



Applications of Smart Grid

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Abstract

The transition from traditional power grids to smart grids signifies a significant change in energy management, distribution, and consumption. A smart grid modernizes the electricity delivery system by monitoring, protecting, and automatically optimizing the operation of its interconnected components. It is often viewed as a solution to global warming, offering great potential for cleaner and more efficient power, improved air quality, and reduced greenhouse gas emissions. The smart grid enhances the 20th-century electrical grid by incorporating two-way communication and intelligent devices. This enables bidirectional flow of electricity and information, potentially improving the delivery network. This paper discusses the key applications of smart grid technology.

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1. Introduction

In today's world, it is hard to imagine a day without electricity. We rely on electricity 24/7, and to support our modern society, we need a continuous supply. In 2012, global electricity generation reached 20,250 terawatt-hours (TWh), and it is projected to rise to 25,500 TWh by 2020 ^[1]. The traditional power system generates and transmits electricity through a one-way transmission and distribution system known as the grid. This basic structure has remained unchanged for about 100 years and is recognized as inefficient and unreliable. Experience has shown that it is ill-suited to the demands of the 21st century. Consequently, the power industry faces both unprecedented challenges and opportunities due to this low efficiency.

The traditional electricity grid, a significant engineering achievement of the 20th century, was designed for a simpler time, allowing predictable, one-way power flow from centralized plants to end-users. However, as global energy consumption rises and the urgency to combat climate change increases, this aging infrastructure is becoming increasingly inadequate. The introduction of the smart grid represents a crucial evolution. It integrates digital information and communication technologies (ICT) to create an intelligent, two-way network. Transitioning to a smart grid is not just an upgrade to the infrastructure; it is a fundamental enabler of a sustainable, efficient, and resilient energy future. By incorporating advanced communication technologies, smart sensors, and automated controls, smart grids offer enhanced efficiency and reliability while also facilitating the seamless integration of renewable energy sources. The U.S. Department of Energy (DOE) is responsible for modernizing the nation's electricity grid to improve its reliability and efficiency. This ongoing modernization effort is commonly referred to as the "smart grid." The term "smart grid" implies that the existing traditional grid is outdated. The word "smart" signifies a grid that possesses intelligence. The smart grid combines the traditional distribution network with a two-way communication network for sensing, monitoring, and information technologies. The primary objective of the smart grid is to provide reliability, flexibility, efficiency, and robustness to the power system. It achieves this by introducing two-way data communication into the power grid, which comprises both power and communication infrastructure corresponding to the flow of power and information,

respectively. This capability enables intelligent operation of the smart grid; however, it also introduces security-related challenges. [2, 3].

2. Methodology

This study employs a qualitative research methodology, based on primary and secondary data analysis, to investigate the applications of smart grid technologies. The review draws on a range of sources, including peer-reviewed scholarly journals and official reports from organizations and industry experts on smart technologies and their key characteristics. The research design is both descriptive and analytical,

combining literature analysis, statistical evaluation, and comparative analysis of grid applications, environmental sustainability, benefits, challenges, and tools for addressing climate change.

3. Concept of Smart Grid

The term “grid” traditionally refers to the electric grid, a network comprising electricity generation, transmission, distribution, and control. It delivers electricity from the power plant to a residential or commercial building. An example of the traditional electric grid is shown in Figure 1 [4]. A typical smart grid is shown in Figure 2 [4].

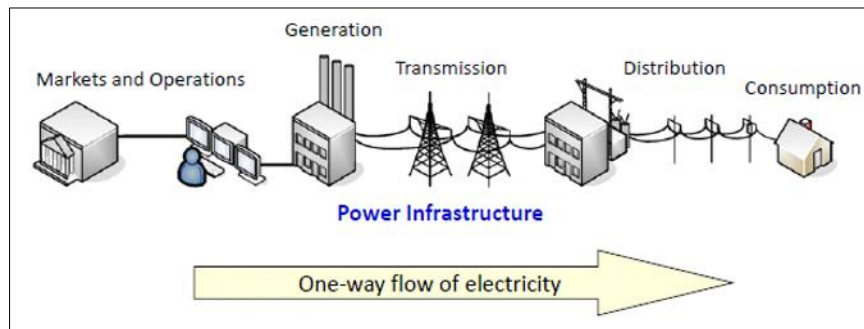


Fig 1: A typical traditional power grid [4].

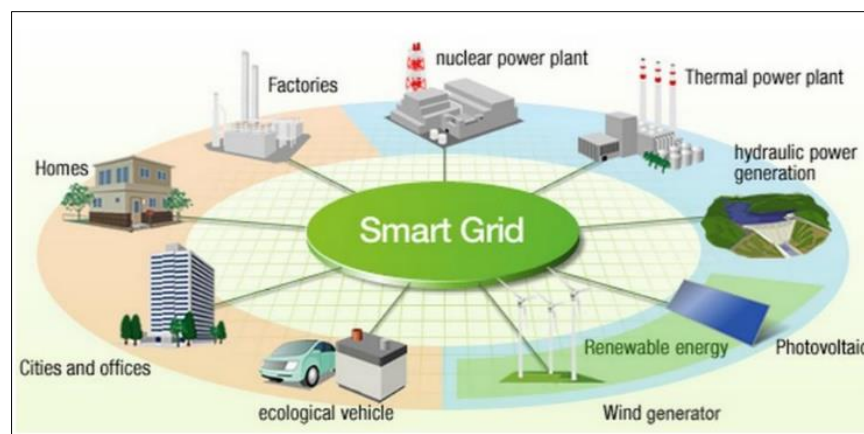


Fig 2: A typical smart grid [4].

A “smart grid” is an advanced version of the traditional electric power grid. It is also referred to as an “intelligent grid” or “Grid 2.0” because it modernizes the way electricity is delivered and managed. Unlike the traditional one-way grid, a smart grid supports a two-way exchange of both electric power and information. It combines technologies, hardware, software, and practices that make the power delivery system more reliable, flexible, secure, resilient, and useful for consumers [5]. In simple terms, a smart grid adds information and communication technologies to the physical power system. As a result, it improves how electricity is delivered, consumed, monitored, and controlled. It is also considered an important application of the Internet of Things (IoT).

From an architectural perspective, a smart grid consists of three main layers: (1) the physical power layer, which includes transmission and distribution; (2) the data transport and control layer, which includes communication and control systems; and (3) the application layer, which includes services and applications. From a technology perspective, smart grid technologies can be broadly classified as well-

established, advanced, or emerging. From a technical perspective, the smart grid can be divided into three major systems [6]:

Smart infrastructure systems refer to the energy, information, and communication infrastructure that supports the smart grid. It enables the two-way flow of electricity and information, allowing users not only to consume electricity but also to supply excess electricity back to the grid. This system also allows different components, such as intelligent devices, specialized software, and control centers, to communicate and work together.

A smart management system provides advanced management and control services essential to the efficient operation of smart grids. Smart grid management includes smart metering, real-time pricing, renewable energy integration, and the management of transmission and distribution networks. The smart protection system improves reliability by supporting fault detection, protection, and security services. These functions are important because existing grid infrastructure is vulnerable to various security threats. Smart grids also connect major systems, including electricity generation,

transmission, distribution, customer information and management, usage and meter management, and billing systems.

3. Characteristics of Smart Grid

The smart grid is poised to transform the current electrical grid by enabling two-way communication, thereby enhancing efficiency, resilience, reliability, affordability, and sustainability of electricity generation, transmission, and distribution. The seven main characteristics of the smart grid are outlined below^[7]. There has long been a desire to improve the efficiency of energy generation and delivery to customers. A smart grid significantly enhances energy efficiency without human intervention, leading to more effective energy production and utilization. It allows individuals to monitor and manage their energy consumption through smart meters. Increased efficiency will help reduce the costs associated with producing, delivering, and consuming electricity. Economic efficiency means maximizing the net value of benefits gained from available resources.

Additionally, a smart grid operates resiliently against attacks and natural disasters, enhancing the electric power system's ability to address emergencies such as blackouts, severe storms, earthquakes, large solar flares, and terrorist attacks. Reliability has always been a priority in electric power operations due to the costs incurred from outages. Smart grid technologies can improve the reliability of the electricity market by enabling utilities to respond to outages and threats. Smart meters allow utilities to electronically identify the location of an outage before a customer even has to report it. The smart grid employs technologies that enhance fault detection and enable the electricity network to self-heal, thereby reducing the need for maintenance technicians. This ensures a more reliable electricity supply and diminishes vulnerability to natural disasters or attacks. Another important technique used in the smart grid is load balancing, also known as load adjustment. The total load connected to the grid fluctuates significantly over time, especially during peak and off-peak periods. The smart grid can alert smart client appliances to reduce their electricity consumption during peak times, enabling the system to serve other high-demand customers.

Affordability is crucial because it enables smart grid technologies to offer customers new options for managing their electricity use and controlling their utility bills. The smart grid accommodates all types of energy generation and storage options, accepting energy from virtually any fuel source. It also facilitates the integration of renewable energy sources in a plug-and-play manner. Renewable resources such as solar and wind are increasingly recognized as sustainable sources of electric power. Several countries have enacted regulations to support the integration of more renewable energy into their overall generation portfolios.

The grid is expected to be environmentally friendly, often referred to as Green Energy. Deploying the smart grid is a key strategy in addressing climate change challenges. Being green is becoming increasingly fashionable. Green energy, sometimes called renewable or sustainable energy, is derived from natural sources like wind, water, and sunlight. It is often labeled "clean" because it generates no pollutants. This makes it an appealing option, offering a clean and environmentally friendly alternative to traditional energy sources. In essence, green energy is virtually limitless because natural processes continuously replenish its supplies.

[8].

These features may also be regarded as the benefits of smart grids.

4. Fundamental Technologies of Smart Grid

The smart grid leverages sensors, smart meters, and automated devices to enhance the electrical power grid. This technology enables the grid to predict, adapt, and reliably reconfigure itself. It can effectively manage schedule uncertainties, facilitate power transfer across regions, address unpredictable events, and ensure a reliable electricity supply^[9]. Key components for the effective operation of a smart grid include energy storage, advanced meters and sensors, grid-compatible plug-in hybrid vehicles, adaptable loads, substation and distribution automation, communication systems, data-intensive analysis, user-friendly visualization interfaces, and the integration of renewable energy sources^[10]. Smart grids employ innovative load-shaping strategies that incorporate energy storage and dynamic pricing. Consumers can sign up for a predetermined energy quota from the grid; if their usage exceeds this quota, they will incur a higher electricity price. Implementing these strategies with low complexity and in a decentralized manner allows for scalability to accommodate a large number of consumers^[11].

4.1. The Architecture of a Smart Grid

The architecture of a smart grid consists of five major components: power architecture, communication networks, wireless sensor networks, supervisory control and data acquisition (SCADA), and smart meters^[12].

Power Architecture consists of three main subsystems: generation, transmission, and distribution, which together form the electric power system.

The smart grid integrates various technologies to produce, distribute, and monitor energy usage among consumers. Power infrastructure generates and distributes electricity to users through a network of transmission lines, switches, and transformers that deliver power from utilities to end customers. Energy is received at the home area network (HAN) and then distributed to all household appliances. Historically, the power industry operated its own communication infrastructure to control power grids; however, the trend has shifted toward utilizing shared public communication networks. Smart grids rely on these communication networks to convey sensing and control data, which enhances the efficiency of energy generation, transmission, and distribution. As a result, the power and communication systems are becoming increasingly interdependent. The smart grid represents the next generation of electric power systems, relying on modern communication networks to support electricity generation, transmission, and consumption. This emerging intelligent power system depends heavily on information and communication technology (ICT).

The communication network encompasses both the physical network architecture and the network protocols used. All components are interconnected via various communication technologies, such as wide-area networks (WANs), WiMAX, and HANs. This communication infrastructure not only controls the power infrastructure but also makes it intelligent, efficient, and reliable. It is essential that these communications are secure, devices are protected, and privacy is respected. The communication system measures,

collects, stores, and facilitates interaction between all devices. Wireless Sensor Networks (WSNs) typically consist of a large number of sensor nodes—ranging from hundreds to thousands—deployed over a geographical area. These wireless sensor nodes are compact, lightweight, and battery-powered, making them suitable for use in nearly any environment. WSNs enable utilities and customers to effectively transfer, monitor, predict, and manage energy usage. They are recognized as one of the most promising technologies for smart grid applications due to their low complexity and cost-effectiveness. Furthermore, the smart grid can be viewed as a combination of several microgrids, with each microgrid operating autonomously within its own supervisory control and data acquisition (SCADA) system. SCADA is a control system designed for managing large-scale, automated industrial operations. When applied to the electric power industry, it helps save time and money, reduce operational costs, and improve efficiency. SCADA provides real-time monitoring and automation for the smart power grid and is extensively integrated with external systems, serving as both the control system and the communication network [13].

Smart meters are the first step towards establishing a smart grid. These wireless, high-tech digital communication devices replace traditional analog electricity meters, allowing remote readings. Essentially digital meters, smart meters read energy consumption over a secure wireless network. They are a crucial component of smart grid infrastructure, enabling real-time monitoring of energy usage and billing, as well as the measurement of voltage and frequency, the connection and disconnection of loads, and the communication of diagnostic information for efficient energy use. The smart meter, along with the home area network (HAN), advanced sensors, control systems, standardized software interfaces, and information management systems, facilitates the exchange of information between consumers and utilities. Collectively, these elements comprise the advanced metering infrastructure (AMI), which includes the SCADA center, smart meters, and wireless sensor networks [14]. AMI allows automatic readings of customer power consumption, enabling utilities to automate billing from a centralized interface.

4.2. The Security of Smart Grid

A nation's security, economic prosperity, and citizens' well-being depend on reliable and secure energy infrastructure. Because energy systems are critical to national stability, governments and private industries must work together to protect them from physical and cyber threats.

As smart grids increasingly rely on computer communication networks to manage energy generation, distribution, and consumption, they become more exposed to vulnerabilities and cyberattacks. The potential impact of these attacks can be significant because disruptions to the grid can affect public safety, economic activity, and essential services. For this reason, cybersecurity is a critical requirement for a sustainable modern grid. Security refers to the level of protection the grid provides against possible loss, damage, or unauthorized interference. As the Internet of Things continues to expand, the number of connected devices within the smart grid also increases, creating more opportunities for malicious actors to exploit weaknesses. A breach of smart grid security can seriously undermine its reliability [15].

The smart grid has several unique security requirements and

objectives [16]. These objectives include availability, authentication, confidentiality, nonrepudiation, and integrity. Availability refers to the ability of the smart grid to maintain correct operation even under adverse conditions. In power systems, availability is usually the highest priority because users depend on continuous and reliable access to electricity. Attacks that target availability often result in denial-of-service incidents, which can disrupt communication and system operations. Authentication, by contrast, verifies the identity of users, devices, or systems attempting to access the network. Common authentication methods include usernames, passwords, certificates, and other validation mechanisms. Together, authentication and integrity help protect the smart grid against impersonation, forgery, and man-in-the-middle attacks.

Confidentiality ensures that smart grid information is accessible only to authorized individuals or systems. This is especially important for privacy-sensitive data, such as users' personal information and meter readings. Nonrepudiation provides assurance that an entity cannot deny responsibility for an action. For example, a sender should not be able to deny sending a message, and a receiver should not be able to deny receiving it. This objective supports accountability and liability. Integrity ensures that data, devices, and processes remain accurate and free from unauthorized modification, deletion, injection, or corruption. When integrity is compromised, nonrepudiation may also be affected.

Security threats in the smart grid typically aim to compromise one or more of these security objectives. Because the smart grid depends heavily on computer networks, it is vulnerable to a range of security and privacy risks. Cyber attackers may target the grid through different methods, including unauthorized access, malicious attacks, and privacy violations. Physical-layer security in the smart grid also addresses unauthorized access, malicious activity, and privacy concerns [17]. Some common threats to smart grid communication networks include the following [18].

Unauthorized access is a major security threat because it can involve improper access to data, devices, systems, or networks. Effective access control should include user authentication, network access control, and device authentication to ensure that only authorized entities can interact with smart grid resources.

Malicious attacks occur when individuals or groups target the communication infrastructure in ways that damage or disrupt smart grid operations. These attacks can include eavesdropping, jamming, and injection attacks [19]. Through eavesdropping, an unauthorized actor can monitor data transmissions and gain access to sensitive information, thereby violating confidentiality requirements. Jamming interferes with or blocks the flow of information across the network. Injection attacks introduce false or misleading data into the system, which can misguide the control center and lead to improper decisions.

Privacy issues are also a major concern because smart grids may collect or transmit personal information. This information can include a customer's name, address, account number, billing history, meter IP address, and service provider details. Therefore, smart grid security must protect sensitive data while also balancing operational needs and individual privacy.

Computer networks do not operate in isolation, and the human factor plays an important role in cyber-defense operations. Cyberattacks may originate from many sources,

including individual hackers, disgruntled former employees, terrorist groups, or foreign actors. To reduce the risk of malicious activity, analysts must continuously monitor and protect smart grid systems ^[20].

Several mechanisms are needed to secure a smart grid, including authentication protocols, cryptographic algorithms, firewalls, anomaly detection, and intrusion detection systems ^[21].

Authentication confirms the identity of any entity attempting to access the network. Firewalls are also highly important because they help protect smart grid assets from malicious cyberattacks. In addition, anomaly detection uses event correlation to identify possible cyber intrusions, while intrusion detection systems help prevent, detect, and tolerate attacks within smart grid environments.

Encryption should also be a basic requirement for smart grid systems. By enabling secure communication among smart grid devices, encryption helps protect sensitive information

from unauthorized access and supports the overall reliability and security of the grid.

5. Smart Grid Applications

Applications for smart grid technologies can be found everywhere in the world. Smart grid has worldwide applications, with each nation having slightly different goals in pursuing smart grid technologies. Electricity uses are evolving positive-energy buildings, electric mobility, variable-intensity urban lighting, storage batteries, etc. New uses include renewable energies, electric vehicles, and connected houses. Applications of smart grid technology include integrating renewable energy sources, demand response and energy management, electric vehicle (EV) integration, and implementing self-healing mechanisms to improve grid resilience. Figure 3 shows some applications of smart grid ^[22]. Common applications include the following ^[23, 24].

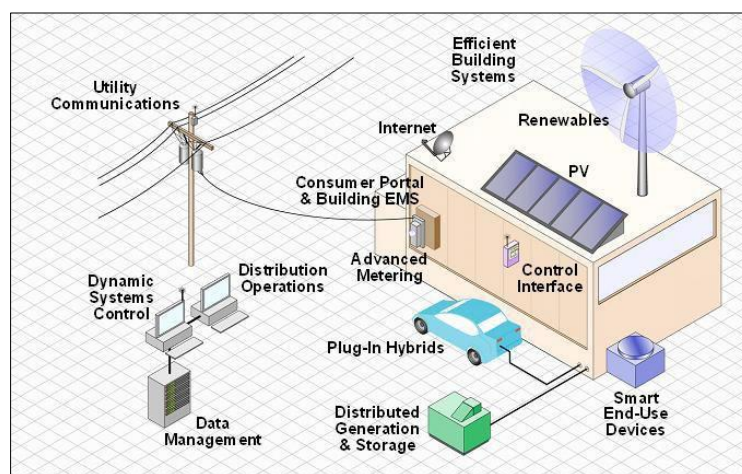


Fig 3: Some applications of smart grid ^[22].

- Renewable Energy Sources (RES):** One of the most critical applications of smart grids is the seamless integration of renewable energy sources (RES), such as solar and wind power. Smart Grids support the integration of renewable energy sources. To meet the world's energy appetite, renewable energy technologies are becoming increasingly feasible and offer alternative generation options. Since the energy crisis in the 1970s, the development of renewable energy has received great attention. Renewable energy comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished) forms of energy. It relies upon the natural forces at work on the earth. It is often inexhaustible in duration but limited in the amount of energy available per unit time. Renewable energy often displaces conventional energy in four important areas: electricity generation, water cooling/ heating, transportation, and rural energy services ^[25]. Renewable energy sources (RESs) and energy storage systems (ESSs) are the key technologies for smart grid applications. The most rapidly expanding renewable resources are expected to be wind and solar. Smart grid technologies enable high levels of renewable integration in an electricity system.
- Electric Vehicles:** An area with the potential for increased electricity consumption is transportation. A growing number of automobile manufacturers are introducing plug-in EVs (PEVs), which can drastically reduce our dependence on oil and emit no air pollutants when running in all-electric modes. The smart grid will have the infrastructure needed to enable the efficient use of this new generation of PEVs. The key factor for acceptance of PEVs in the marketplace will be the availability of charging stations ^[26].
- Smart Home:** Smart homes should be regarded as the building blocks of smart cities and intelligent communities. It is becoming a reality in the developed world, with energy efficiency and carbon footprint reduction riding high on the agendas of most governments and states. The main objectives of a smart home are to improve the quality of life, increase automation, facilitate energy management, and minimize environmental emissions. Smart homes automate electrical devices and control the environment inside ^[27]. Figure 4 illustrates a typical smart home ^[4].

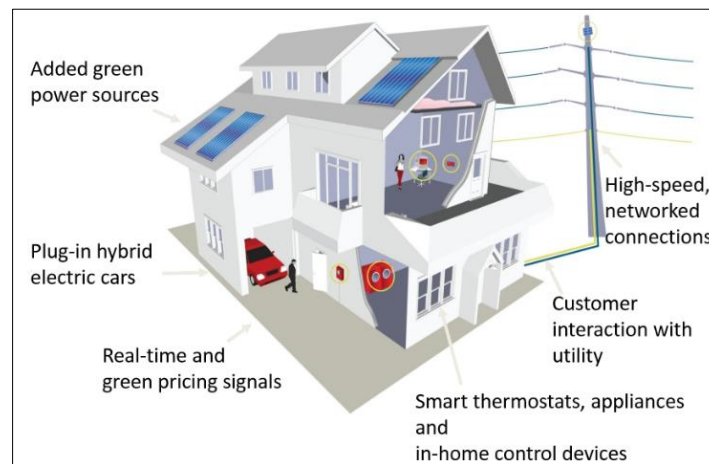


Fig 4: A typical smart home [4].

- **Advanced Metering Infrastructure (AMI):** At the consumer level, Advanced Metering Infrastructure (AMI), centered around smart meters, is a foundational element. The system includes smart meters, communication networks, and data management systems to enable two-way communication between utilities and consumers. Smart meters provide detailed, real-time data on energy consumption, empowering users to make informed decisions and participate in dynamic pricing schemes. They allow homeowners to monitor their energy usage in real time, enabling them to adjust their consumption patterns and reduce costs. They record energy consumption in real time and transmit the data back to the utility. This two-way communication enables dynamic pricing models, such as time-of-use rates, which incentivize consumers to shift their energy usage to off-peak hours. AMI also facilitates rapid outage detection and enables utilities to manage demand more effectively.
- **Energy Storage Systems:** Energy storage is the critical buffer in a renewable-heavy grid. Advanced battery technologies, such as lithium-ion and emerging solid-state batteries, store excess energy generated during periods of high renewable output (e.g., sunny afternoons or windy nights) and discharge it when demand peaks or renewable generation drops. Beyond batteries, long-duration energy storage solutions, including pumped hydro and compressed air, are essential for ensuring grid reliability over extended periods of low renewable availability.
- **Demand Response:** Demand response (DR) is a cornerstone application of smart grids, fundamentally changing how energy consumption is managed. These are programs and technologies that allow consumers to adjust their electricity usage in response to supply conditions, often incentivized by dynamic pricing. DR programs incentivize consumers to adjust their electricity use during peak-demand periods, thereby alleviating strain on the grid and reducing the need for expensive, carbon-intensive “peaker” power plants.
- **Digital Twins:** A rapidly emerging technology in grid management is the “digital twin”—a virtual replica of the physical electrical grid. By integrating real-time sensor data with advanced analytics, a digital twin enables operators to simulate scenarios, assess the impact of integrating new DERs, and optimize load

distribution without risking the physical infrastructure. This capability is crucial for proactive grid management and strategic planning.

- **Microgrid:** A microgrid is a localized grid that can operate independently or in conjunction with the main grid, often incorporating renewable energy sources and energy storage systems. The proliferation of microgrids will enhance local resilience. Microgrids, powered by local solar and battery storage, are becoming vital for critical facilities like hospitals and military bases, ensuring power continuity even if the central grid fails.
- **Smart Appliances:** These appliances are set to consumer’s predefined preference level, and they have an idea of when to consume energy at what level. These tech appliances have an important impact on grid generators, as they help in understanding the power position and reducing peak load factors.
- **Smart Substations:** Substations are located in every region as a sub-branch for their main station. They monitor the station's performance and control critical and non-critical data, including power status, power performance, circuit breakers, security, and transformer operation. Smart grid substations require heavy equipment and workforce to be fully operational. This equipment may include transformers, switches, capacitor banks, circuit breakers, and a network-protected relay.

6. Future of Smart Grid

The smart grid is currently a topic of significant public interest, as it offers a way to create a more efficient, renewable electricity grid infrastructure. Utility companies are acutely aware of the challenges associated with transitioning their systems toward an uncertain future. Future smart grids are expected to be more closely integrated with cyber infrastructure for functions such as sensing, control, scheduling, dispatch, and billing. Moreover, the increase in distributed generation from intermittent renewable energy sources, combined with rising local demand, is anticipated to pose substantial challenges to existing electricity grids. The security and privacy of smart grids and smart metering networks are crucial for gaining public acceptance. Users of smart meters need to feel confident that their data is protected. These smart meters and other intelligent energy technologies have the potential to enhance energy efficiency and possibly reduce electricity costs. Ideas regarding the evolution of the smart grid abound, often presenting it as a

technological solution for greener power systems. The planning and design of smart grids require collaboration between designers and engineers to integrate diverse elements and create a cohesive vision for the future of electricity consumption. One essential aspect of future smart grids will be the automated control of consumer electricity loads [28]. The future of the smart grid is inextricably linked to the future of global energy. It will transform three key concepts: decentralization, digitalization, and decarbonization. Developing a smart grid is an evolutionary process that necessitates cooperation among utilities, technology providers, universities, regulatory bodies, and

research and development organizations. The US Department of Energy is actively promoting innovations in smart grid technologies, and additional research and development are needed to support the deployment of smart grids nationwide. Currently, countries such as those in Europe, the United States, and Japan have explored the development of smart grids and advanced metering infrastructure. Their ultimate objective is to achieve complete automation of the smart grid, from power generation to distribution. As we look to the future, smart grids will continue to evolve to address emerging challenges and seize opportunities in the energy sector. Figure 5 shows the smart grid of the future [29].

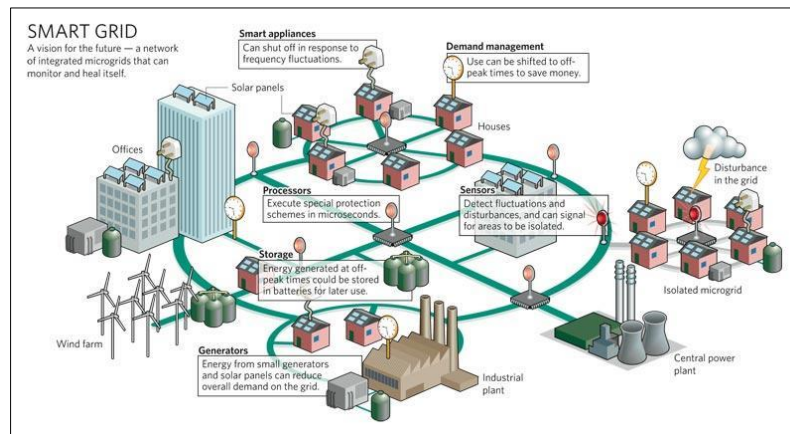


Fig 5: Smart grid of the future [29].

7. Smart Grid Worldwide

Worldwide, electrical grids are aging. The basic structure of the electrical power grids has remained unchanged for about 100 years. The grids are being adapted to meet modern needs such as communication and information technologies. Therefore, government bodies, research organizations, electric utilities, grid operators, and consumers worldwide are opting for a smarter grid. The smart grid has emerged as the next-generation electric power system.

The smart grid is one of the most engineered systems of our modern times. A pressing concern for national energy security, climate change, and grid reliability has ushered in an increased political will to deploy smart grid technologies around the globe. Each nation has plans and programs for deploying smart grid technologies. Nations are investing to transform their traditional power grids into smart grids, which are expected to become the new industry platform. The worldwide smart grid initiative involves a complete transformation of the networking infrastructure used to manage the power grid with billions of connected devices. This is a colossal task that must be done. Examples are presented as follows: the worldwide adoption of the smart grid.

In the United States, the National Grid has chosen to implement smart grid in a unified manner. In the late 1990's, a supervisory control and data acquisition (SCADA) pilot was conducted on the distribution system. Before the smart grid can be fully deployed in the US, three things must occur. First, federal resources must be directed to smart grid innovations. Second, regulators, industry, and consumers must renegotiate the traditional regulatory compact with the specific intent of designing a clean energy future. Third, incumbent private utilities will have to retool their business models to optimize their use of available funds [30].

The European Union (EU) countries invest heavily in upgrading their electrical systems to smart grids. The EU has a policy requiring each member to increase the share of renewable energy in electricity generation by 2020. For example, the United Kingdom provides extensive information about its smart grid, ensuring that everything is readily available for learning. UK government regulation of electricity grids both enables financialization and forecloses opportunities to manage the infrastructure for wider environmental and public benefit.

China, as a fast-developing country, has the largest installed wind power capacity. It faces a far more complicated situation than Europe and North America. In China, the pressure on the current power grid due to growing demand, environmental issues, and an unbalanced energy mix makes the transition to a "smarter" and "cleaner" grid inevitable. China seeks a smart grid as a solution to its energy problem and as a means to spur technological breakthroughs. The nation is devoted to research into cutting-edge technologies, such as renewable energy, microgrids, and EVs [31].

In Canada, the Canadian law emphasizes the importance of protecting consumer privacy and places the responsibility on data collectors, i.e., grid operators and utility companies. It is expected that Plug-In Hybrid Electric Vehicles (PHEVs) will find a niche market in the near future, given the expected smart grid in Canada [32]. In Ontario, Canada is in the midst of a large-scale Smart Grid initiative, deploying a standards-compliant communications infrastructure from Trilliant.

8. Benefit

A smart grid is an intelligent electricity network that uses communication technologies, smart meters, sensors, and automated control systems to manage distributed energy resources more effectively. Its key benefits include a more

reliable power supply, lower transmission and distribution losses, improved grid security, and support for market-based electricity pricing. Smart grids also help reduce transmission congestion, minimize blackouts and forced outages, diagnose and respond to faults, reduce peak demand, increase system capacity, strengthen power-system security, and support the management of hybrid and electric vehicles. Other benefits include ^[23]:

One of the most important promises of the smart grid is improved reliability and security. At the same time, smart grids can be targets for cyberattacks, and smart grid protocols vary widely in their security features and vulnerabilities. When properly designed and protected, however, a smart grid can provide higher efficiency, greater transparency, and better service for electricity consumers.

The smart grid represents the modernization of power infrastructure. It offers a significant opportunity to move the energy industry toward greater reliability, availability, and efficiency. Delivery companies, suppliers, consumers, and society as a whole can benefit from the opportunities created by smart grid technologies.

Smart meters: Smart meters replace traditional analog meters and enable two-way, real-time communication between utilities and customers. This communication gives both parties the information they need to reduce costs, manage demand, and limit waste. Customers no longer must wait for a monthly statement to understand how much electricity they have consumed.

A smart power grid can support cleaner and more efficient

energy delivery. It can help improve air quality, reduce greenhouse gas emissions, promote clean energy, manage energy-consumption patterns, and strengthen grid security. Smart grids also make it easier to use renewable energy sources and integrate customer-owned power generation, such as rooftop solar systems.

Extreme weather events and equipment failures pose significant threats to grid reliability. Smart grids address these threats through “self-healing” capabilities, which allow the system to automatically detect, isolate, and respond to faults without direct human intervention. Using intelligent electronic devices and automated switches, a self-healing grid can identify a disruption within milliseconds. It can then reroute electricity through alternative pathways, restore power to most customers, and isolate the damaged section for repair.

Environmental sustainability is another major promise of smart grid technology. The transition to a low-carbon economy depends heavily on integrating variable renewable energy sources, such as wind and solar power. Because these sources are intermittent, they create challenges for traditional grids, which must continuously balance electricity supply and demand. Smart grids provide the flexibility and intelligence needed to manage this variability. The Pacific Northwest National Laboratory has estimated that smart grid technologies could reduce utility-sector carbon emissions by up to 15% annually by 2030. Some of the benefits of the smart grid are shown in Figure 6. ^[33].

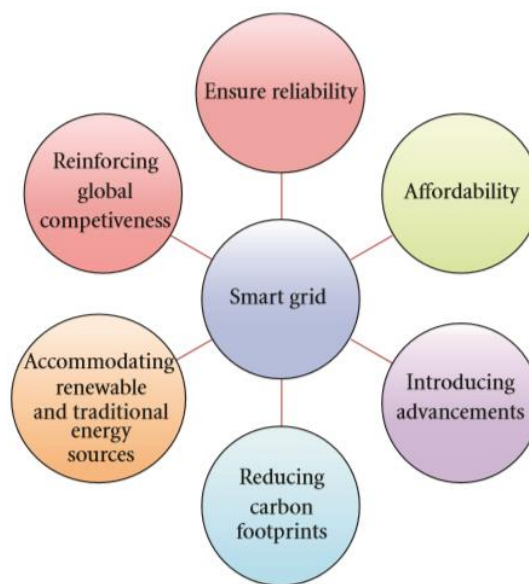


Fig 6: Some benefits of the smart grid ^[33].

9. Challenges

Despite the many benefits of the smart grid, its implementation involves several risks and challenges. Major concerns include cybersecurity, interoperability, regulatory requirements, and the need for substantial capital investment. Rebuilding and modernizing the existing electrical grid is also expected to be both time-consuming and costly. Other challenges include the following ^[23, 24]:

Although smart grids provide significant benefits, their high implementation cost remains a major disadvantage.

The transition to smart grids requires significant investment in infrastructure, technology, and workforce training.

Upgrading existing power systems with advanced capabilities such as Advanced Metering Infrastructure (AMI), automated grid management tools, and energy storage systems involves substantial financial commitment. Although smart grids offer long-term benefits in reliability, efficiency, and environmental sustainability, the high initial cost can slow widespread adoption. Therefore, effective funding mechanisms and financial incentives are essential to support smart grid development and deployment.

Cybersecurity is also a major challenge in smart grids. One of the most pressing concerns is the increased exposure to cyber threats. By transforming a traditionally isolated

physical network into an interconnected Internet of Things (IoT)-based system, the smart grid greatly expands the attack surface available to malicious actors. Smart grids depend on Advanced Metering Infrastructure (AMI), smart sensors, and Supervisory Control and Data Acquisition (SCADA) systems. Because these components communicate through Internet-based protocols, they are vulnerable to a wide range of cyberattacks.

Privacy concerns are closely linked to cybersecurity. Smart meters collect highly detailed data, often at minute-by-minute intervals, unlike traditional meters that typically record monthly usage. Although this data is valuable for demand response and load balancing, it can also reveal sensitive information about household routines, appliance use, and occupancy patterns. Without strong data governance, encryption standards, and clear consumer consent frameworks, the widespread deployment of smart meters may face significant public resistance. Defending SCADA systems from cyberattacks is also difficult because of the wide range of attack methods, decentralized control structures, deregulation, and limited coordination among entities within the electric grid.

Electricity service providers also face practical challenges when implementing smart meters. Replacing old analog meters requires substantial investment, and managing the large volume of data generated by smart meters can be complex. In addition, the absence of consistent standards for advanced metering systems creates interoperability concerns. Ensuring that equipment from different vendors can work together is essential for successful smart grid development.

Load shaping is another important challenge in power grid management. With energy storage systems in place, consumers can optimize energy use by adjusting charging and discharging patterns according to demand and electricity prices. This process supports optimal load shaping, but it also requires reliable technology, accurate forecasting, and effective control strategies.

The smart grid ecosystem includes many manufacturers that develop proprietary software and communication protocols. When utilities integrate devices from different vendors, they may encounter siloed systems that cannot exchange actionable data. This fragmentation limits holistic grid optimization and reduces overall efficiency.

Legacy infrastructure, including aging transformers, substations, and transmission lines, is increasingly vulnerable to failure and can contribute to more frequent power outages. Upgrading these systems to support smart grid technologies, such as bidirectional power flow and high-voltage transmission, requires major capital investment. Modernizing the U.S. grid is expected to require hundreds of billions of dollars over the coming decades.

A skills gap is another significant challenge. As the grid evolves from a primarily electromechanical system into a highly digitized, AI-driven network, the skills required to operate and maintain it are changing rapidly. The energy sector faces a shortage of qualified personnel, which may hinder the successful implementation of smart grid technologies.

Finally, interoperability remains a major concern. The smart grid consists of many devices and software systems from different vendors and ensuring that these systems communicate and operate seamlessly is a significant technical challenge. A lack of universal industry standards can lead to fragmented systems, limiting scalability and

efficiency. Developing and enforcing open communication protocols is therefore essential for achieving true interoperability.

10. Conclusions

The energy sector, which includes electricity, natural gas, and petroleum, is one of the 16 critical infrastructure sectors designated by the Department of Homeland Security. Modern society depends heavily on these sectors, and the energy sector is especially important. Because of this dependence, the U.S. power grid has long been viewed as a likely target for a major cyberattack.

Electricity is essential in the modern world, and the smart grid represents the latest major development in electric power systems. It is commonly understood as a digital upgrade to the existing power grid. By combining sensors, communication technologies, and control systems, the smart grid enables two-way communication between electricity providers and consumers.

The transition to smart grids is more than an infrastructure upgrade; it is a major change in how society generates, distributes, and uses energy. Future smart grids should improve the security, reliability, and efficiency of power systems. However, implementation will be a long, continuous process because it requires significant technological and financial investment, as well as international cooperation. Governments will also need clear policies to guide smart grid development. As smart grid technology becomes more common in homes, greater attention will be placed on consumer awareness, adoption, and services.

The smart grid is widely considered the future of the power system because it offers greater flexibility, reliability, efficiency, and intelligence. These capabilities create new possibilities for improving grid operations and electricity delivery. Smart grids have already transformed the energy sector by making power systems faster, more reliable, and more efficient. For additional information about smart grids, readers may consult the books listed in ^[1,5,9,34–46] and the two related journals listed below:

- IEEE Transactions on Smart Grid
- IEEE Power & Energy Magazine

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