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Research Article

Smart Grid Technologies Moving Toward Two-Way Communication in the Digital Age

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Abstract

The convergence of cutting-edge technologies, including Power Electronics Interfaces, the Fourth Industrial Revolution, Cloud Computing, Block chain, and the Internet of Things (IoT), has heralded a new era of Machine-to-Machine (M2M) connectivity, fundamentally transforming the landscape of modern power systems. These technological advancements are driving the evolution of power systems toward greater automation, reliability, resilience, and sustainability, all while aligning with the imperatives of green and clean energy. The Smart Grid emerges as an electro-information ecosystem, seamlessly integrating two-way, cyber-secure communication technologies and computational intelligence across all facets of the power system, including generation, transmission, substations, distribution, and consumption. This paradigm shift aims to achieve an energy system that is clean, secure, safe, reliable, resilient, efficient, and sustainable. This paper presents a comprehensive literature survey on the key technologies enabling the Smart Grid. It delineates two critical components: The Smart Infrastructure System and the Smart Management System. Furthermore, the paper outlines prospective future guidelines for the development and implementation of these systems, offering valuable insights for advancing the next generation of intelligent power systems.

Keywords

Smart Grid, Microgrid, Smart Management & Networking, Future Grid

1. Introduction

The traditional power grid, which primarily relied on centralized generation and unidirectional power flow, is evolving rapidly to meet the demands of the 21st century. With the increasing integration of renewable energy sources, rising energy consumption, and the need for greater operational efficiency, the limitations of conventional grid systems have become apparent. This has necessitated the transition to a more advanced and intelligent system known as the Smart Grid [1].

The Smart Grid represents a transformative approach to electricity generation, transmission, distribution, and consumption. By incorporating advanced communication technologies, computational intelligence, and cyber-secure frameworks, it facilitates bidirectional energy and data flows across the entire power network. This two-way communication capability, a hallmark of the Smart Grid, enables real-time monitoring, control, and optimization of grid operations while fostering consumer participation through demand response and distributed generation [2].

In the digital age, the convergence of cutting-edge technologies such as the Internet of Things (IoT), Block chain, Cloud Computing, Artificial Intelligence (AI), and Power

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Electronics has accelerated the evolution of the Smart Grid. These technologies support the integration of decentralized renewable energy sources, enhance grid resilience, and enable predictive maintenance, thereby ensuring reliable and sustainable energy delivery. Moreover, the Smart Grid aligns with global initiatives to mitigate climate change by reducing carbon emissions and promoting clean energy transitions [3].

This paper focuses on the enabling technologies driving the Smart Grid's evolution and their role in achieving a more intelligent, resilient, and sustainable energy system. The study examines two critical systems: The Smart Infrastructure System, which underpins the physical and cyber infrastructure of the grid, and the Smart Management System, which optimizes grid performance and resource utilization. Additionally, the paper proposes future directions and guidelines to address existing challenges and advance the deployment of Smart Grid technologies in the digital age [4].

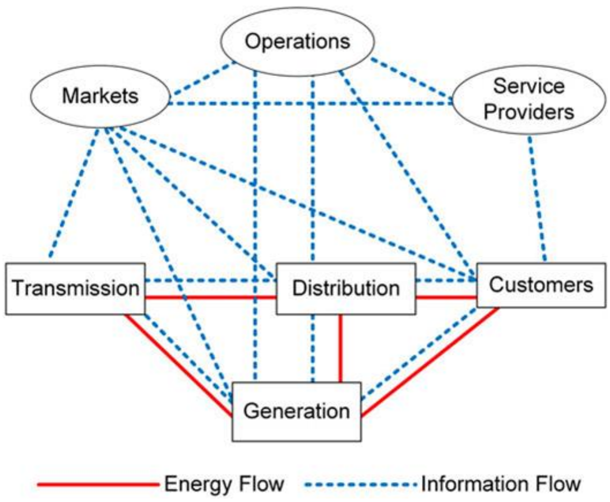

Figure 1. *Conceptual model of a smart grid.*

1.1. Smart Infrastructure System

The Smart Infrastructure System forms the backbone of the Smart Grid, comprising energy, information, and communication infrastructures that enable its functionality. It supports the bidirectional flow of both electricity and information, marking a significant departure from the traditional unidirectional power grid. While the concept of “two-way flow of information” is straightforward, the idea of “two-way flow of electricity” introduces a transformative paradigm. In conventional power grids, electricity is typically generated at centralized power plants, transmitted through high-voltage grids, distributed via lower-voltage networks, and finally delivered to end users. However, in a Smart Grid, electricity can flow in reverse, enabling users to feed energy back into the grid. For instance, homeowners equipped with solar panels can generate excess electricity and supply it back to the grid, contributing to overall energy availability. Similarly, electric vehicles can assist with load balancing by transferring stored energy back to the grid during periods of peak demand, a process known as “peak shaving. “This bidirectional energy flow is particularly critical in scenarios such as Microgrid operations. In the event of an islanded Microgrid caused by power failures, the energy fed back by consumers can help maintain functionality, even if at a reduced level. Such capabilities enhance the resilience and adaptability of the Smart Grid. This survey categorizes the Smart Infrastructure System into three interconnected subsystems: The Smart Energy Subsystem, the Smart Information Subsystem, and the Smart Communication Subsystem. Before delving into these components, it is essential to first provide an overview of the Smart Grid and its underlying principles [1, 5, 6].

1.2. Smart Grid Overview

A typical Smart Grid structure, as illustrated in Figure 1, encompasses four primary subsections: generation, transmission, distribution, and the control network. These networks are interconnected across various locations, with seamless information exchange facilitated by the Smart Communication Subsystem. This subsystem employs wired or wireless communication infrastructures, such as access points, to ensure reliable data flow. Raw information regarding the network's health and performance is gathered through the Smart Information Subsystem, which incorporates advanced devices like smart meters, sensors, and phasor measurement units. Real-time monitoring, management, and control of the network are conducted at the control network, often represented by an electric utility control center.

The distribution network, in particular, exhibits flexibility as it can function independently when embedded with dispersed generation sources such as renewable energy resources. This integration allows electricity to be supplied from both distributed generation and the utility, enhancing the system’s adaptability and sustainability [7-9]. The Smart Grid offers numerous anticipated benefits and fulfills key requirements, including:

1. Improving power reliability and quality,
2. Optimizing resource utilization while avoiding the need for backup (peak load) power plants,
3. Enhancing the capability and efficiency of active electric power networks,
4. Increasing resilience to interruptions,
5. Supporting predictive maintenance and self-healing mechanisms for system disturbances,
6. Promoting the extensive use of renewable energy sources,
7. Enabling cooperative distributed power generation,
8. Automating protection and operation processes,
9. Reducing greenhouse gas emissions by supporting electric vehicles and advanced power sources,
10. Minimizing oil consumption by reducing inefficient peak-period generation,
11. Enhancing grid security,

12. Enabling the adoption of plug-in electric vehicles and advanced energy storage technologies,
13. Expanding consumer choices, and
14. Fostering innovation through new products, services, and market opportunities.

1.3. Smart Energy Subsystem

The bidirectional flow of electricity and information constitutes the foundational infrastructure of the Smart Grid, distinguishing it from traditional power systems. This infrastructure is organized into three critical subsystems: The Smart Energy Subsystem, the Smart Information Subsystem, and the Smart Communication Subsystem. This section delves into existing research on the Smart Energy Subsystem, highlighting its advancements, current challenges, and prospective research directions.

In contrast, the conventional power grid is inherently unidirectional in its operation. Electricity is primarily generated at centralized power plants that rely on electromechanical generators, driven either by the kinetic energy of flowing water or by heat engines powered through chemical combustion or nuclear reactions. To maximize economies of scale, these generation facilities are typically large and situated far from densely populated areas.

Once generated, electrical power is stepped up to high voltages for transmission over long distances via the transmission grid. At substations, the voltage is stepped down to distribution levels before entering the distribution grid. Finally, it is further reduced to meet specific service voltage requirements at the point of consumption. Figure 2 illustrates the conventional power grid, emphasizing its linear and unidirectional flow of electricity.

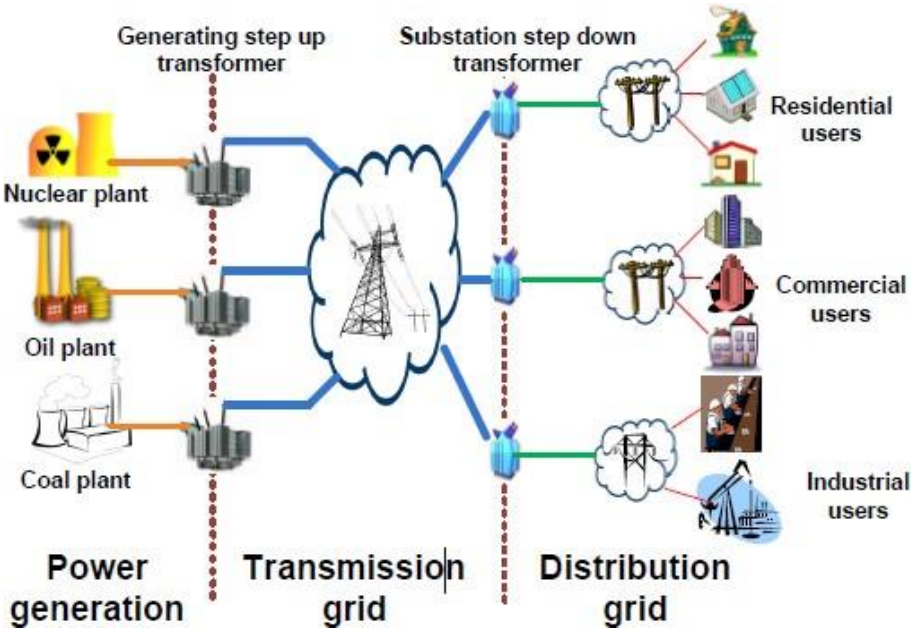

Figure 2. *An Example of the Traditional Power Grid.*

The Smart Grid, however, introduces a transformative and flexible paradigm in electricity generation and consumption. Unlike its traditional counterpart, the distribution grid in a Smart Grid can also function as a source of electricity. Distributed energy resources (DERs) such as solar panels and wind turbines enable localized power generation, with the capability to feed surplus electricity back into the grid when necessary. This bidirectional energy flow enhances the adaptability and resilience of the grid while fostering the integration of renewable energy sources.

This paper further deconstructs the Smart Energy Subsystem into three core components: Power Generation, the Transmission Grid, and the Distribution Grid. Each of these components is critically examined to explore the transformative impact of Smart Grid technologies. Additionally, the discussion identifies existing challenges and outlines opportunities for future research aimed at optimizing and advancing these components within the context of the Smart Grid [10-14].

1.4. Power Generation

Electricity generation involves converting various forms of energy—such as natural gas, coal, nuclear power, solar energy, and wind—into electrical energy. This process is grounded in the principles discovered by British scientist Michael Faraday during the 1820s and 1830s. Faraday demonstrated that electricity could be generated by moving a loop of wire or a copper disc between the poles of a magnet, a principle that remains fundamental to electricity generation today. While fossil fuels have historically dominated electricity generation, the depletion and rising costs of these resources make renewable energy an increasingly important component of future energy systems.

Unlike conventional power generation, which operates in a unidirectional manner, Smart Grid technology enables smarter power generation through its support for bidirectional flows of electricity and information. One transformative paradigm facilitated by the Smart Grid is Distributed Generation (DG), which leverages Distributed Energy Resources (DERs) such as solar panels and small wind turbines. DG systems, typically ranging from 3 kW to 10,000 kW in capacity, enhance power quality and reliability. For instance, a Microgrid—a localized network of electricity generators and loads—can isolate itself from the Microgrid during disruptions. This capability ensures that distributed generators within the Microgrid continue to supply power locally, thereby improving the overall quality and resilience of the energy supply.

The International Energy Agency (IEA) has highlighted the potential of power systems based on numerous reliable small-scale DG units. Such systems can achieve reliability comparable to traditional large-scale generators but with a lower capacity margin, contributing to a more efficient and resilient grid. Distributed energy technologies, including micro turbines, photovoltaic systems, fuel cells, and wind turbines, offer promising solutions; however, their practical deployment faces significant challenges.

One primary issue with DG is the variability of renewable energy sources like solar and wind, which are subject to wide fluctuations. This inconsistency creates a mismatch between generation patterns and electricity demand, necessitating efficient utilization strategies that account for this variability. Furthermore, the high capital costs associated with DG systems must be balanced against their potential to improve power quality and reliability. Systematic research is essential to optimize DG deployment, particularly as the Smart Grid evolves toward greater decentralization [8, 15-17].

The transition to a decentralized power system with DG can be envisioned in three stages:

1. Integrating DG into the existing power system.
2. Developing a hybrid system where DG cooperates with centralized generation.
3. Shifting to a predominantly DG-based power system with minimal reliance on central generation.

The integration of Distributed Generation (DG) empowers users to deploy their own power generation units, fundamentally redefining the conventional design of power grids, where generation has traditionally been centralized and linked primarily to the transmission network. The widespread adoption of DG has also facilitated the emergence of the Virtual Power Plant (VPP), an innovative paradigm that aggregates multiple distributed generators into a unified system managed through centralized control. A VPP offers the collective capacity of a traditional power plant while surpassing it in efficiency and operational flexibility. This flexibility enables the system to adapt dynamically to variations in energy demand and supply, thereby enhancing grid stability and responsiveness. However, the intricate structure of a VPP necessitates the deployment of advanced optimization techniques, robust control strategies, and secure communication protocols to ensure seamless and effective operation. As the Smart Grid continues to evolve, the integration of DG and VPPs is poised to play a pivotal role in fostering a decentralized, resilient, and highly efficient energy ecosystem, paving the way for a more sustainable and adaptive power infrastructure.

1.5. Transmission Grid

On the power transmission front, the evolution of smart transmission grids is driven by a confluence of factors, including infrastructure challenges such as increasing load demands and aging components, as well as the integration of novel technologies like advanced power electronics, new materials, and modern communication systems. The smart transmission grid represents an integrated system that encompasses three key interactive components: smart control centers, smart power transmission networks, and smart substations.

Smart control centers in the future will offer enhanced capabilities for systematic analysis, real-time monitoring, and strategic decision-making. These advanced features will enable more effective management of the transmission grid, ensuring greater efficiency and reliability.

Smart power transmission networks, while based on the existing electrical transmission infrastructure, will leverage cutting-edge technologies such as new materials, advanced electronics, and sophisticated sensing and communication systems. These advancements will enhance power utilization, improve power quality, and bolster system security and reliability. The integration of such technologies will pave the way for innovative structural architectures in transmission networks, meeting the growing demands of a modernized grid.

Smart substations, a cornerstone of the smart transmission grid, represent a significant leap in substation technology. Although the core configurations of high-voltage substations have remained relatively unchanged over time, the monitoring, measurement, and control systems have undergone substantial advancements. Smart substations will embody features like digitalization, automation, coordination, and self-healing capabilities. These attributes will not only improve operator safety but also ensure rapid and efficient responses to grid anomalies, further strengthening the resilience of the power system.

In summary, the smart transmission grid, underpinned by a unified digital platform, will enable greater flexibility in control and operation, facilitate embedded intelligence, and enhance the overall resilience and sustainability of the grid. By adopting such advancements, smart transmission grids will play a pivotal role in shaping the future of reliable and efficient power systems [3, 18-21].

1.6. Distribution Grid

In the distribution grid, the primary challenge lies in efficiently delivering power to end users while adapting to the complexities introduced by integrating numerous distributed generators. While the inclusion of distributed generation enhances system flexibility and resilience, it simultaneously complicates power flow management. This necessitates the development of smarter power distribution and delivery mechanisms to ensure optimal performance. Two innovative approaches have emerged for addressing these challenges: the alternating current (AC) circuit switching system and the direct current (DC) power dispatching system utilizing power packets. The AC-based system represents the traditional method of power distribution, while the DC-based approach introduces a revolutionary concept of energy packetization. In this method, electrical energy from generation sources is divided into discrete units, or "packets," each comprising a payload accompanied by a header and a subtitle. These headers contain routing information, enabling the packets to be sorted and directed to their respective destinations using intelligent routers. This ensures precise synchronization of power delivery by controlling the number of packets sent, offering a flexible and efficient mechanism for managing power flows. The concept of energy packetization, while innovative, presents significant challenges due to the need for advanced high-power switching devices capable of handling the segmentation and routing processes. Nevertheless, the DC-based distribution system holds promise, particularly for in-home power distribution, where many devices operate on DC power and incorporate built-in circuits to convert AC input voltage. By utilizing DC power directly, these systems can simplify in-home energy distribution, improve efficiency, and enhance the ease of control over power flows. Ultimately, these advancements in distribution grid technologies not only address the growing complexity of power flow management but also lay the groundwork for more efficient, reliable, and user-centric energy delivery systems in the era of smart grids [4, 14, 22-30].

1.7. Microgrid

Distributed generation is driving the evolution of a new grid model known as the Microgrid [2], which is considered one of the foundational elements of the future Smart Grid. The anticipated progression of the Smart Grid is expected to occur through the seamless integration of MicroGrids in a plug-and-play manner. A Microgrid is a self-contained system comprising electricity generation, energy storage, and loads. Typically, it operates in conjunction with a conventional power grid (macro-grid). However, users within a Microgrid can generate low-voltage electricity using distributed energy resources such as solar panels, wind turbines, and fuel cells.

In normal operation, the Microgrid is connected to the macro-grid through a single point of common coupling. Yet, in the event of a disruption, this connection can be disconnected, allowing the Microgrid to function autonomously. This transition results in an islanded Microgrid, where distributed generators continue to supply power to users within the Microgrid, independent of the electric utility's power from the macro-grid. As illustrated in Figure 3, this configuration ensures a highly reliable and consistent electricity supply.

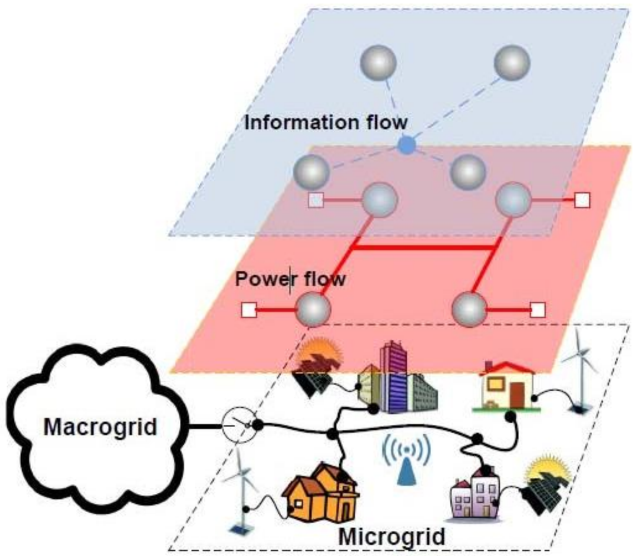

Figure 3. *Microgrid connection.*

The ability to isolate the Microgrid from the larger grid during disturbances enhances local reliability, offering potentially higher resilience than the larger power system itself. Even though users in the islanding mode are not receiving power from the macro-grid, they may still exchange vital information with it. For example, users may seek to assess the status of the macro-grid and determine whether reconnection is advisable in order to resume drawing power from the utility.

This decentralized approach offers several advantages, including improved reliability, enhanced access to renewable energy sources, self-healing capabilities, active load control, and greater overall efficiency. For instance, in the event of an outage, MicroGrids can automatically switch to islanding mode, ensuring that users within the Microgrid are not affected by the broader grid disturbances, thereby maintaining continuous service [1-6, 9-10, 21, 31, 32].

1.8. Smart Information Subsystem

The development of the Smart Grid hinges not only on advancements in power equipment technology but also on the enhancement of complex computer-based monitoring, analysis, optimization, and control systems that extend from centralized utility locations to the distribution and transmission grids. A significant portion of the challenges associated with distributed automation must be addressed from an information technology perspective, particularly concerning the interoperability of data exchanges and the seamless integration of existing and future devices, systems, and applications. To this end, a smart information subsystem is employed to facilitate the generation, modeling, integration, analysis, and optimization of information within the context of the Smart Grid. This section focuses on the smart information subsystem. First, we examine information metering and measurement, which generates critical data from end entities such as smart meters, sensors, and phasor measurement units (PMUs) within the Smart Grid. This information is crucial for multiple functions, including billing, monitoring the status of the grid, and controlling user appliances. Next, we delve into information management, which encompasses data modeling, information analysis, integration, and optimization. These processes are essential for transforming raw data into actionable insights that drive efficient decision-making and operational effectiveness across the grid. Finally, the section outlines future research directions and challenges in this field, focusing on the continued evolution of smart information subsystems to ensure the Smart Grid can adapt to the increasing complexity and demands of modern energy systems [33-38].

1.9. Information Metering and Measurement

The study of information metering and measurement can be classified into smart metering and smart monitoring and measurement. The following explains this classification in detail:

a) Smart Metering:

Smart metering is a critical component of the Smart Grid, serving as the primary mechanism for collecting data from end users' devices and appliances while also controlling their performance. Automatic Metering Infrastructure (AMI) systems, which are built upon traditional Automatic Meter Reading (AMR) systems, are widely regarded as an effective strategy for enabling Smart Grids. AMR involves the routine collection of analytical, expenditure, and status data from energy meters and transferring this information to a central database for purposes such as billing, troubleshooting, and analysis. AMI extends the functionality of AMR by enabling two-way communication with the meter. This enhanced capability allows data to be available in real time and on demand, facilitating more efficient system operations and better management of customer power demand.

Smart meters, which facilitate two-way communication between the meter and the central system, are often considered part of the AMI infrastructure. A smart meter typically records energy consumption in intervals of an hour or less and transmits this information at least once a day to the utility for monitoring and billing purposes. Additionally, smart meters have the capability to disconnect/reconnect and manage user appliances and devices to regulate loads and demands within future smart buildings**.** Figure 4 illustrates a typical usage scenario for smart meters.

From the consumer’s perspective, smart metering offers several advantages, such as enabling users to estimate their bills and manage energy consumption to reduce costs. From the utility’s perspective**,** smart meters provide real-time data that supports dynamic real-time pricing**,** which can encourage users to reduce demand during peak periods. Utilities can also optimize power flow based on the information provided by smart meters from the demand side.

b) Smart Monitoring and Measurement:

A key function in the vision of the Smart Grid is the monitoring and measurement of grid status. Two primary approaches for monitoring and measurement are sensors and phasor measurement units (PMUs).

Sensors: Sensor networks have long been utilized for various monitoring and measurement purposes. In the context of power grids, sensors are employed to detect mechanical failures, such as conductor failures, tower collapses, hot spots, and extreme mechanical conditions [18]. These sensors, integrated into the power grid, enable real-time monitoring of the mechanical and electrical conditions of transmission lines, providing a comprehensive physical and electrical snapshot of the system. This real-time data aids in analyzing both temporary and permanent faults, and it can guide system operators in taking appropriate corrective actions. Wireless Sensor Networks (WSNs), in particular, offer a cost-effective and feasible solution for remote system monitoring and diagnostics. Studies have shown that WSNs can detect and isolate single incidents in the power grid before they escalate into cascading failures that could lead to widespread system breakdowns.

1.10. Information Management

The management of the data generated by smart metering and monitoring systems is vital to ensure the optimal operation of the Smart Grid. This involves data modeling, information analysis, integration, and optimization. Effective information management supports decision-making, facilitates the dynamic operation of the grid, and enhances overall system reliability and efficiency [32, 39, 40].

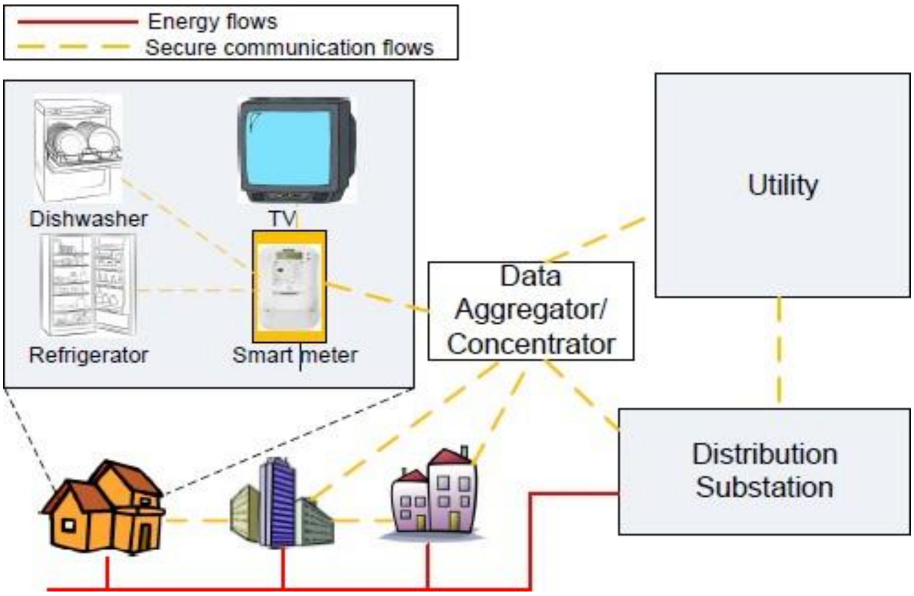

Figure 4. *Smart metering system.*

c) Data Modeling:

The primary objective of data modeling within Smart Grid (SG) information technology is to establish a framework for creating consistent, displayable, compatible, transferable, and editable data representations that can be utilized across the evolving Smart Grid ecosystem. In essence, the aim is to maximize interoperability through the adoption of relevant standards. This is particularly focused on the data that represents the state information of various grid components and entities within it. These components span from power generation units to end-user devices, all of which generate state information that must be captured, stored, transmitted, and analyzed.

Why is data modeling crucial? There are two primary reasons:

1. Effective Information Exchange: The exchange of information between two application elements is only meaningful when both elements can use the information to carry out their respective tasks. Therefore, the structure and semantics of the exchanged information must be clearly understood by both parties, ensuring compatibility and enabling the successful execution of tasks across systems.
2. Interoperability: Data modeling ensures that diverse systems and components within the Smart Grid can work together seamlessly, facilitating the sharing of relevant data. This is essential for optimizing grid operations, enhancing reliability, and enabling more efficient energy management.

d) Information Analysis, Integration, and Optimization:

Information Analysis: With the large volumes of data generated by the widespread deployment of metering and monitoring systems in Smart Grids, robust information analysis is required to process, interpret, and correlate these data streams. The analytics process supports decision-making, identifies trends, and provides actionable insights for utility operators. Some of the analysis will be performed by existing applications, while new applications, along with customizable tools for engineers, will allow for the creation of tailored analytics dashboards in a self-service model. This flexible approach enables utilities to meet the dynamic demands of grid management and optimization.

Information Integration: Information integration involves the synthesis of data from multiple sources with varying theoretical, contextual, and typographical formats. In a Smart Grid, vast amounts of data must be integrated across a wide range of components. Initially, data generated by new Smart Grid technologies needs to be incorporated into existing applications, and legacy metadata stored in traditional systems should be accessible to newer Smart Grid applications. This integration ensures that different layers of the grid's operational and planning data work cohesively, facilitating more informed decision-making.

One of the key challenges today is the limited integration capability across the various systems involved in grid management, such as those related to system planning, power distribution, and customer operations. Typically, the data within each department is isolated, creating information silos. These silos impede cross-departmental collaboration and hinder the overall efficiency of the organization. As the Smart Grid matures, there is a growing need for enterprise-level integration of these isolated data islands. This integration will allow for enhanced information utilization across the entire organization, ultimately optimizing the operation, planning, and management of the Smart Grid [10, 41-44].

2. Smart Management System

In the Smart Grid, the two-way flows of both electricity and information form the foundational infrastructure necessary to achieve a broad range of functions and management objectives. These include enhancing energy efficiency, reducing operational costs, balancing demand and supply, controlling emissions, and maximizing utility performance. While a common perception is that the "smartness" of the grid is confined to the energy, information, and communication infrastructure itself, this is an incomplete understanding. A more precise assessment is that the grid evolves into an increasingly "smarter" system through the development and integration of new management applications and services. These applications harness the capabilities and technological advancements enabled by the underlying infrastructure, allowing the grid to continuously improve its performance and responsiveness to dynamic needs.

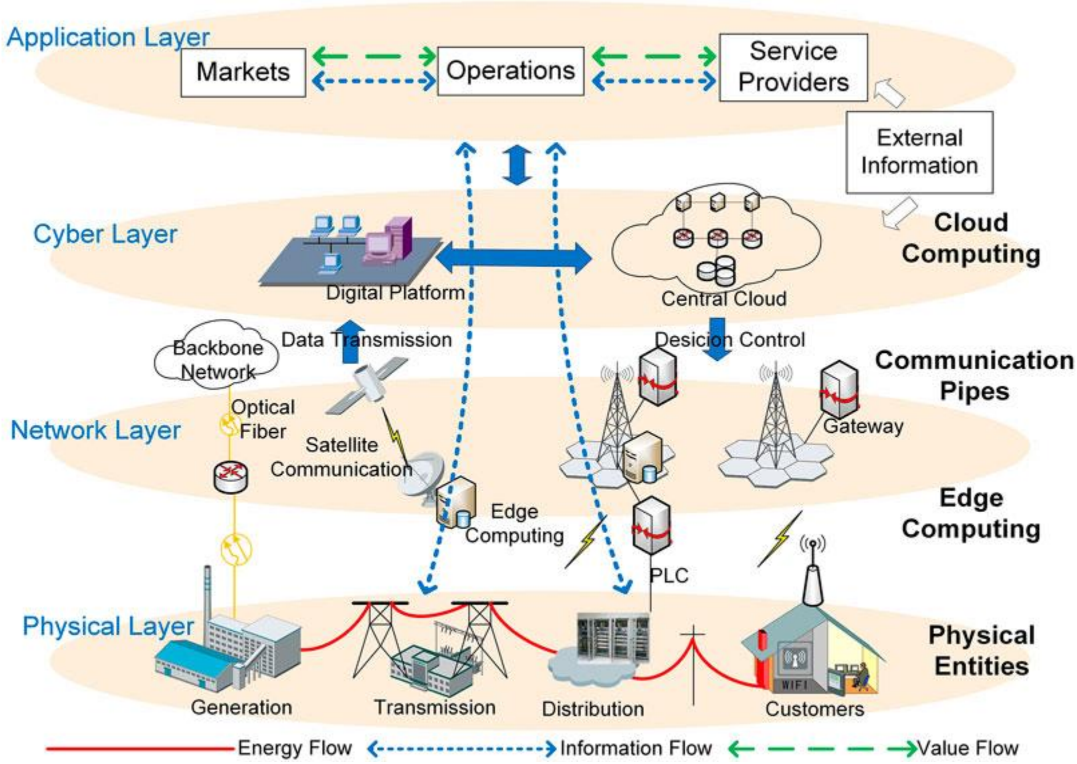

Figure 5. Layered architectures and enabling technologies of the CPPS.

Demand response, one of the most pivotal concepts underpinning the Smart Grid. Traditionally, electric utilities have strived to match the supply of energy to the demand. However, this approach is not only costly but may also be impractical, if not outright infeasible, over the long term. The reason for this is that the total energy demand from consumers follows an extraordinarily wide probability distribution, which necessitates keeping additional generating plants in standby mode to accommodate rapidly fluctuating power usage. The final 10% of generating capacity may be required during as little as 1% of the time. Attempts to meet such fluctuating demand can lead to significant system failures, including brownouts (a reduction in voltage), blackouts (complete power outages), and even cascading failures across the grid.

In contrast, the Smart Grid addresses this challenge through demand response, which involves managing customer electricity consumption in direct response to supply conditions. Rather than striving to match supply to demand, the Smart Grid aligns demand with the available supply using advanced control technologies and by incentivizing consumer participation, such as through variable pricing strategies. This approach optimizes capacity utilization and helps avoid the need for costly standby generation.

This section explores the concept of smart management within the Smart Grid. It begins by classifying smart management techniques according to their overarching management objectives and subsequently categorizing them based on the methods and strategies employed to achieve these objectives [13, 16, 17, 32].

2.1. Management Objectives

Within the framework of the Smart Grid, many management objectives that were previously difficult, if not infeasible, to achieve in conventional power grids have become not only possible but also more easily attainable. To date, research on smart management has primarily focused on the following three key objectives:

1. Energy Competence and Demand Profile Development;
2. Effectiveness and Cost Optimization, and Price Stabilization;
3. Emission Organization.

The research on energy efficiency and demand profile development is primarily concentrated on two main areas. The first is demand profile shaping, which seeks to align energy demand with available supply. Common strategies to reshape demand profiles include demand shifting, scheduling, or dipping, all aimed at transforming a demand curve characterized by significant peaks into a more balanced, smoothed profile. This reduction in peak demand and smoothing of the demand curve not only diminishes the peak-to-average ratio but also leads to lower peak demand for the total energy consumption. As previously discussed, since electrical generation and transmission systems are typically designed to meet peak demand, lowering peak demand and smoothing the overall demand profile can significantly reduce plant and capital costs, while simultaneously enhancing system reliability.

The second area of research concerning energy efficiency and demand profile optimization is focused on minimizing energy losses. The integration of distributed energy generation within the Smart Grid, however, complicates this issue. To address this challenge, studies have proposed the determination of the optimal integration of distributed renewable energy generation in a manner that minimizes energy loss. This is typically achieved through the use of optimal multi-period alternating current (AC) power flow models, which help to minimize system energy losses while accommodating renewable energy sources effectively [2, 5, 6, 10, 45].

2.2. Management Methods and Tools

To address management objectives, researchers have employed a diverse range of methods and tools. The predominant approaches to solving various management challenges in energy systems include optimization techniques, machine learning, game theory, and auction-based mechanisms.

In the realm of optimization, commonly utilized mathematical tools include convex programming and dynamic programming. Given the inherently time-varying nature of renewable energy supply, additional optimization techniques such as stochastic programming and robust programming have gained widespread adoption. Furthermore, particle swarm optimization has emerged as a preferred method due to its ability to efficiently solve complex constrained optimization problems with high accuracy, irrespective of dimensional limitations or physical memory constraints.

Machine learning, on the other hand, is centered on the design and development of algorithms that enable control systems to adapt and evolve their behaviors based on empirical data, such as inputs from sensors or Phasor Measurement Units (PMUs). Online learning applications are particularly valuable in these contexts, as they allow for the implicit estimation of the impact of future energy prices and consumer decisions on long-term costs, thereby facilitating the scheduling of residential device usage in an optimal manner [9, 32].

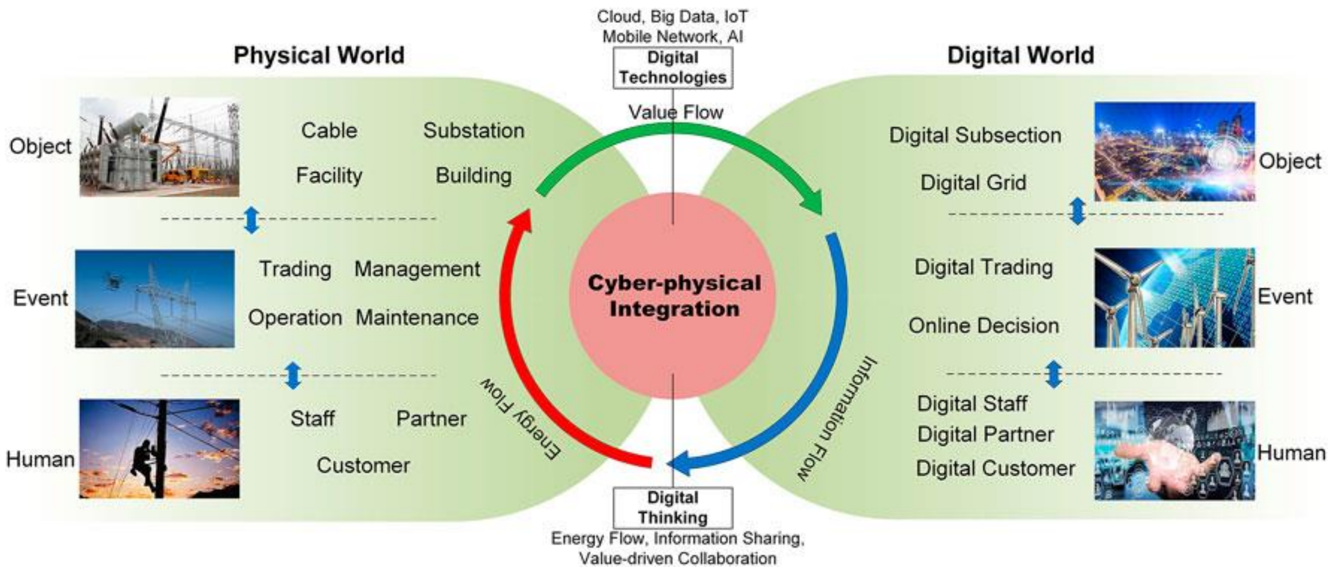

Figure 6*. Conceptual framework of the CPPS.*

Online machine learning techniques have been employed to analyze the strategy for utilizing renewable energy resources in islanded MicroGrids. Specifically, the focus is on how a customer can determine the optimal renewable energy source from a variety of options in order to maximize profit. Despite the inherent uncertainty in the power generation patterns of renewable energy sources, it has been demonstrated that, when the time horizon is sufficiently long, the gap between the expected profit achieved by using the optimal renewable energy source and that obtained by following a machine learning-based strategy is negligibly small on average.

As large numbers of smart meters, sensors, and Phasor Measurement Units (PMUs) are expected to be deployed within these systems, machine learning is anticipated to play a pivotal role in analyzing and processing both user data and grid states. Additionally, game theory serves as a powerful analytical tool for Smart Grid (SG) management. One of the key advantages of game theory is its ability to model situations where not all users are assumed to cooperate. By leveraging game theory, we can design robust strategies and schemes to address these non-cooperative scenarios effectively [15, 39, 41, 44].

3. Conclusion

This article presents a comprehensive literature review of the current advancements in Smart Infrastructure and Smart Management Techniques. It delves into the following critical areas:

1. Energy Subsystem, with a particular focus on: Power generation, transmission, and distribution systems.
2. Emerging Grid Paradigms, notably the concept of MicroGrids, which represent a revolutionary shift in power network configurations.
3. Smart Information Subsystem, emphasizing innovative solutions for information metering, measurement, and management within the context of the Smart Grid.
4. Smart Communication Subsystem, which integrates both wired and wireless communication technologies, along with end-to-end communication management strategies.

The article also explores a broad array of management objectives that, in conventional power grids, may be challenging, if not impossible, to address. In the context of a smart grid, these goals are rendered not only attainable but also more manageable.

To ensure the reliable and stable operation of the Smart Grid, the article further highlights the importance of System Reliability Analysis and the evaluation of Failure in Protection Mechanisms. While the Smart Grid enhances the power network with intelligent and advanced capabilities, it simultaneously introduces a range of new challenges and risks. Therefore, the article briefly discusses these challenges, alongside potential solutions for mitigating them. Nonetheless, it emphasizes that further, more in-depth research into the physical protection systems is crucial to ensure the continued reliability and stability of smart grid operations.

Abbreviations

AMI	Advanced Metering Infrastructure
BMS	Battery Management System
DER	Distributed Energy Resources
EMS	Energy Management System
ICT	Information and Communication Technology
IoT	Internet of Things
ML	Machine Learning
PMU	Phasor Measurement Unit
PV	Photovoltaic
SCADA	Supervisory Control and Data Acquisition
SG	Smart Grid
VPP	Virtual Power Plant
WAN	Wide Area Network
WiMAX	Worldwide Interoperability for Microwave Access

Author Contributions

Yam Krishna Poudel: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Rajiv Kumar: Supervision, final drafting

Conflicts of Interest

The authors declare no conflicts of interest.

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