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TOPICAL REVIEW

Smart Grids Empowered by Software-Defined Network: A Comprehensive Review of Advancements and Challenges

WASHINGTON VELASQUEZ, (Senior Member, IEEE), **GUILLERMO Z. MOREIRA-MOREIRA**, AND **MANUEL S. ALVAREZ-ALVARADO**, (Member, IEEE)
Faculty of Electrical and Computer Engineering, Escuela Superior Politécnica del Litoral, ESPOL, Guayaquil 090902, Ecuador

Corresponding author: Washington Velasquez (wavelasq@espol.edu.ec)

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ABSTRACT The integration of Software-Defined Networking (SDN) technology in Smart Grids has emerged as a transformative approach to modernizing energy infrastructures and enhancing operational efficiency. This comprehensive review paper explores the advancements, challenges, and future perspectives of SDN implementation in Smart Grid environments. It delves into the applications of SDN in areas such as real-time monitoring, energy distribution optimization, grid resilience, integration of renewable energy sources, and demand response management. Additionally, the paper addresses key challenges including security concerns, interoperability issues, scalability constraints, and regulatory compliance requirements that accompany the adoption of SDN in Smart Grids. Looking ahead, the paper discusses future perspectives such as leveraging artificial intelligence, edge computing, and blockchain technology to further enhance the capabilities of SDN in Smart Grids. Through an in-depth analysis of current developments and future trends, this review provides valuable insights for researchers, practitioners, and policymakers seeking to harness the full potential of SDN for advancing Smart Grid infrastructures.

INDEX TERMS Applications, cybersecurity, energy efficiency, grid resilience, smart grid, software-defined network.

NOMENCLATURE

ACL	Access Control List.
AI	Artificial Intelligence.
API	Application Programming Interface.
IoT	Internet of Things.
ML	Machine Learning.
MQ	Main Question.
QoS	Quality of Service.
REST	Representational State Transfer.
$SDN - SGRID$	Software-defined Networks applied to Smart Grid.
SDN	Software-defined Network.
SQ	Sub-Question.
SSH	Secure Shell.

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I. INTRODUCTION

The global energy landscape is experiencing a profound transformation driven by escalating energy demands, the imperative of environmental sustainability, and the rapid evolution of technology [1]. At the heart of this transformative era lies the concept of Smart Grids, representing a revolutionary approach to managing and optimizing energy distribution. Smart Grids are designed to empower utilities and consumers with intelligent, data-driven tools that enhance electric power systems' reliability, efficiency, and sustainability. These advanced networks respond to the challenges posed by outdated, centralized grid structures and embrace a more decentralized, adaptive, and responsive approach [2].

The core idea of a Smart Grid revolves around leveraging digital technology and data analytics to optimize every aspect of energy management, from generation to distribution to consumption [3]. These grids have sensors, meters [4], and communication infrastructure that enable real-time monitoring and control. This level of granularity and agility in the network is a game-changer, allowing for predictive maintenance, fault detection, and load balancing, among other capabilities [5]. As a result, Smart Grids offer several benefits, including reduced energy losses, improved power quality, greater resilience to outages, and support for renewable energy integration [6]. However, the transition to Smart Grids has introduced new challenges in network management. These systems' scale, complexity, and dynamism necessitate innovative solutions to ensure optimal performance. In this context, Software-Defined Networking (SDN) emerges as a promising technology that can revolutionize how Smart Grids are managed.

SDN is well-known in computer networks for its ability to separate the control plane from the data plane, allowing for centralized control and programmability of network resources [7]. This architectural paradigm has applications in diverse domains, including data centers [8], telecommunications [9], and the energy sector [10]. The principles of SDN align closely with the requirements of Smart Grids, where dynamic, real-time management of network resources is essential.

This review paper explores the fusion of Smart Grids and SDN, focusing on the advances and challenges encountered in this evolving partnership. The aim is to provide a comprehensive overview of research, identifying key advancements and addressing the obstacles. By examining the symbiotic relationship between these two domains, it can be seen how SDN redefines Smart Grids' management and drives innovation within it. This review serves as a roadmap for researchers, practitioners, and policymakers seeking to understand the evolving landscape of Smart Grids enhanced by SDN, offering insights into the exciting possibilities and the need for innovative solutions in this dynamic field.

This review paper is structured into eight sections. Section II describes the research methodology. Section III begins by establishing the fundamental principles of Smart Grids, the traditional challenges they address, and the technologies that underpin them. Section IV delves into the intricacies of SDN's integration into the domain of Smart Grids, highlighting the components, controllers, and the most used protocols. Section V describes the different SDN applications for Smart Grid, analyzing aspects such as Real-time monitoring, energy distribution optimization, grid resilience, integration of renewal energies, and demand response and load management. Section VI presents a small analysis of the environmental impact of incorporating SDN into Smart Grids. Section VII explores SDN's challenges and future outlook in Smart Grids, emphasizing the potential avenues for further research and development. Finally, the conclusions of this review are described in section VIII.

II. METHODOLOGY

The approach employed in developing this paper begins with identifying scientific challenges, subsequently progressing to formulating research questions; this is followed by establishing a search strategy and selecting relevant articles in the context of Software-Defined Networks applied to Smart Grids (SDN-SGRID). Each of these steps is elaborated upon in the following sections.

A. REVIEW OBJECTIVES

The primary goals of this review encompass a multifaceted exploration, including 1) documenting the main advances in SDN applications applied to Smart Grid, 2) analyzing the implications on energy efficiency and environmental impact when it uses an SDN, 3) categorizing research study efforts within the domain of SDN-SGRID, and 4) identify the main challenges and possible problems associated with the evolution of SDN-SGRID.

B. RESEARCH QUESTIONS

The research's central inquiry, denoted as the Main Question (MQ) and its associated Sub-Questions (SQ), serves as the guiding framework for this review, as presented in Table 1. The overarching aim behind formulating the MQ is to provide insights into the forthcoming trends within Software-Defined Networks applied to Smart Grids. Each question addresses specific and critical aspects of the topic, ranging from identifying future trends to exploring existing documents related to SDN-SGRID. Additionally, there is an emphasis on understanding the taxonomy of different SDN technologies involved in Smart Grids and analyzing the environmental implications and energy efficiency associated with implementing SDN-SGRID. These questions serve as focal points for research, providing a clear framework to explore the diverse dimensions of the intersection between SDN and Smart Grids.

TABLE 1. Research questions.

Identifier	*Issue*
MQ	What are the future trends regarding SDN applied to Smart Grids?
SQ1	What are the existing documents that explore SDN-SGRID in different contexts?
SQ2	What is the taxonomy of the different SDN technologies involved in Smart Grids?
SQ3	What are the implications of using SD-SGRID on environmental impact and energy efficiency?

This review paper is anchored in using IEEE Xplore as the primary database. Harnessing IEEE Xplore's robust full-text search capabilities, its extensively explored publication titles and bodies yield substantial results. This comprehensive dataset underwent a meticulous evaluation to pinpoint potential challenges, technologies, and standards related to SDN-SGRID. A tailored search string was crafted and applied across various scholarly resources to ensure comprehensive coverage. Given its expansive reach, the search initially commenced on IEEE Xplore, next in Scopus and

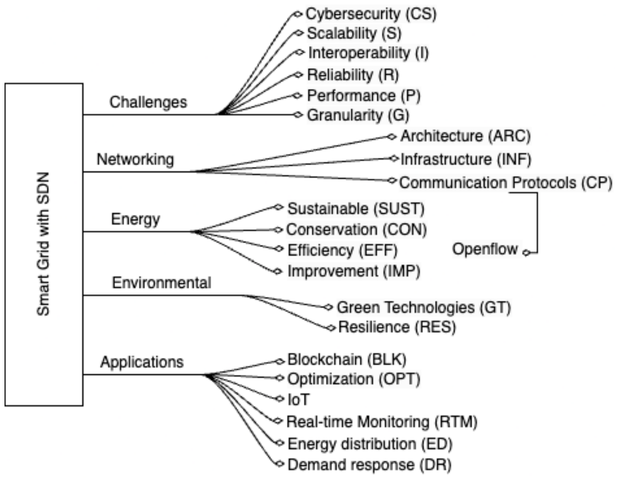

FIGURE 1. **Search string map (IEEE Xplorer).**

WOS. This multifaceted approach thoroughly explores existing literature, enriching the review with diverse perspectives and insights. The search string considers specific attributes and parameters elucidated in the subsequent sections to facilitate this investigation. Figure 1 visually illustrates the meticulously crafted and deployed research string in the context of this paper.

C. ARTICLE SELECTION

The investigation utilized the search query on 05/01/2024 through IEEE Xplorer. The search was limited to the most recent five years, covering the period from 2019 to 2023, excluding patents. The screening aimed to evaluate the pertinence of the search query while addressing the SQ1 and SQ2 questions posed. Some manuscripts were omitted based on the criteria specified in Table 2 during the categorization process. The in-depth analysis of publications within the last 5 years offers insights into addressing SQ1. A more detailed response to this inquiry is depicted in Figures 2.

TABLE 2. **Publication search criteria.**

Criterion	*Issue*
1	Restrict the selection to publications published within the last five years, excluding publications published outside the period from 2019 to 2023.
2	Exclude any publications not about SDN-SGRID, including doctoral theses.
3	Include additional technologies to the search strings, e.g. IoT, protocols, etc.

III. FUNDAMENTALS OF SMART GRIDS

There are several definitions of a smart grid, however, one of the most comprehensive definitions is stablished by the IEEE, which states the following [11]:

"The smart grid is a revolutionary undertaking-entailing new communications-and control capabilities, energy sources, generation models and adherence to cross jurisdictional regulatory structures."

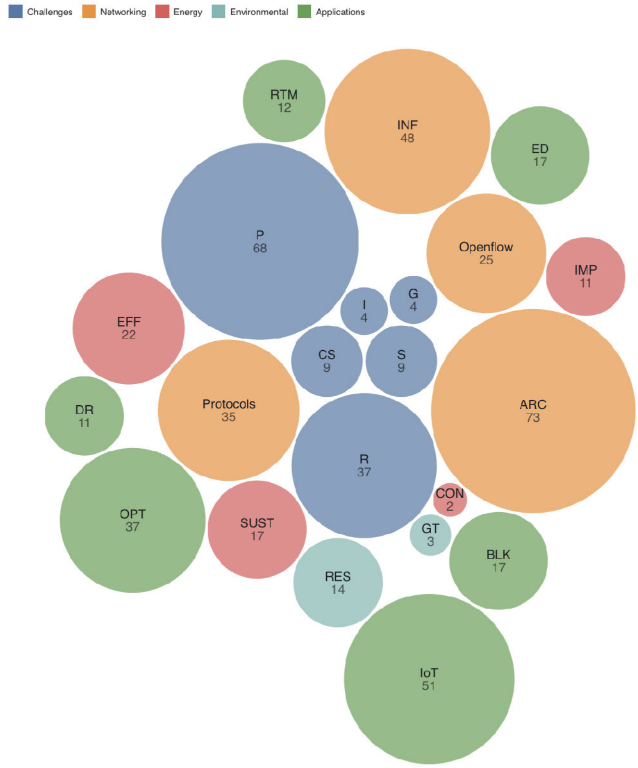

FIGURE 2. **Bubble chart of article selection (2019-2023).**

In this context, smart grids are advanced electrical grids that incorporate a range of information and communication technologies to enhance the efficiency, reliability, and sustainability of electricity distribution. Smart grids enable two-way energy and information flow, allowing for active consumer involvement, management of all generation and storage options, and the creation of new products, utilities, and markets. Smart grids are characterized by digital technology, pervasive control, sensors throughout, self-monitoring, self-healing, and the ability to adapt and island in response to failures. They support distributed generation and offer many consumer choices, contrasting with the traditional grid, which is electromechanical, has minimal control, one-way communication, manual monitoring, and centralized generation [2].

Smart grids rely on several key pillars to modernize electricity infrastructure and enhance grid efficiency, reliability, and sustainability. Advanced metering infrastructure forms the backbone of smart grids, integrating smart meters and communication networks for real-time data exchange between utilities and consumers [12]. Grid automation technologies, including sensors and control systems, optimize grid operations by enabling remote monitoring, outage detection, and efficient electricity flow management. The vision of smart grids is steadily unfolding, propelled by advancements in information and communication technologies. Both the Federal Energy Regulatory Commission

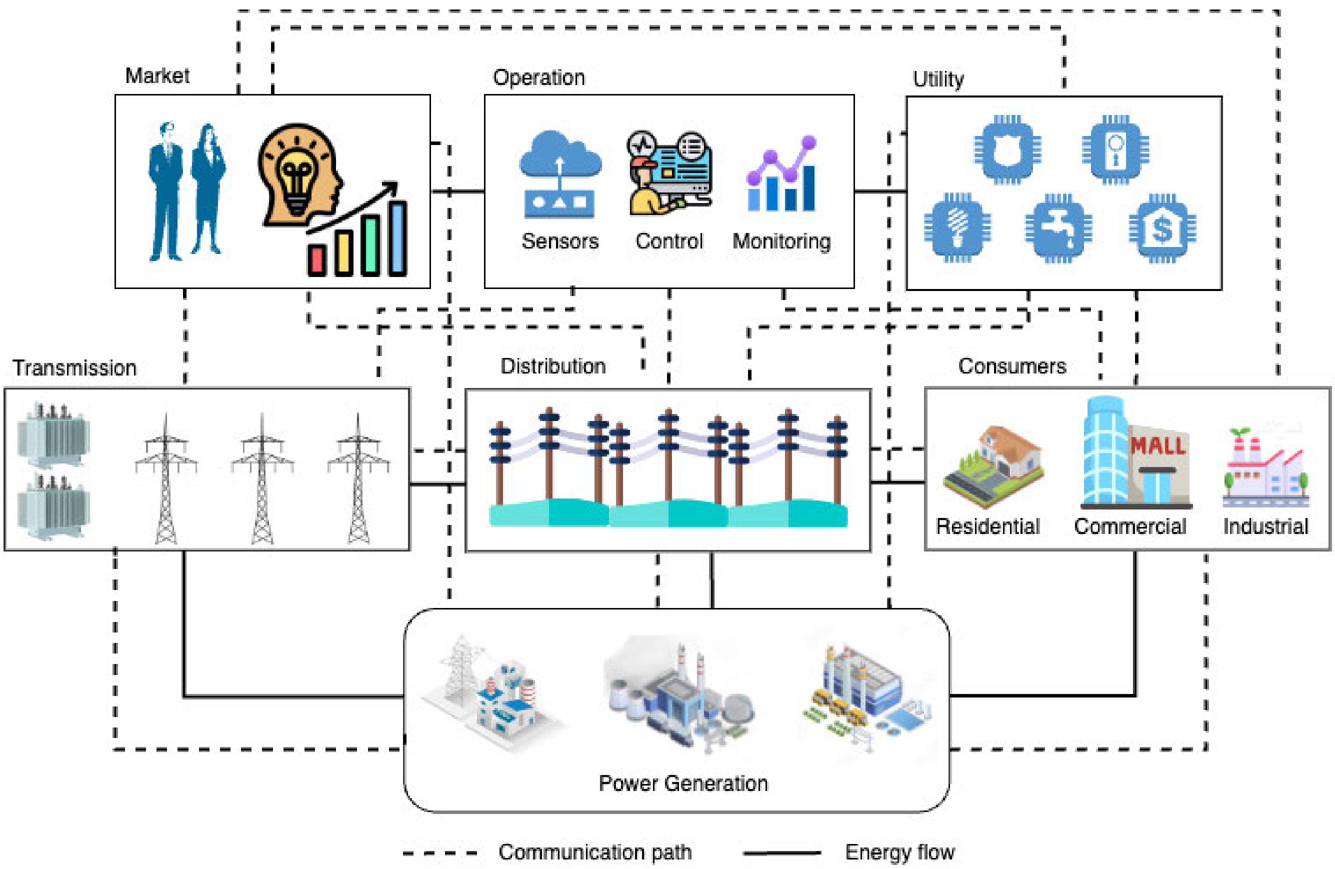

FIGURE 3. **Smart grids architecture.**

(FERC) and the Department of Energy (DOE) in the U.S. have acknowledged that a predominant trend within this vision emphasizes the paramount importance of reliability. Consequently, a significant challenge arises ensuring the uninterrupted operation of power systems while adhering to stringent reliability standards [13]. Under this need, smart grids facilitate the integration of renewable energy sources through advanced forecasting and grid balancing mechanisms, promoting sustainability and reducing reliance on fossil fuels. Demand response programs incentivize consumers to adjust their electricity usage, helping utilities manage peak demand and improve overall grid efficiency. Energy storage systems play a crucial role in balancing supply and demand, enhancing grid flexibility and resilience. Robust cybersecurity measures ensure the integrity and reliability of smart grid systems, while data analytics techniques provide insights for optimizing grid performance and asset management. Effective policy and regulatory frameworks are essential to incentivize investment and drive widespread adoption of smart grid technologies, fostering collaboration among stakeholders and supporting grid modernization efforts.

The architecture of smart grids is structured into distinct levels to comprehensively manage and optimize the entire electricity supply chain. At the foundational level, power generation is encompassed by various sources such as fossil fuels, renewable energy, and nuclear power. This generation capacity forms the backbone of the grid's energy supply. Moving up to the second level, the transmission system is responsible for transporting electricity over long distances from power plants to distribution substations. Simultaneously, at this level, the distribution system operates, with electricity distributed from substations to end consumers, including residential, commercial, and industrial users. At the third level, components crucial for optimal power system operation are found. This includes market regulation mechanisms that govern energy trading, pricing, and market participation. Additionally, utilities play a pivotal role in managing grid operations, ensuring stability, reliability, and efficiency. Advanced communication systems serve as the linchpin connecting these various levels and components of the smart grid architecture. These communication networks enable real-time monitoring, control, and coordination of power flow, facilitating efficient energy management and response to dynamic grid conditions. Together, these interconnected levels and components form a robust architecture for smart grids, enabling enhanced reliability, resilience, and sustainability in the delivery of electricity to consumers [2], [14]. Figure 3 presents a systematic view of the architecture described.

The integration of SDN technology with smart grids establishes a crucial link by leveraging SDN's centralized control and programmability to manage communication networks effectively. In smart grid contexts, SDN enables utilities to centrally control network devices such as switches and routers, facilitating efficient management of communication networks connecting various grid components [15]. This centralized control allows for dynamic network configuration, adapting to real-time changes in grid conditions such as fluctuations in electricity demand or renewable energy generation. Additionally, SDN optimizes traffic flows within smart grid networks, prioritizing traffic based on grid priorities to ensure reliable and efficient communication between grid components. Furthermore, SDN enhances grid security and resilience by facilitating the implementation of advanced security measures and enabling utilities to detect and mitigate cyber threats more effectively. Overall, the integration of SDN technology empowers utilities to optimize communication networks, enhance grid reliability, and unlock new opportunities for innovation in modern energy systems.

SDN in a smart grid environment, coupled with the Internet of Things (IoT) for communication, revolutionizes the way utilities manage and optimize grid operations. SDN introduces a centralized and programmable approach to network management, while IoT devices provide real-time data collection and communication capabilities. In smart grids, SDN facilitates efficient communication network management by centralizing control and allowing for dynamic allocation of resources based on grid conditions. This enables utilities to optimize network performance, prioritize critical data traffic, and respond swiftly to grid events. IoT devices enhance this communication infrastructure by providing a wealth of real-time data from various grid assets, such as sensors in substations, smart meters, and grid-connected devices. The implementation of SDN with IoT in power systems communication enables utilities to achieve several key objectives [16], [17], [18], [19], [20]:

- Enhanced Grid Monitoring and Control: IoT sensors deployed across the grid infrastructure continuously collect data on grid parameters such as voltage levels, current flows, and equipment status. SDN controllers aggregate and analyze this data, providing utilities with comprehensive insights into grid performance and enabling proactive grid monitoring and control.
- Improved Grid Resilience and Reliability: By integrating IoT devices with SDN, utilities can quickly detect and respond to grid disturbances, such as equipment failures or fluctuations in renewable energy generation. SDN enables automatic rerouting of traffic and resource allocation to mitigate the impact of disruptions, improving grid resilience and reliability.
- Optimal Resource Utilization: SDN's programmable nature allows utilities to dynamically allocate network resources in real-time, optimizing bandwidth usage and ensuring efficient communication between grid devices. IoT data analytics further enhance resource utilization by identifying opportunities for load balancing and optimizing energy distribution.
- Support for Advanced Grid Applications: The combination of SDN and IoT facilitates the deployment of advanced grid applications such as predictive maintenance, demand response, and grid optimization. IoT data streams provide valuable insights into asset health and performance, enabling utilities to implement predictive maintenance strategies and optimize asset utilization. SDN enables seamless integration of these applications into the communication network, enabling utilities to realize the full potential of their smart grid investments.

More details concerning each declared objective is discussed in the following section.

IV. SOFTWARE-DEFINED NETWORK FOR SMART GRIDS

The proposed architecture in Figure 4 integrates SDN in the Smart Grids environment to improve the management and efficiency of the electrical network. This architecture is made up of the following key elements [21]:

- *SDN Controller:* The central core of the architecture resides in the SDN controller, playing a crucial role in the intelligent management of the electrical grid. This central component employs algorithms and policies to make dynamic decisions based on information provided by the application layer. Its open interface facilitates the integration of specific applications, enabling efficient and adaptive management [22].
- *Application Layer:* The application layer hosts a variety of specific applications designed to address particular challenges in Smart Grids. From real-time monitoring to the optimization of energy distribution and active demand management, these applications interact with the SDN controller, receiving information and sending commands to optimize network performance.
- *Infrastructure Layer:* SDN-compatible devices such as switches and routers enable dynamic reconfiguration in response to controller decisions. The inclusion of sensors and measurement devices provides real-time data on the state of the network and power consumption [23]. Efficient communication between these devices is achieved through SDN protocols like OpenFlow.
- *Data Layer:* The data layer centralizes critical information in a database, facilitating organized storage of data on network status, consumption histories, and load patterns. Integration with Big Data technologies allows advanced analytics to forecast trends and optimize the operation of the electrical grid.
- *The user interface*, in the form of a management dashboard, provides an intuitive visual representation of the network. Operators and administrators can access key graphs and metrics, receiving alerts and notifications about critical events for informed decision-making.
- *Security Layer:* The security layer implements robust protocols to encrypt and authenticate communications

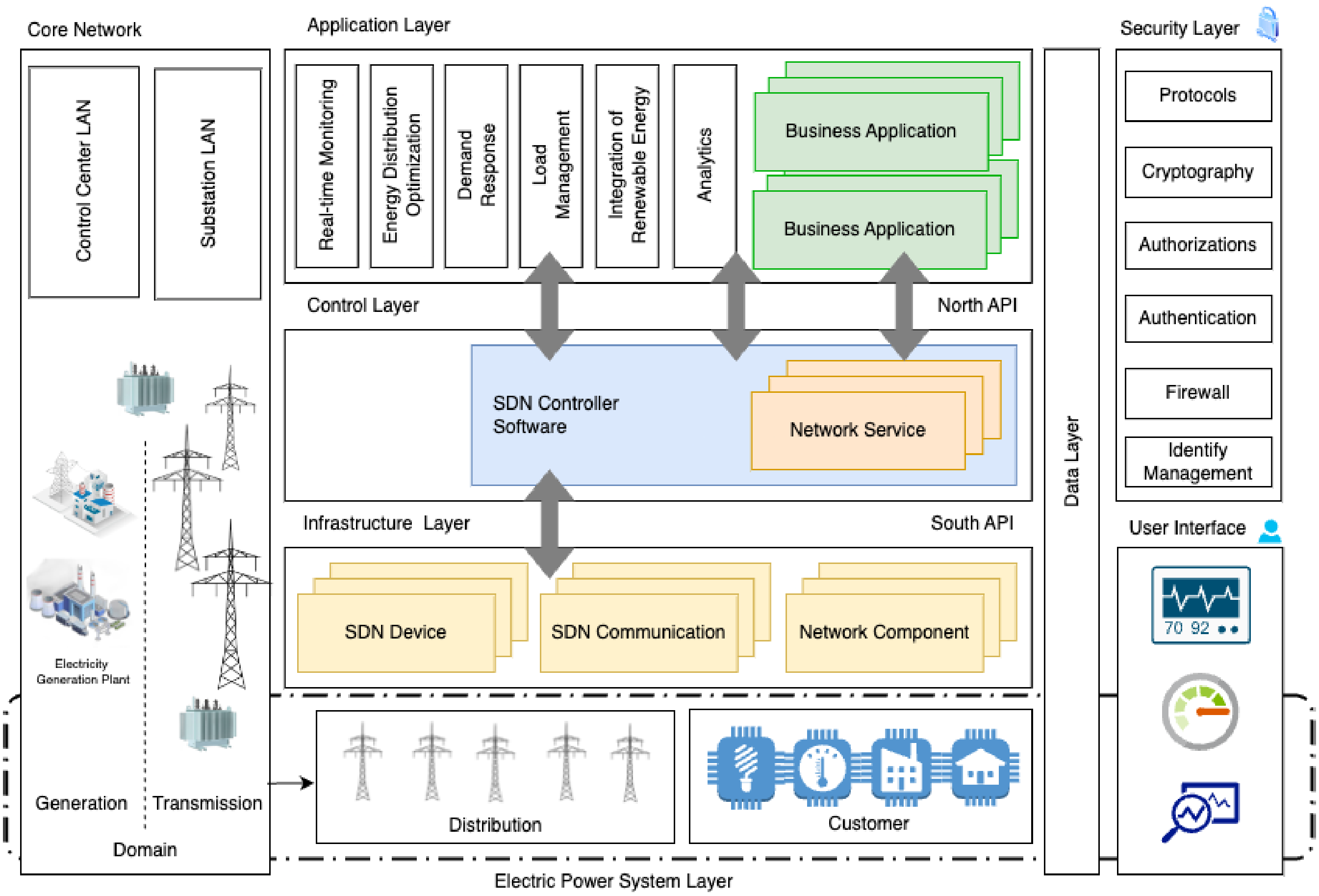

FIGURE 4. **SDN architecture for smart grid.**

between the controller and network devices [24]. Additionally, identity management, firewalls, and continuous network monitoring ensure the integrity and security of the system against potential cyber threats.

A. INFRASTRUCTURE LAYER

The infrastructure layer forms the foundation of SDN for Smart Grids, providing the necessary hardware and software components to enable network programmability and flexibility. This section delves into the key components and functionalities comprising the infrastructure layer and their significance in enhancing the resilience, efficiency, and intelligence of Smart Grid networks as shown in Table 3.

B. SDN CONTROLLER TECHNOLOGIES

SDN controllers designed for Smart Grids exhibit diversity across multiple dimensions influencing their performance and applicability [25]. This section pretends to answer the SQ2 question focusing on SDN Controllers. The following taxonomy addresses key categories for evaluating these technologies in the specific context of smart electric grids as shown in Figure 5.

1) CATEGORIZATION BY PROTOCOLS

Communication protocols are fundamental in defining the interoperability and efficiency of SDN controllers. Noteworthy options include OpenFlow, NETCONF, and RESTful APIs, each offering distinct advantages in terms of standardization, reconfigurability, and interface flexibility [26]. Table 4 shows a brief description and comparison of the most popular protocols:

2) BASED ON PROCESSING CAPACITY

Processing capacity is a determining factor in controller selection. They are categorized into central controllers, suitable for global decisions, and distributed controllers, which decentralize functions for enhanced scalability and redundancy. Table 5 shows a comparison between centralized and distributed controllers using different evaluation metrics.

3) SCALABILITY AND PERFORMANCE

The ability to scale horizontally and vertically, along with performance under high-load scenarios, is evaluated to ensure effective responses in dynamic and demanding

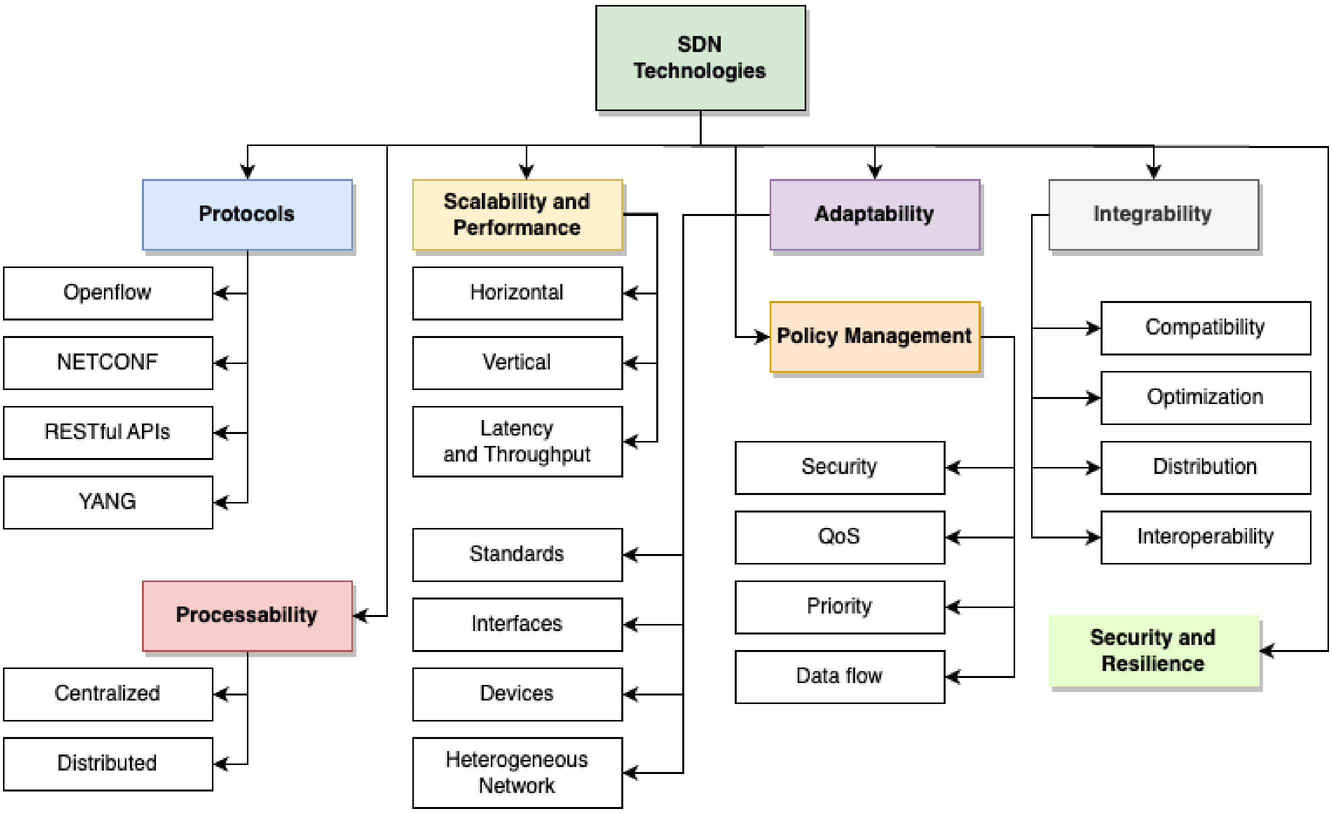

FIGURE 5. SDN controller taxonomy.

TABLE 3. Components of the SDN infrastructure layer for smart grids.

Components	Description
Physical Network Infrastructure	Physical components such as switches, routers, and gateways that facilitate the distribution of data and power in the smart grid.
SDN Controllers	Central elements that orchestrate network behavior and enforce policies based on real-time conditions and requirements.
Southbound Interfaces	Interfaces enabling communication between SDN controllers and network devices, allowing dynamic configuration and resource management.
Northbound Interfaces	Interfaces facilitating communication between SDN controllers and higher-layer applications, allowing service requests and updates.
Network Virtualization	Techniques allowing the creation of independent virtual network segments within the physical infrastructure, improving efficiency and scalability.
Security Mechanisms	Implemented mechanisms to protect the network against cyber threats and unauthorized access, ensuring data integrity and confidentiality.
Resilience and Redundancy	Mechanisms of redundancy and resilience mitigating network failures and ensuring continuous operation, minimizing downtime.
Scalability and Performance Optimization	Techniques to optimize network performance and scalability, including load-balancing algorithms and r esource allocation strategies.

environments [27]. An evaluation of the protocols is described in Table 6.

4) ADAPTABILITY TO HETEROGENEOUS NETWORKS

Adaptability to various network technologies and standards is critical. Evaluation includes the controller's capacity to integrate with different technologies such as optical fiber, LTE, and support multiple interfaces and device types.

5) POLICY MANAGEMENT CAPABILITIES

Implementation of security policies and Quality of Service (QoS) management are essential [28]. The examination focuses on how the controller handles network security and effectively prioritizes traffic [29]. Also, robust security protocol implementation and the ability to self-heal in the face of faults and cyber threats are prioritized aspects A comparison of the protocols analyzing those aspects is shown in Table 7.

6) INTEGRATION WITH SPECIFIC SMART GRID APPLICATIONS

The ability to integrate with specific Smart Grid applications is crucial for effectiveness. Compatibility with real-time monitoring applications, demand management strategies, and energy distribution optimization is assessed. Seamless integration with energy storage systems and the ability to collaborate with renewable energy generation systems for coordinated and sustainable operation are examined [30], [31].

TABLE 4. Communication protocols comparison in SDN controllers for smart grids.

Protocol	Description	Strengths	Weaknesses	Example
OpenFlow	Widely adopted standard for southbound communication between controller and switches.	Simple, versatile, large community support.	Limited security features, potential performance overhead.	NOX, Floodlight, Ryu
NETCONF	XML-based protocol for configuration management.	Mature standard, supports configuration and operational data.	Not real-time, complex configuration options.	OpenDaylight, ODL-NETCONF
YANG	Data modeling language for NETCONF messages.	Enables structured data exchange, simplifies configuration.	Requires expertise in YANG modeling, potentially slower than binary protocols.	OpenDaylight, ONOS
RESTful APIs	Web-based APIs for flexible communication.	Easy to integrate with existing tools, supports various data formats.	Security needs careful consideration, can be less performant than binary protocols.	ONOS, ODL-REST
OpenMBTS	Protocol specifically designed for smart grid monitoring and control.	Focuses on real-time data and control messages, good security features.	Less widely adopted compared to OpenFlow, may require specific controller support.	SunSpec OpenMBTS
IEC 61850 Goose	Real-time data exchange protocol for substation automation.	Standardized for interoperability in substation networks, high performance.	Limited to substation communication, complex configuration.	Various commercial implementations

TABLE 5. SDN controller comparison: centralized vs. distributed.

Feature	Centralized	Distributed
Processing Capacity	High, but limited by single controller	Scalable, leverages distributed resources
Global Decisions	Ideal for strategic decision-making and network-wide control	Can be complex for large-scale networks with numerous local decisions
Scalability	Limited by single controller's resources	Highly scalable, can easily expand with network growth
Redundancy	Single point of failure, requires backup strategies	More resilient, failures in one node minimally impact overall network
Latency	Can introduce higher latency due to centralized processing	Lower latency as decisions are made closer to devices
Complexity	Simpler management due to centralized configuration	More complex setup and ongoing management of distributed nodes
Cost	Generally lower initial cost	May have higher initial cost due to multiple components

TABLE 6. Scalability and performance comparison of protocols.

Protocol	Scalability	Performance
OpenFlow	Highly scalable, supports a large number of switches and devices.	Moderate performance, can be affected by processing overhead on the controller.
NETCONF	Scalability limited by configuration complexity and data volume.	Performance varies, depends on server implementation and network load.
YANG	Highly scalable, thanks to its modular and flexible structure.	Efficient performance, leverages the lightweight nature of YANG messages.
RESTful APIs	Flexible scalability, adaptable to different architectures and workloads.	Performance varies, depends on API design, server load, and network infrastructure.
OpenMBTS	Moderate scalability, optimized for medium-sized networks.	Efficient performance, designed for real-time communication with low latency.
IEC 61850 Goose	Scalability limited to substation networks.	High performance, optimized for real-time data delivery with low latency.

C. ANTICIPATED ADVANTAGES BEYOND CORE FEATURES OF THE ARCHITECTURE

The holistic SDN architecture for Smart Grids promises a spectrum of far-reaching advantages, shaping the landscape of energy distribution and management. Beyond the foundational elements outlined, the expanded expected benefits encompass [32], [33], [34]:

- *Enhanced Grid Resilience:* The architecture's dynamic adaptability enhances the grid's resilience against unforeseen events, reducing downtime and improving overall system reliability. Rapid response mechanisms, enabled by real-time data and intelligent decision-making, contribute to a more robust and dependable electrical infrastructure.
- *Optimized Resource Utilization:* Through continuous monitoring and optimization, the SDN-enabled Smart Grid architecture ensures the efficient use of resources [15]. This optimization extends to the distri-

TABLE 7. Protocol comparison based on security, resiliency, and QoS.

Protocol	Security	Resiliency	QoS
OpenFlow	Basic ACLs	Limited, relies on controller and switch security	No inherent QoS features
NETCONF	Supports strong cryptography (SSH) & authorization	High, utilizes separate management & data channels	Limited QoS support, relies on external mechanisms
YANG	Inherits security from NETCONF	High, leverages NETCONF resiliency features	Limited QoS support, relies on external mechanisms
RESTful APIs	Security needs careful implementation (auth, encryption)	Moderate, depends on server implementation & redundancy	Can support QoS through API features and server configuration
OpenMBTS	High, implements end-to-end encryption, authentication & authorization	High, designed for real-time control with redundancy features	Supports basic QoS through traffic classes and priority settings
IEC 61850 Goose	High, robust security based on IEC 62351 standard	High, designed for substation automation with redundancy features	Limited QoS support, focus on real-time data delivery

bution of energy, where smart algorithms intelligently allocate resources, minimizing waste and maximizing the utilization of renewable energy sources.

- *Empowered Consumer Engagement:* The architecture fosters a paradigm shift in consumer engagement by providing real-time insights into energy consumption patterns [35]. Empowered by this information, consumers can actively participate in demand response programs, adjust their energy usage based on pricing signals, and contribute to overall energy conservation efforts.
- *Adaptive Load Management:* The system's ability to dynamically adjust to varying demand patterns enables adaptive load management. By intelligently redistributing loads during peak periods, the architecture minimizes stress on the grid, prevents overloads, and ensures a stable and optimized energy distribution network.
- *Operational Cost Reduction:* Optimized energy distribution, predictive maintenance based on data analytics, and efficient load management collectively contribute to a reduction in operational costs. By addressing potential issues before they escalate, the architecture enhances the overall cost-effectiveness of managing and maintaining the Smart Grid [36].
- *Facilitated Integration of Emerging Technologies:* The architecture's flexibility accommodates seamless integration with emerging technologies, such as Internet of Things (IoT) devices and advanced sensing technologies. This adaptability positions the Smart Grid to harness the potential of cutting-edge innovations, ensuring a future-proof infrastructure.
- *Environmental Sustainability:* By promoting the use of renewable energy sources and optimizing energy distribution, the architecture significantly contributes to environmental sustainability [37]. The reduction of energy wastage and reliance on traditional energy sources aligns with global initiatives for a greener and more sustainable energy ecosystem [38].
- *Scalability for Future Expansion:* The modular nature of the architecture allows for scalability, facilitating the incorporation of new functionalities and accommodating the expansion of the Smart Grid. This scalability ensures that the architecture remains adaptable to evolving technological landscapes and changing energy demands over time.

V. SDN APPLICATIONS FOR SMART GRIDS

This section delves into the heart of the collaboration between Software-Defined Networking (SDN) and Smart Grids. This section focuses on the practical and operational domain, where technological advancements translate into tangible improvements in the management and efficiency of the electric grid. The intersection of SDN and smart grids has led to innovative applications transforming how electrical energy is generated, distributed, and consumed. Each application is a testament to how SDN has become an essential tool for addressing critical challenges in the energy sector [39], [40], [41]. This section explores these applications, including monitoring the health of an electric grid in real-time and making informed decisions, optimizing energy distribution, and integrating renewable energy sources. Furthermore, it analyzes how SDN enables active demand management and effective load administration, engaging consumers in decision-making and promoting energy efficiency. Figure 6 shows a conceptual map of the different SDN applications applied to Smart grids.

A. REAL-TIME MONITORING AND ANALYTICS

Real-time monitoring and analytics are pivotal components of Software-Defined Networking (SDN) in Smart Grids, transforming how we manage electrical distribution. This section examines how SDN provides real-time insight and enables data-driven decision-making in Smart Grids. SDN facilitates proactive energy management by continuously monitoring and analyzing grid health and performance.

In the era of Smart Grids, real-time monitoring and analytics are the eyes and brains of the system. Table 8

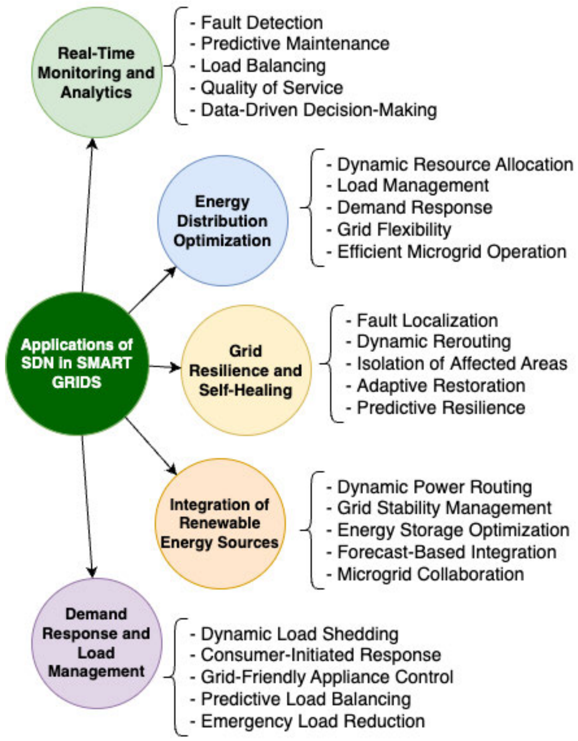

FIGURE 6. Applications of SDN in smart grids.

describes the capabilities that enable utilities and operators to implement this application:

TABLE 8. Real-time monitoring and analytics applications.

Application	Description	References
Fault Detection	Instantly identify grid faults and outages, enabling rapid response. *Example:* When a power line fault occurs, SDN redirects power to minimize disruptions.	[42]–[45]
Predictive Maintenance	Anticipate equipment failures and perform maintenance proactively. *Example:* Sensors predict transformer issues, allowing preemptive replacements.	[46]–[48]
Load Balancing	Continuously balance power loads, preventing overloads and blackouts. *Example:* SDN dynamically adjusts load distribution during peak demand.	[49], [50]
Quality of Service Assurance	Ensure the delivery of consistent, high-quality power to consumers. *Example:* SDN maintains power quality even during fluctuations or disturbances.	[51], [52]
Data-Driven Decision Making	Use real-time analytics to optimize grid operations and respond to changing conditions. *Example:* SDN adjusts energy routing based on data from weather sensors to avoid disruptions during storms.	[53], [54]

B. ENERGY DISTRIBUTION OPTIMIZATION

Energy Distribution Optimization is a cornerstone in the marriage of Software-Defined Networking (SDN) and Smart Grids, redefining how electrical energy is distributed and utilized. This section delves into the applications where SDN is pivotal in optimizing power distribution within Smart Grids. SDN contributes to a more efficient and adaptive energy distribution system by dynamically allocating resources and intelligently managing loads. Table 9 describes the different applications:

TABLE 9. Applications of energy distribution optimization in smart grids.

Application	Description	References
Dynamic Resource Allocation	Dynamically allocate energy resources based on real-time demand and supply. *Example:* During periods of high demand, SDN redirects power to critical areas for optimal usage.	[55]–[58]
Load Management	Intelligently manage and balance loads across the grid. *Example:* SDN adjusts the distribution of loads to prevent overloading and enhance overall stability.	[59], [60]
Demand Response	Respond to fluctuations in demand by adjusting energy distribution *Example:* SDN redirects energy during peak demand or incentivizes consumers to shift usage patterns.	[15], [61], [62]
Grid Flexibility	Enhance the flexibility of the grid to accommodate changes in energy generation and consumption. *Example:* SDN facilitates seamless integration of renewable energy sources, adapting to their variable output.	[63]–[65]
Efficient Microgrid Operation	Optimize the operation of microgrids within the larger grid ecosystem. *Example:* SDN ensures efficient energy transfer between microgrids based on real-time conditions.	[66], [67]

C. GRID RESILIENCE AND SELF-HEALING

Grid Resilience and Self-Healing epitomize the fortitude of Smart Grids empowered by Software-Defined Networking (SDN). This section delves into how SDN contributes to the robustness of the electrical grid, ensuring its ability to withstand disruptions and autonomously recover from faults. SDN transforms Smart Grids into resilient and self-healing infrastructures by providing real-time adaptive mechanisms. Table 10 briefly describes the different applications.

D. INTEGRATION OF RENEWABLE ENERGY SOURCES

The *Integration of Renewable Energy Sources* represents a critical frontier in the evolution of Smart Grids, and Software-Defined Networking (SDN) plays a pivotal role in facilitating this integration. This section explores how SDN enables the seamless assimilation of renewable energy sources into the electrical grid. SDN contributes to a sustainable and efficient energy landscape by providing dynamic adaptability and real-time management. Table 11 briefly describes the different applications.

TABLE 10. Applications of grid resilience and self-healing in smart grids.

Application	Description	References
Fault Localization	Quickly identify the location of faults or disturbances in the grid. *Example:* SDN uses sensors and analytics to pinpoint the exact location of a power line fault.	[68]–[71]
Dynamic Rerouting	Dynamically reroute energy flow to minimize the impact of faults or outages. *Example:* When a fault is detected, SDN redirects energy through alternative paths to maintain continuity.	[72]–[74]
Isolation of Affected Areas	Isolate affected sections to prevent cascading failures. *Example:* SDN autonomously isolates the faulty section, preventing disruptions from spreading.	[75], [76]
Adaptive Restoration	Adaptively restore services after fault resolution. *Example:* SDN gradually restores power, prioritizing critical services to ensure a smooth recovery process.	[77]–[79]
Predictive Resilience	Anticipate potential vulnerabilities and proactively enhance grid resilience. *Example:* SDN continuously analyzes grid conditions to predict and mitigate vulnerabilities before disruptions occur.	[80]–[83]

TABLE 11. Applications of integration of renewable energy sources in smart grids.

Application	Description	References
Dynamic Power Routing	Dynamically route power from renewable sources based on availability and demand. *Example:* SDN adjusts solar and wind energy distribution in response to fluctuating conditions.	[84]–[86]
Grid Stability Management	Ensure grid stability with the integration of intermittent renewable sources. *Example:* SDN balances the intermittent nature of renewable energy, preventing grid instability.	[87], [88]
Energy Storage Optimization	Optimize the use of energy storage systems in conjunction with renewable sources. *Example:* SDN manages the charging and discharging of batteries, maximizing the utilization of stored energy.	[89]–[91]
Forecast-Based Integration	Integrate renewable energy based on real-time weather forecasts. *Example:* SDN incorporates forecasts to adjust solar and wind power integration proactively.	[92], [93]
Microgrid Collaboration	Facilitate collaboration and energy exchange between microgrids and the primary grid. *Example:* SDN ensures seamless integration and coordination between renewable-powered microgrids and the larger grid.	[94], [95]

E. DEMAND RESPONSE AND LOAD MANAGEMENT

The *Demand Response and Load Management* section underscores the dynamic capabilities of Software-Defined Networking (SDN) in reshaping how it interacts with and manages energy consumption within Smart Grids. This section explores how SDN facilitates active participation from consumers and optimizes the distribution of loads, contributing to a more responsive and efficient energy ecosystem. Table 12 describes the different applications.

TABLE 12. Applications of demand response and load management in smart grids.

Application	Description	References
Dynamic Load Shedding	Dynamically shed non-critical loads during peak demand periods. *Example:* SDN identifies high-demand periods and sheds non-essential loads to prevent grid overloads.	[96], [97]
Consumer-Initiated Response	Enable consumers to actively adjust their energy consumption based on real-time prices or grid conditions. *Example:* SDN communicates pricing information to consumers, who can adjust their usage to save costs during peak times	[98], [99]
Grid-Friendly Appliance Control	Integrate with intelligent appliances to optimize their operation based on grid conditions. *Example:* SDN communicates with smart appliances to adjust their operation for optimal energy efficiency during high-demand periods.	[35], [100], [101]
Predictive Load Balancing	Use historical data and predictive analytics to proactively balance loads. *Example:* SDN anticipates peak demand periods and redistributes loads in advance to prevent disruptions.	[102], [103]
Emergency Load Reduction	Implement emergency load reduction measures during grid emergencies. *Example:* SDN automatically reduces non-essential loads to stabilize the grid during emergencies or faults.	[104]–[106]

F. ADVANCED MAINTENANCE TRENDS

The advent of SDN in Smart Grids presents a transformative approach to energy distribution and management, offering a wide array of advantages that extend far beyond the traditional grid systems. In this context, there are different maintenance schemes, such as condition monitoring SDN-enabled Smart Grids are equipped with a network of sensors and smart devices (i.e., infrared spectroscopy [107], [108], wireless sensor for communication [109], etc.) that continuously collect real-time data about various components of the grid, resulting in better fault diagnosis for components. In addition, the literature presents under the scheme of predictive maintenance optimized schedules to minimize disruptions to the grid and ensure a more reliable power supply [110]. Another maintenance paradigm is called Smart Maintenance [111] in which SDN enables utilities to dynamically manage their assets based on real-time conditions and demands. In some cases, SDN can automate responses to certain issues, such as rerouting power flow or isolating faulty components while maintaining service to unaffected areas.

VI. ENVIRONMENTAL IMPACT AND ENERGY EFFICIENCY OF SDN IN SMART GRIDS

This section responds to the SQ3 question where the deployment of SDN in smart grids can have a significant positive environmental impact and enhance energy efficiency. The following are some of the aspects related to environmental impact:

- *Reduction of CO2 Emissions*: By optimizing energy distribution and reducing transmission losses, SDN can significantly contribute to decreasing the use of fossil fuels and, consequently, reducing associated carbon dioxide (CO_2) emissions [112], [113]. By ensuring more efficient energy distribution, the need for generating additional electricity from polluting sources such as coal or oil is minimized. This not only has environmental benefits by lowering the carbon footprint of the electrical grid but also contributes to climate change mitigation by reducing greenhouse gas emissions.
- *Increased Integration of Renewable Energies*: SDN can facilitate the integration of intermittent renewable energy sources such as solar and wind power into the electrical grid. These energy sources are crucial for reducing dependence on fossil fuels and promoting a transition to a more sustainable and clean energy system [47], [95], [114]. By enabling more efficient management of the variable energy flow generated by these renewable sources, SDN helps maximize their penetration into the grid without compromising system stability or reliability.
- *Reduced Material Usage*: The more centralized and flexible management of the electrical grid through SDN can reduce the need for additional hardware and, consequently, the generation of electronic waste. By optimizing existing network infrastructure and maximizing its operational efficiency, SDN can help minimize resource waste and reduce the environmental impact associated with network equipment's production, deployment, and disposal [60], [105], [115]. This is especially relevant in the continued demand for communication and connectivity services, where resource efficiency has become increasingly critical in addressing environmental and sustainability challenges.

The implementation of SDN in smart grids not only brings environmental benefits but also significantly enhances energy efficiency. Let's delve deeper into the aspects related to energy efficiency [116], [117], [118]:

- *Optimization of Energy Pathways*: SDN facilitates the dynamic routing of energy through the grid, allowing for real-time adjustments based on demand, supply, and network conditions. By intelligently directing energy flows along the most efficient pathways, SDN reduces transmission losses and maximizes the utilization of grid resources. This optimization leads to overall energy savings and improves the operational efficiency of the electrical grid.
- *Flexible Demand Control*: SDN enables more granular and flexible control over energy demand by implementing demand-response mechanisms and dynamic pricing strategies. Through SDN-enabled applications, utilities can incentivize consumers to adjust their energy consumption patterns based on pricing signals or grid conditions [35]. For example, during periods of peak demand, SDN can automatically adjust energy tariffs to encourage load-shifting behaviors or prioritize critical loads, thereby reducing strain on the grid and enhancing overall efficiency.
- *Self-Diagnosis and Remediation*: SDN empowers the grid with self-diagnostic capabilities, allowing it to identify inefficiencies or anomalies in real-time and take corrective actions autonomously [70]. By continuously monitoring grid performance and analyzing data from sensors and devices, SDN can detect issues such as equipment failures, voltage fluctuations, or power imbalances. Subsequently, SDN can trigger automated responses, such as rerouting energy flows, isolating faulty equipment, or optimizing resource allocation, to rectify the detected inefficiencies promptly. This proactive approach to grid management minimizes energy wastage and ensures optimal system performance.
- *Predictive Analytics*: SDN leverages advanced data analytics and machine learning algorithms to predict future energy demand patterns, grid congestion, and potential efficiency bottlenecks. By analyzing historical data, weather forecasts, and other relevant parameters [46], [47], SDN can anticipate changes in energy consumption and generation, allowing utilities to proactively adjust operational strategies and resource allocation. By aligning energy supply with demand more accurately, SDN enhances grid efficiency and reliability while optimizing resource utilization [66].
- *Continuous Improvement*: One of the key features of SDN is its adaptability and ability to evolve. By continually analyzing performance metrics and user feedback, SDN controllers can iteratively optimize network operations, fine-tune algorithms, and implement new efficiency-enhancing features [42]. This iterative process of continuous improvement ensures that the grid remains responsive to changing conditions, technological advancements, and evolving consumer needs, thereby perpetuating the cycle of energy efficiency and sustainability.

VII. CHALLENGES AND FUTURE PERSPECTIVES

The integration of SDN technology into Smart Grid infrastructures presents numerous challenges that must be addressed to ensure the successful deployment and operation of these advanced energy systems [16], [17]. This section adds concise information to the MQ question identifying issues such as security, interoperability issues, and scalability challenges that stakeholders face when adopting SDN in Smart Grids:

- *Security Concerns*: Integrating SDN into Smart Grids introduces new cybersecurity risks, including unauthorized access, data breaches, and network vulnerabilities. Ensuring robust security measures and implementing encryption protocols are crucial to safeguarding critical infrastructure and data integrity [20], [22].
- *Interoperability Issues*: Smart Grids comprise diverse devices and protocols from multiple vendors, leading to interoperability challenges when deploying SDN solutions [95]. Standardizing protocols and fostering collaboration among stakeholders are essential to enable seamless integration and interoperability across heterogeneous systems.
- *Scalability and Performance*: As Smart Grids continue to expand in size and complexity, scalability becomes a significant challenge for SDN deployments. Ensuring that SDN architectures can efficiently scale to accommodate growing network demands while maintaining performance and reliability is paramount [25], [42].
- *Legacy Infrastructure Compatibility*: Many existing Smart Grid infrastructures are built on legacy systems and protocols, posing compatibility challenges for SDN integration [12], [75]. Retrofitting legacy systems to support SDN functionalities without disrupting ongoing operations requires careful planning and investment.
- *Regulatory and Compliance Requirements*: Compliance with regulatory standards and industry regulations adds complexity to SDN deployments in Smart Grids. Ensuring compliance with data privacy laws, cybersecurity regulations, and industry standards necessitates robust governance frameworks and adherence to best practices.

Table 13 presents a list of key challenges identified, along with specific technologies and solutions to address each. These solutions offer practical and effective approaches to overcome the obstacles associated with implementing SDN in Smart Grids.

As the energy landscape continues to evolve, the future of Software-Defined Networking (SDN) in Smart Grids holds immense promise for revolutionizing grid operations, enhancing energy efficiency, and enabling sustainable energy solutions. Embracing advancements in artificial intelligence, edge computing, and blockchain technology, among others, opens up new horizons for SDN deployment in Smart Grids. Some future proposals are described below:

- *Advancements in AI and Machine Learning*: Integrating artificial intelligence (AI) and machine learning (ML) algorithms into SDN controllers enables intelligent decision-making, predictive analytics, and proactive network management in Smart Grids [46], [61]. AI-driven SDN solutions can optimize energy distribution, predict grid failures, and adapt to dynamic operational conditions more effectively.

TABLE 13. Technologies and solutions to address challenges in implementing SDN in smart grids.

Challenge	Technologies and Solutions
Security Concerns	Implementation of advanced firewalls, intrusion detection and prevention systems (IDPS), data encryption, certificate-based user authentication, network segmentation, and role-based access control policies.
Interoperability Issues	Development of standardized and open communication protocols, implementation of interoperability gateways, protocol adapters, and integration middleware, and participation in industry standards initiatives and collaborative working groups.
Scalability and Performance	Utilization of horizontal and vertical scaling techniques, implementation of load management and load balancing solutions, adoption of distributed and elastic architectures, and optimization of routing algorithms and resource scheduling.
Legacy Infrastructure Compatibility	Development of compatibility adapters, translation protocols, and bridging and encapsulation solutions, gradual migration to SDN-compatible architectures, and modernization of legacy infrastructures through virtualization and containerization.
Regulatory and Compliance Requirements	Implementation of compliance policies and procedures, regular security audits, participation in certification and accreditation programs, and collaboration with regulatory bodies and industry standards organizations.

- *Edge Computing and Fog Networking*: Leveraging edge computing and fog networking technologies in conjunction with SDN enhances real-time processing, data analytics, and decision-making capabilities at the network edge [105]. This distributed computing paradigm improves latency, reliability, and resilience in Smart Grid operations, enabling faster response times and better resource utilization.
- *Blockchain for Secure Transactions*: Integrating blockchain technology with SDN enables secure and transparent transactions, data provenance, and smart contracts in Smart Grids [22], [83]. Blockchain-based SDN solutions enhance trust, integrity, and accountability in energy transactions, facilitating peer-to-peer energy trading, grid balancing, and demand-side management.
- *5G Connectivity and IoT Integration*: The rollout of 5G networks and the proliferation of Internet of Things (IoT) devices present opportunities to enhance SDN capabilities in Smart Grids. Leveraging 5G connectivity and IoT sensors enables real-time monitoring, control, and optimization of grid infrastructure, supporting dynamic energy management and grid automation initiatives [58], [92].
- *Resilient and Self-Healing Networks*: Future SDN architectures for Smart Grids will focus on building resilient and self-healing networks capable of withstanding cyberattacks, natural disasters, and other disruptions. Implementing proactive threat detection, automated incident response, and adaptive network reconfiguration

mechanisms strengthens the resilience and reliability of Smart Grid infrastructures [33], [83].

VIII. CONCLUSION

In this comprehensive review, the exploration navigated through the intricate landscape of Software-Defined Networking (SDN) in Smart Grids, unveiling its transformative potential, inherent challenges, and promising trajectories. Among all these, the following stand out:

- SDN emerges as a linchpin technology, reshaping conventional energy management paradigms and ushering in an era of unprecedented efficiency, flexibility, and resilience in grid operations.
- Through meticulous examination of its myriad applications, SDN was revealed to empower grid operators with real-time monitoring, predictive analytics, and dynamic resource allocation capabilities, enabling optimized energy distribution, disruption mitigation, and agile response to shifting demands.

However, amidst the promising opportunities, formidable challenges loom large on the horizon, demanding strategic mitigation and collaborative action. Security concerns, interoperability issues, and scalability constraints stand as formidable hurdles on the path to widespread SDN adoption, necessitating the development of robust governance frameworks, industry standards, and collaborative initiatives to safeguard critical infrastructure and ensure seamless integration. As the journey towards the future is charted, it is imperative to acknowledge the collective responsibility of industry stakeholders, policymakers, and researchers in harnessing the full potential of SDN to address the pressing energy challenges of the 21st century.

Looking ahead, the horizon of SDN in Smart Grids appears promising, buoyed by rapid advancements in complementary technologies such as artificial intelligence, edge computing, blockchain, and 5G connectivity. These innovations hold the potential to further augment the capabilities of SDN, enabling autonomous decision-making, edge intelligence, secure transactions, and real-time responsiveness at an unprecedented scale. As the transformative journey is embarked upon, fostering interdisciplinary collaboration, promoting innovation, and embracing a culture of continuous learning and adaptation will be paramount to unlocking the transformative potential of SDN and shaping a smarter, more sustainable energy future powered by Software-Defined Networking.

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WASHINGTON VELASQUEZ (Senior Member, IEEE) received the Ph.D. degree in telematics system engineering and the master's degree in telematics services and network engineering from the Universidad Politécnica de Madrid, Madrid, Spain. He is currently a Professor with the Faculty of Electrical and Computer Engineering, Escuela Superior Politécnica del Litoral, Guayaquil, Ecuador. He has authored/coauthored several articles in indexed journals and has led projects related to sensing and networking. He also holds international certifications in UBIQUITI, HUAWEI, and MIKROTIK. His research interests include telemetry, remote control, smart cities, and big data.

GUILLERMO Z. MOREIRA-MOREIRA was born in Guayaquil, Ecuador. He received the degree in telematics engineering from the Escuela Superior Politécnica del Litoral (ESPOL), enriching his comprehension of the symbiotic relationship between telecommunications and information systems, in 2024. This educational trajectory ignited his enthusiasm for utilizing technology to effect positive societal change. He has been captivated by the intersection of technology and innovation since his formative years. His fascination with electronics sparked a journey into technical education.

MANUEL S. ALVAREZ-ALVARADO (Member, IEEE) was born in Guayaquil, Ecuador, in 1988. He received the degree in electrical power engineering and the master's degree (Hons.) in physics education from the Escuela Superior Politécnica del Litoral, Guayaquil, in 2011 and 2013, respectively, the M.Sc. degree (Hons.) in power and energy systems from New Jersey Institute of Technology, Newark, NJ, USA, in 2015, the Ed.D. degree in physics from the National Polytechnic Institute of Mexico, and the Ph.D. degree in power systems from the University of Birmingham, Birmingham, U.K. He is currently a Professor with the Faculty of Electrical and Computer Engineering, Escuela Superior Politécnica del Litoral. His research interests include educational physics, quantum mechanics, renewable energy, and reliability of power systems.