA) enables specific gadgets to detect operational states of surrounding lattice then influence necessary changes to streamline operation

		physically recognizes and break down the energy system physically and remotely enact gadgets or dispatch an expert to intervene.	making the network more proficient and solid. The DA facilitates change of controls to suit fluctuation, control inclining and bi-directional power streams.
5	Substation Automation and substation automation systems	Through automation of substations, the equipment or components of substations are made digital (or numeric) with related communication systems to facilitate remote operation.	Substation automation cuts down interruptions and downtime caused by equipment failures, strikes from lightning, accidents and natural catastrophes, surges or power disturbances and substation outages. Substation's automation enables the utility company to remotely monitor, control, coordinate and operate power distribution components at substations
6	Advanced metering infrastructure (AMI) or Smart Metering system	comprises of equipment or devices like Smart Meters, Data Concentrator Units (DCUs) also referred to as gateways, routers or access points, Meter Data Management System (MDMS), Home Area Network (HAN), Head End System (HES).	The smart meter electronically records electricity consumption normally on hourly intervals or less and communicates with the utility on regular basis for monitoring and billing. They facilitate a two-way communication between computer systems/computers at the utility control centers and the meter the consumer point
7	Block Chain Technology infrastructure	The block chain technology is made up of distributed information and communication technology	It supports decentralized structure of local energy markets and facilitate direct interaction between smart grid users

From table 3, it is noted that the main elements of the smart grid architecture and operations are the Supervisory Control and Data Acquisition System (SCADA), Block Chain Technology infrastructure, Advanced metering infrastructure (AMI) also called Smart Metering system, Distribution automation (DA), Substation Automation, Wide Area Monitoring System (WAMS) and the energy management system (EMS). Other components of the smart grid architecture are household appliances, energy sources, Smart Meters, the Power Utility Centers. The smart meter contains a microcontroller that has memory, digital ports, timers, real-time, and serial two-way communication facilities. Smart meters join house or user devices and the external systems to the utility monitoring and control systems.

C. Summary of features and capability of smart grids [7]

The smart grid system has several capabilities that enables it to function. These capabilities are summarized in table 6 below.

Table 6: Capabilities and benefits of smart grids

	Capability/function	Sustainability impact
1	Seamless connection of generators of different sizes, features, sources of energy	Prevents ower loss and maximizes use of variable loads and power sources
2	Enhances reliability, security, and stability of supply	Guarantees sustainable electricity supply

3	Enable automatic loading and re-routing of electricity whenever equipment fails	Avoids unnecessary power supply losses and reduces downtown hence high supply security and reliability.
4	Prevent transmission oscillations and overload which often cause blackouts	Reliability of power supply and more absorption of variable loads like electric cars and variable supply like wind and solar power.
5	They provide real-time information on consumption to stakeholders	Facilitates social sustainability and technology acceptance which is a sustainability requirement.
6	Enable consumers to adjust in time and quantity of energy usage	This will reduce overload on generation facilities, improves efficiency and hence avoids wasteful generation and consumption.
7	Facilitate higher integration of renewable energy	Facilitates fossil fuel substitution in power generation.
8	Convert consumers to prosumers who produce and sell their own	Provides a revenue source for consumers, motivation to consume less and generate more and enable economic sustainability of power systems.
9	Optimize overall grid operations from generation to consumption.	This will reduce wastes and pollution, avoid unnecessary generation and consumption as well as avoid unnecessary investment and costs in the power system.

From table 6, it is observed that the smart grid has several capabilities like ability to seamlessly integrate variable renewables and optimize grid operations which gives it a significant role to place in the energy transition from fossil fuel based to low carbon and renewable energy resources.

D. The Recent Developments and future Smart Grids

Recent developments in smart grid technology include:

AI-Powered Grid Intelligence which has transformed grid operations by enabling capabilities like predictive maintenance, fault detection, outage prevention, load forecasting, which facilitate utility companies to anticipate demand-supply, equipment failures, maintenance needs, etc., and helping companies optimize operations and reduce operational expenditure.

Distributed Energy Resources Management System (DERMS) used to support companies in operation management and optimizing of distributed energy resources, and others in the modern grid.

High-Voltage Direct Current (HVDC) Integration which is an efficient long-distance power transmission supporting as bidirectional power transfer among the renewable power sources, energy storage systems, electric vehicles, and other grid elements consuming DC power in a way that minimize the energy losses during the conversion from AC to DC and vice versa.

Virtual Power Plants which are digital platforms that aggregate, manage, and coordinate many decentralized assets by use real-time communication and artificial intelligence to balance the supply and demand to improve the overall grid reliability and capacity to integrate more resources.

Power-to-X Integration which are systems that convert excess power from the grid into forms like hydrogen, synthetic fuels, or heat for storage and later use done various electrochemical processes, like electrolysis, methanation, ammonia synthesis, and methanol synthesis, for efficient energy conservation.

VII.CONCLUSIONS

The concept of the smart grid has evolved to efficiently meet energy consumption needs and reduce carbon emissions by enhancing the uptake of renewable energy sources by the grid. Additionally, the improvement on reliability, efficiency, and quality of power flows is transforming the traditional grid and consumer behavior. The transition to smart grids has also raised concerns in terms of confidentiality of data with concerns over infringement of user privacy. A smart grid is a digitized, intelligent energy network used to deliver energy between sources and consumers in a way that combines information, telecommunications, and power technologies using a two-way communication channel between the service provider and customers. This enables an efficient and reliable exchange of electricity and data between users and the grid operator and electricity sources. The architecture of a smart grid consists of components like energy storage, smart meters, smart substations, phasor measurement units, distributed energy generators and energy sources, and communication systems. Recent developments in smart grid systems include on-grid smart chargers for electric vehicles, innovative power converter topologies, AI-based electricity theft detection in power grids, and others.

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