Building a Resilient and Sustainable Grid: A Study of Challenges and Opportunities in AI for Smart Virtual Power Plants

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ABSTRACT

In recent years, integrating distributed energy resources has emerged as a pervasive trend in competitive energy markets. The idea of virtual power plants (VPPs) has gained traction among researchers and startups, offering a solution to address diverse social, economic, and environmental requirements. A VPP comprises interconnected distributed energy resources collaborating to optimize operations and participate in energy markets. However, existing VPPs confront numerous challenges, including the unpredictability of renewable energy sources, the intricacies and fluctuations of energy markets, and concerns related to insecure communication and data transmission. This article comprehensively reviews the concept, historical development, evolution, and components of VPPs. It delves into the various issues and challenges encountered by current VPPs. Furthermore, the article explores the potential of artificial intelligence (AI) in mitigating these challenges, investigating how AI can enhance the performance, efficiency, and sustainability of future smart VPPs.

CCS CONCEPTS

• **Computing methodologies** → **Artificial intelligence**; • **Hardware** → **Energy distribution**; **Power estimation and optimization**; • **Security and privacy**;

KEYWORDS

Virtual Power Plant, Artificial Intelligence, Energy Infrastructure, Challenges

ACM Reference Format:
Md Romyull Islam, Long Vu, Nobel Dhar, Bobin Deng, and Kun Suo. 2024. Building a Resilient and Sustainable Grid: A Study of Challenges and Opportunities in AI for Smart Virtual Power Plants. In *2024 ACM Southeast Conference (ACMSE 2024), April 18–20, 2024, Marietta, GA, USA.* ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3603287.3651202

1 INTRODUCTION

In recent years, many countries have significantly transitioned their power systems from the conventional "source follows load" paradigm to a more dynamic "source-load interaction" model. The large-scale grid connection of renewable energy, such as wind turbines and solar power, has dramatically changed the structure of the traditional centralized power generation method. However, distributed power generation faced challenges, including limited capacity, large amounts of data, and poor controllability. Random connection of massive electric vehicles (EV) to the grid also changes the power flow characteristics and makes the grid load more unpredictable. In addition, another observation of the current power system is that the double peaks of usage (i.e., winter and summer peaks, morning and evening peaks) become much sharper but keep a short duration, resulting in low efficiency and high cost of the redundant design of the traditional grid. This change refers to a more pronounced and sudden increase in electricity demand during specific periods, impacting the efficiency and cost of the traditional grid design. The system's flexibility in handling a high proportion of fluctuating renewable energy is crucial for ensuring the future power system's security. In this context, components other than the power generation sides represented by virtual power plants (VPPs) become increasingly critical. A VPP utilizes the internet and current communication technologies to consolidate distributed power sources, energy storage, loads, and other resources dispersed throughout the power grid for collaborative optimization of operation, control, and market transactions, which achieves energy complementarity and load adjustments like peak shaving, frequency regulation, and energy backup. Based on the report of the Grand View Research [12], the estimated market value of the global virtual power plant industry stood at approximately USD 3.42 billion in 2022. This market size is expected to increase with a compound annual growth rate of 22.0%, with this growth trajectory expected to continue from 2023 through 2030.

However, the implementation and advancement of VPPs face various challenges. Notably, the escalating share of renewable energy sources and the resultant instability in power grid supply pose significant concerns from the standpoint of energy sources and resource allocation. The incorporation of energy storage and its seamless integration into the existing grid present formidable obstacles. In the context of market transactions, VPPs deal with issues such as price fluctuations, regulatory changes, dynamic compliance, and evolving consumer behavior, making their operation and management increasingly complex. Furthermore, VPPs share common challenges with traditional power systems, including big data management and communication security. As the landscape of electricity users transitions from just consumers to hybrid producers and consumers, all these factors will challenge the security, reliability, and economic efficiency of VPPs and their power networks. In light of these challenges, this article delves into the potential solutions offered by artificial intelligence (AI) in addressing the key

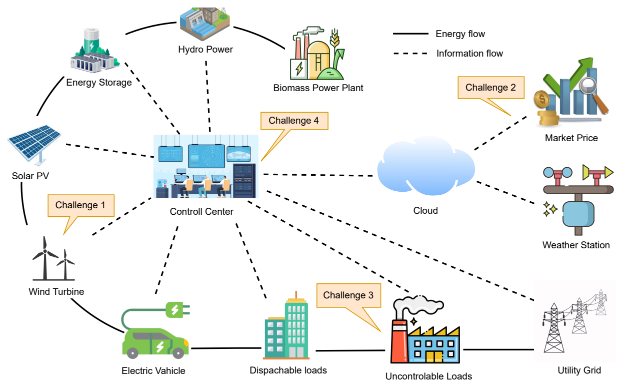

Figure 1: Concept and Challenges of Virtual Power Plant

issues faced by VPPs.

Our study provides a comprehensive review of the concept, history, evolution, and components of VPPs and discusses how VPPs can integrate distributed energy resources, enhance grid stability, and participate in energy markets. We identify four major challenges in operating and managing current VPPs: energy sources and resource allocation, transactions due to market price fluctuations, dynamic loads and demands, and communications and security. Considering the above issues, this article focuses on researching and summarizing the challenges and opportunities of applying AI to the next-generation smart VPPs, including solving energy instability and resource inefficiency, analyzing market fluctuations, and adapting to regulatory changes, overcoming uncertainty and better understanding consumers, and promoting effective communication through solid security measures. This study pioneers a systematic and critical analysis of the latest AI technologies for VPPs, exploring their potential advantages in enhancing performance, efficiency, security, and sustainability. This study explores the potential and advantages of AI in improving the performance, efficiency, security, and sustainability of VPPs. This article can shed light on academic scholars and industrial researchers in related fields to explore the new generation of smart VPPs.

The remaining sections of the paper are outlined as follows. Section 2 reviewed the background of the VPP, including the history, case studies, and structures. Section 3 discussed the existing challenges of VPPs, including resource allocation, assuming market price and energy transaction, dynamic load demand, and communication and security. In Section 4, we explore and evaluate the opportunities and solutions offered by AI for smart VPPs, discuss how AI can help tackle the challenges and issues in each aspect of VPPs, and provide some examples of the use of AI. Section 5 provides an overview of related research in this field. Finally, the paper concludes with a summary in Section 6.

2 BACKGROUND

Traditional power plants are mainly built to generate electricity, adjust peak and frequency, and participate in energy market transactions. It is estimated that the number of large power stations on the grid, such as nuclear or gas plants, will be reduced by half in the next 20 years, and more than 70% of the electricity in the future will be renewable energy [8]. The energy revolution has also profoundly changed the structure of the power grid. Unlike centralized, traditional power plants, as illustrated in Figure 1, virtual power plants (VPPs) aggregate distributed power sources and energy storage facilities using modern intelligent technology. They participate in electricity market transactions with dynamic, fine-grained control [41, 46, 68]. VPPs effectively reduce generation losses and emissions, optimize resource use, control grid peaks, and enhance power supply reliability.

2.1 History and Evolution of VPPs

Virtual power plants (VPPs) built on distributed and renewable energy sources have a long history. From the end of the nineteenth century to the beginning of the twentieth century, the world's first wind turbine [61] and a large-scale solar generator [6] were built near Glasgow, UK, and Cairo, Egypt, respectively. ARCO Solar developed the first large-scale commercial photovoltaic power plant and came online in 1982 near Hesperia, California, with a capacity of 1MW [4]. From the 1980s to the 1990s, the use and development of distributed energy resources continued to increase, and the power supply system gradually transformed from centralized to decentralized. In order to coordinate and power monitoring, Dr. Shimon Awerbuch first proposed the concept of a VPP in 1997 [35]. In the twenty-first century, the development of smart grid technology paved the way for more efficient energy management. Advanced metering, communications, and control systems enable utilities to monitor and control distributed energy resources remotely [76]. Through sophisticated software and control systems, VPP further enables the management and optimization of decentralized energy. These platforms can aggregate and coordinate the output of various distributed energy sources, including solar, wind, and batteries, and even respond to dynamic consumer demand [69]. In the industry, VPP solution startups such as Next Kraftwerke, Kiwi Power, and Sunverge Energy have also been established in recent years [15–17]. In the next decade, VPP is expected to become increasingly adopted in regions with a high proportion of renewable energy, such as Europe and Australia [13, 76]. Recently, with significant advancements in AI and the Internet of Things (IoT), the capabilities of VPP can be further enhanced to achieve more effective energy monitoring, prediction, control, and optimization [40, 69].

2.2 How VPP Works

A Virtual power plant (VPP) is a network that integrates dispersed energy resources, orchestrating them to operate cohesively as an extensive power generation facility. The primary goal of a VPP is to enhance grid stability, efficiency, and reliability while mitigating emissions and costs associated with conventional power generation [21]. Generally, the architecture of a VPP contains three essential elements. Firstly, a diverse array of energy assets, ranging from solar panels and wind turbines to energy storage systems and energy-efficient buildings, form the foundation of the VPP. Energy Management Systems (EMS) play a pivotal role in efficiently overseeing various energy resources, including dispatchable power plants, intermittent generation units, storage facilities, and demand response systems. The second component is the communications network, facilitating data exchange and control signals among different VPP elements. For instance, EMS facilitates energy trading within the VPP through bidirectional communication [37, 66] and real-time status updates. The third component, the control system, handles data collection and analysis, power market prediction, resource modeling, aggregation, and transaction decisions. It oversees the real-time operation of distributed energy production and consumption. Cloud-based software is used for data analysis, optimization, and decision-making [19], targeting cost reduction, pollution minimization, and profit maximization.

2.3 Case Studies of Existing VPPs

Tesla's Suburban VPP in South Australia. In 2018, Tesla launched its VPP project [9] in the suburban of South Australia to utilize distributed energy resources and improve the resilience of the grid [11]. This VPP project connects thousands of Tesla Powerwall batteries in residence to form a network [23]. It provides grid stabilization services, including frequency regulation and backup power during grid outages. This project demonstrates the scalability and effectiveness of residential battery storage systems in supporting grid operations and mitigating grid fluctuations caused by intermittent renewable energy [9]. Upon completion, Tesla's VPP is anticipated to produce 250 MW of solar energy and store 650 MWh of storage capacity to serve this region [23].

TEPCO's VPP within Metropolis Tokyo. Japan's Tokyo Electric Power Company (TEPCO) established its VPP to enhance energy security after the Fukushima nuclear disaster [7], and the project began operations in 2017 [18]. TEPCO VPP integrates rooftop solar panels, battery storage systems, and EV charging infrastructure. It optimizes distributed energy resources to achieve demand response and peak shaving and provides backup power in emergency situations to enhance disaster recovery capabilities [7]. TEPCO's VPP is part of a larger project that includes rooftop solar power facilities with a total capacity of 100 MW within the city. This VPP project improves grid resilience and encourages sustainable energy practices in the populous metropolis, promoting the adoption of electric vehicles and smart grid technologies in Tokyo.

Centrica's VPP across Multiple Countries. Centrica is a leading energy company that operates a VPP in the UK. Europe's inaugural extensive, multi-asset clean energy smart grid has been inaugurated at Terhills leisure park in Belgium by Centrica Business Solutions. This marks the establishment of the world's most sophisticated VPP, which was established in 2018 [10] and aggregates various renewable energy sources, including wind farms, solar installations, and biomass facilities. It utilizes advanced control systems and real-time monitoring to enhance the performance of distributed energy assets. The Terhills site boasts 140 lithium-ion batteries, collectively possessing an energy capacity of 18 megawatts. In conjunction with the energy adaptability of the Belgian plant and other prominent energy producers, these batteries form a VPP with a total capacity of 32MW [14]. Centrica's VPP significantly improves the UK's grid stability and reduces greenhouse gas emissions. It is also a model for efficient integration of renewable energy and resilience of the grid in different European countries.

3 CHALLENGES IN EXISTING VIRTUAL POWER PLANTS

Although virtual power plants (VPPs) contain many advantages and are put into use by various parties, existing virtual power plants still face different kinds of limitations and challenges. As shown in Figure 2, based on the research and analysis of current systems, this chapter summarizes four main categories of challenges, including different aspects of resources, markets, operations, and communications.

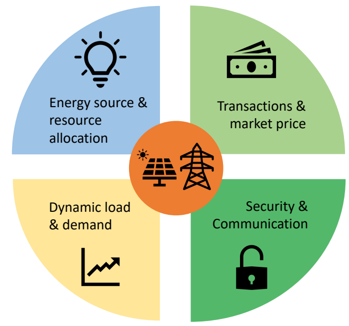

Figure 2: Major Challenges of Existing VPPs

3.1 Energy Source and Resource Allocation

Growing Share of Renewable Energy. Virtual Power Plants (VPPs) are crucial in harnessing large quantities of renewable energy sources (RES), like wind and solar power. However, the time-dependent nature of these resources significantly influences their operational stability. The unpredictability of wind power generation is primarily attributable to the stochastic variations in wind speed, which, in turn, are impacted by environmental factors like geographical area and weather conditions. Besides, solar radiation heavily impacts solar energy production, resulting in daily and seasonal fluctuations [65]. The sudden onset of cloud cover or other weather changes can have a substantial and adverse effect on renewable energy output. Nevertheless, the current wind and solar power generation forecasts continue to exhibit a notable margin of error, typically ranging from 20% to 30% [65]. This uncertainty and the growing share of renewable energy can introduce significant instability and resource wastage within VPPs.

Insufficient Energy Storage Capacity. VPPs commonly leverage diverse energy storage systems to address the inherent instability of renewable energy sources. However, the efficacy of these storage systems is often contingent on factors such as chemical composition, battery life, and other relevant variables [45]. Exploring optimal configurations for energy storage systems that account for intricate relationships, including multiple factors, objectives, and constraints, requires further investigation. Moreover, the energy storage power stations within a VPP are dispersed and numerous, with variations in capacity configuration, maximum charge power, and other attributes. Notably, the comprehensive consequences of integrating energy storage devices into VPPs have yet to be fully explored in existing literature [36].

Difficulties in Integrating with Existing Grids. The widespread adoption of distributed renewable energy sources has introduced considerable unpredictability, significantly impacting the security, stability, and economic performance of the current power grid [52]. For producers, opting for high-capacity, easily deployable energy sources often reduces costs by simplifying transmission infrastructure. Conversely, from a consumer standpoint, the growing popularity of distributed renewable energy is anticipated to yield future cost savings, making it a more economically advantageous option compared to traditional energy sources. Modern power stations face the challenge of meeting diverse functional requirements across various time scales and output precisions, including frequency and peak regulation, emergency control, and fluctuation suppression. The effective integration of these resources into the existing grid, mitigating the impact of their intermittency and volatility, and coordinating diverse energy storage systems and load conditions represent significant challenges for today's virtual power plants.

3.2 Transactions and Market Price

Massive Trading and Real-time Prices. The volatility of market prices and the substantial transaction volumes constitute a significant source of uncertainty in virtual power plants (VPPs) management. Energy markets are characterized by high volatility and frequent fluctuations in prices. From a supply perspective, Conventional energy sources which include coal, gas, and oil, experience price variations influenced by changes in global markets and local policies [74]. As the share of renewable energy grows, introducing its own uncertainties, the supply price of energy in virtual power plants also becomes increasingly unstable. The high intermittent nature of renewable energy will bring electricity markets closer to real-time trading markets as well. Additionally, energy prices are contingent on factors such as demand, trading volumes, and transmission networks, which all contributes to substantial fluctuations in electricity market prices. As per the U.S. Department of Energy's report [55], this fluctuation may reach up to 359.8%. These dynamic factors pose significant challenges to the development and operation of VPPs, requiring strategic considerations to navigate the complexities of the evolving energy landscape.

Diverse Markets and Regulatory Complexities. Energy markets are subject to diverse regulations, tariffs, and market rules that vary across regions [67]. The intermittent nature of renewable energy is poised to increase cross-region transactions in the electricity market. Virtual power plants often operate across multiple markets, each governed by its own distinct regulations. Navigating these intricate situations can present considerable challenges. A comprehensive understanding of local and national energy policies and regulations is imperative to ensure regulatory compliance while optimizing transactions and fostering revenue growth. Given the potential for losses due to regulatory changes and market price fluctuations, participants in the electricity market, including VPPs, must ascertain effective electricity pricing and quality trading methods. Pandvzic et al. [60] investigated weekly self-scheduling for VPPs, including intermittent renewables, energy storage, and traditional power plants. They used a mixed-integer linear programming model to maximize weekly VPP profits, respecting long-term contracts and technological constraints.

Operation Optimization and Risk Management. Many VPPs aim to boost profits by purchasing energy at lower cost and selling them at higher prices, necessitating sophisticated optimization algorithms and effective risk management strategies. The intricate task of precisely allocating energy resources to align with market prices while considering potential shifts in supply and demand adds complexity to VPP operations [50]. Managing risks associated with price instability, weather-induced uncertainty, and asset performance further compounds the challenges. Therefore, having an optimized operation and robust risk management plan is crucial for VPP operators to protect against financial losses. Tajeddini et al. [73] proposed a two-stage stochastic mixed-integer linear programming method to formulate optimal VPP operations. In another related study [82], Zhang et al. investigated the impact of price fluctuations on the transaction dynamics and the costs of VPPs. These endeavors underscore the challenges inherent in VPP operations, emphasizing the importance of overcoming these obstacles for the financial stability and long-term sustainability of VPPs.

3.3 Dynamic Load and Demand

Load and Demand Uncertainty. One of the primary challenges associated with Variable Power Plants (VPPs) is the inherent uncertainty linked to load and demand. In their research, Shah et al. [70] delved into the intricacies of forecasting electricity demand and price, highlighting the complexities arising from unique characteristics such as high frequency, volatility, extended trends, non-constant mean and variance, mean regression, and others. Furthermore, the fluctuations in load demand are contingent on seasonal variations and are influenced by factors like consumer habits, financial conditions, production activities, and emergencies, rendering the characteristics of uncertain load demand even more intricate [31]. As an illustration, the Electric Reliability Council of Texas observed a peak demand of 69,215 MWh during the February 2021 cold snap [22].

Uncontrollability of the Grids. The variability in load introduces a significant challenge to the controllability of virtual power plants [28]. Typically, various components of a grid operate interdependently, following predetermined rules and schedules. These loads, with their predictable operating patterns, can be made more cost-effective through controlled load tariffs, provided that power consumption is restricted to specific periods (usually during off-peak hours). However, the growing prevalence of electric vehicles in recent years has exacerbated the unpredictability within the VPP system. According to a study by Pandey et al. [59], the number of electric vehicles is projected to reach approximately 11 million by 2025. If the current disorderly charging practices of electric vehicles persist—charging occurring at any time, anywhere, and without a structured plan, the existing power grid may struggle to accommodate a higher penetration of new energy vehicles.

Different Consumer Behaviors. Consumer behavior plays a crucial role in influencing energy demand, shaped by diverse lifestyle choices and household activities [58]. Electricity consumption behavior encompasses the decisions, actions, and patterns demonstrated by individuals or households in acquiring and using goods and services [26]. Significantly, the electricity consumption behavior varies across regions and consumer groups. For instance, in affluent areas where consumers prioritize environmental consciousness, the proliferation of electric vehicles with high penetration rates and frequent use can result in a substantial upswing in the power grid system's peak load. On the other hand, groups with lower spending power often exhibit electricity demand during off-peak hours, primarily at night. The key to the future development of intelligent virtual power plants lies in empowering customers to modify their electricity consumption patterns, actively engaging in smart power distribution [64], and promoting the adoption of measures with optimal emission reduction efficiency, operability, and acceptability. This approach is crucial for steering the trajectory of smart VPPs toward a sustainable and consumer-centric direction.

3.4 Communication and Security

Data Transmission and Information Aggregation. Data transmission and information aggregation play integral roles across all facets of power production, transmission, monitoring, and operation within virtual power plants (VPPs) [57, 80]. They are pivotal for effectively managing and controlling distributed energy within the VPP framework. Specifically, digital technology within VPPs encompasses data collection (e.g., power plant operation conditions, meteorological data, market prices, etc.), secure and rapid communication (e.g., among VPPs, individual resources, transmission system operators, and power markets), and precise regulation based on load and requests. VPPs exhibit distinctive characteristics, including a large number of short-term services, high concurrency rates, wide cross-regional operations, and significant load fluctuations. Consequently, there are stringent requirements for data transmission and information communication in VPPs. Failures in communication systems can have severe implications on a VPP's revenue and operational efficiency. As the scale and application scope of VPPs continue to expand, the need for efficient, safe, and reliable information communication networks becomes increasingly critical to achieve large-scale, multi-temporal, and spatial-scale distributed resource aggregation and control.

Cybersecurity and Privacy Protection. Traditional power grid enterprises typically employ closed management and control, utilizing private networks for scheduling, operation, and control data. This approach enhances grid communication security, providing a robust defense against potential network attacks. In contrast, VPPs interface with equipment and systems from various organizations, introducing multiple access methods. Each organization employs distinct technologies and security measures, resulting in variations in identity management, encryption methods, networking modes, and security mechanisms. Simultaneously, VPPs encounter the challenge of collecting and analyzing a substantial amount of energy data, exposing them to potential data security [47] and privacy risks [44]. Any network attack, unauthorized access, or tampering with the data in a VPP constitutes a substantial risk to the operation of the power system. Therefore, when constructing a VPP, it is imperative to guarantee the reliability and protection of a distributed energy system. This includes implementing robust data security protections such as secure data transmission, encryption, and identity authentication to safeguard against potential vulnerabilities.

Data Interoperability and IoT Integration. Ensuring rapid data transmission and aggregation is crucial for establishing interconnections and effectively managing and monitoring distributed energy resources in virtual power plants [32]. To facilitate seamless communication across diverse interfaces and optimize the development and operation of application software on heterogeneous platforms, VPPs need to address challenges related to intercommunication, interconnection, and interoperability among various devices [30]. The wide range of communication technologies requires different networking equipment, and with many equipment manufacturers, achieving interoperability and efficient data management across diverse systems and equipment poses technical challenges. The need for comprehensive interconnection, interoperability, and compatibility grows as renewable energy, electric vehicles, and the Internet of Things integrate into VPPs. These are essential to support the advanced sensing, data fusion, and intelligent applications anticipated in future VPPs.

4 OPPORTUNITIES WITH AI FOR SMART VPPS

4.1 Tackling Unstable Energy and Inefficient Resource

Artificial intelligence plays a vital role in the evolution of smart grids, enabling seamless regulation from source and grid to load and storage. This shift, in particular, enables Virtual Power Plants (VPPs) to manage volatile renewable energy sources like solar and wind effectively. Utilizing state-of-the-art artificial intelligence algorithms, like long short-term memory (LSTM) and simulated annealing methods, can help more accurate predictions of solar and wind power [42, 54]. Elsaraiti et al. [42] demonstrated a deep learning technology based on the LSTM algorithm to help predict solar power generation capacity under different conditions. Muneeb et al. [54], use simulated annealing and deep learning models to determine the ideal time step for wind power forecasting. Their work allows efficient discovery of optimal lookback periods within a limited number of epochs, thereby reducing training time and greatly enhancing grid stability. In addition to helping overcome fluctuations generated by renewable energy, AI also has the potential to improve energy storage systems in VPPs by taking into account past data and load forecasts. A report from STEM [20] found that AI-driven software and hardware systems can greatly improve the efficiency and reliability of various energy storage devices. For example, digital twin algorithms can quickly decide when to discharge or charge energy storage devices, guided by the latest data [49]. In the field of electrochemical energy storage, benefiting from the predictive capabilities of artificial intelligence in modeling battery charging and discharging behavior, the industry has simplified the simulation and refined management of battery operations in large-scale energy storage facilities, thereby improving the reliability and security of lithium-ion batteries [72]. Finally, in terms of integration with traditional power grids, artificial intelligence can also help automate control of all aspects of the VPP, achieve efficient and precise control, and improve power generation efficiency and quality. Qin et al. [63] utilized a novel deep reinforcement learning algorithm to minimize operating costs of off-grid VPPs that incorporate battery storage and flexible loads, utilizing fossil fuel-based generators as necessary backup. Shibl et al. [71] focused on artificial intelligence in VPPs using electric vehicles. They proposed an LSTM-based management system that effectively reduces power loss and voltage fluctuations, achieving grid load curve smoothing.

4.2 Analyzing Market Fluctuations and Adapting to Regulatory Changes

Artificial intelligence has the capability to construct predictive models by analyzing historical market data, policy shifts, and other pertinent factors, enabling the anticipation of future energy market prices. For instance, virtual power plant (VPP) operators can gain insights into current market dynamics through machine learning

Table 1: Challenges in Existing VPPs and Possible Solutions with AI Comparison

Characteristic	Challenges and Issues	Opportunities with AI for Smart VPPs
Energy Source and Resource Allocation	Growing Share of Renewable Energy [65], Insufficient Energy Storage Capacity [36, 45], Difficulties in Integrating with Existing Grids [52]	Accurate Predictions of Wind and Solar [42, 54], Advanced Energy Storage Software [20], Digital Twin Management [49], Battery Charging Behavior [72], Flexible Loads and Backup [63], Vehicle-to-grid and Grid-to-vehicle [71]
Transactions and Market Price	Massive Trading and Real-time Prices [55, 74], Diverse Markets and Regulatory Complexities [67], Operation Optimization and Risk Management [50]	Forecasting the Daily Electricity Price [25], Automatic Operations with Evolving Regulations [75], Risk-constrained Management [50], Autonomously Optimize Power Sales [27]
Dynamic Load and Demand	Load and Demand Uncertainty [22, 31, 70], Uncontrollability of the Grids [28, 59], Different Consumer Behaviors [26, 58, 64]	Consumer Demand Forecasting [5, 56, 62], EV Charging and Routing Management [39], Digital Platform and Data-driven Modelling [34, 53]
Communication and Security	Data Transmission and Information Aggregation [57, 80], Cybersecurity and Privacy Protection [44, 47], Data Interoperability and IoT Integration [30, 32]	Blockchain Integration [65], Communication Parameter Mapping [48], Data Protection and Security Analysis [24, 77], Hybrid Traffic Scheduling [78], Enhance Data Interoperability with IoT [29, 33]

techniques like time series analysis. AI can also rapidly process extensive data from diverse sources, encompassing seasons, weather conditions, historical trends, and supply and demand metrics. Subsequently, the model can predict real-time market price movements and potential rule changes, facilitating informed decisions regarding resource allocation and trade strategies. In a recent study [25], researchers sought to establish a reliable model incorporating the most impactful predictors for predicting the Maximum Daily Electricity Price (MDEP) within the Iranian electrical energy market. They employed an artificial intelligence model featuring a convolutional neural long-short-term memory network, demonstrating exceptional forecast accuracy for both MDEP and Average Daily Electricity Price (ADEP) in the Iranian energy market. Artificial intelligence also plays a crucial role in adapting to shifts in energy regulations, tariffs, and market rules across diverse regions. For instance, natural language processing (NLP) is instrumental in extracting key information from regulatory filings and tracking updates. Based on that, machine learning models then automatically adjust operations within the VPP system, ensuring compliance with evolving regulations. Thimm et al. [75] are engaged in an extensive and ongoing research program that focuses on leveraging intelligent systems, machine learning, and NLP to aid corporate environmental compliance managers in monitoring and evaluating new regulations and oversight renewals. They advocate for a comprehensive conceptual data model designed to encapsulate critical elements of environmental regulatory announcements and assess their relevance. In the realm of operational optimization and risk management, artificial intelligence proves invaluable for VPPs by enabling the simulation of diverse scenarios and the formulation of effective risk management strategies to shield against financial losses. This includes the implementation of hedging strategies, diversification, and decisions based on risk thresholds, empowering VPP operators to make informed decisions regarding market participation or exit strategies to mitigate risk exposure [50]. For instance, Gridmatic, a specialized company in power trading technology, utilizes artificial intelligence in its proprietary system to autonomously optimize power sales at the most favorable prices [27]. By offering fixed-price offtake agreements, Gridmatic reduces energy production risk while leveraging artificial intelligence to enhance power sales. It is crucial to have a model that improves and becomes more accurate as it learns from factual information and adjusts its predictions. Given its iterative learning capability, reinforcement learning becomes pivotal in this context. A recent study [79] explores the feasibility of using reinforcement learning in power producer bidding strategies. The study proposes a multi-agent reinforcement learning (MARL) approach, merging Win or Learn Fast and Policy Hill-Climbing algorithms to tackle the bi-level game model iteratively, ultimately achieving market equilibrium outcomes.

4.3 Overcoming Uncertainties and Better Understanding Consumers

Artificial intelligence has gained prominence as a viable approach to address challenges arising from uncertainty in load and demand. Electrical load profiles, shaped by a complex interplay of predictable and stochastic elements influenced by time, geography, and emerging technologies such as electric vehicles (EVs), pose unique challenges. Nevertheless, AI technology presents innovative solutions, enabling virtual power plants (VPPs) to balance supply and demand more efficiently and accurately. The demand response industry is experiencing growth in North America, the UK, and Europe. Within North America, the market is assumed to exceed 18 billion USD by 2022, increasing from its value of 8 billion USD in 2018 [14]. In a comprehensive research endeavor [56], an organized review of electricity demand forecasting explores the hypotheses and variables influencing electricity consumption. The findings reveal that 50% of electricity demand forecasts hinge on weather and financial indicators, 8.33% on household lifestyle factors, 38.33% on historical energy consumption data, and 3.33% on stock market indexes. Furthermore, AI plays a pivotal role in optimizing charging needs, overseeing, and coordinating availability [3]. Its utility extends to monitoring and coordinating charging requirements, enhancing grid stability by promptly identifying and addressing anomalies in generation, consumption, or transmission. Many VPP companies, such as Karit VPP, leverage advanced data modeling and machine learning techniques to analyze grid, demand, market, weather, and asset performance data, facilitating automated responses [5]. Recently, substantial efforts have been dedicated to enhancing the controllability of the grid, as evidenced by extensive research [62]. These endeavors focus on predicting EV demand, devising optimal EV charging schedules, facilitating the integration of EVs into the grid, and addressing issues related to damaged EV batteries. For instance, Qaisar et al. [62] investigated the application of machine learning methods in EV charging and energy management within smart grids. Their study delves into the advantages and challenges of various approaches, which include deep neural networks (DNN), support vector machines, and reinforcement learning (RL). The research evaluates the accuracy and reliability of these models using diverse metrics and datasets. Cao et al. [38] developed a Smart Charging Algorithm (SCA) grounded in action critical learning to optimize electric vehicle charging while considering the uncertainty in electric vehicle charging behavior. Furthermore, VPPs can also leverage artificial intelligence and machine learning [53] to analyze and predict consumer behavior based on historical data and real-time information. Antonopoulos et al. [34] employed a variety of machine learning models, like linear regression, gradient boosting, random forests, and dense neural networks, to create a model that understands the relationship between household characteristics and the median response of each household. Additionally, the authors utilized model-agnostic interpretation techniques like ranked feature importance to identify key elements and assess their impact on response behavior. The research further emphasizes that AI-driven smart meters and IoT devices empower consumers to adjust electricity consumption in response to real-time pricing, peak demand periods, and the availability of renewable energy. This active participation enhances consumer empowerment and bolsters the VPP's capacity to manage demand uncertainty effectively. Managing the power grid in extreme situations like blackouts is challenging. Zhenting Zhao et al. [83] explore reinforcement learning for enhanced power grid control and show that applying methods like "reduced action spaces" significantly improves RL agents' performance in simulating large-scale blackouts and sub-networked grids.

4.4 Facilitating Effective Communication with Robust Security Measures

Artificial intelligence is increasingly employed in virtual power plants (VPPs) for intrusion detection, encryption, data protection, security analysis, and dynamic resource allocation within energy networks. Li et al. [48] conducted an evaluation of VPP communication technology, emphasizing security, efficiency, trustworthiness, and standardization. The study emphasizes the utilization of blockchain, collaboration between cloud and edge computing, machine learning, and emerging Information and Communication Technologies (ICT) for energy transaction, exchange, and dispatch processes within VPPs. Roozbehani et al. [65] explore the use of artificial intelligence in tackling communication challenges, proposing a novel method to enhance two-way communication in VPPs. Wu et al. [78] also proposed a three-layer VPP communication architecture incorporating 5G and time-sensitive networks to achieve determinism and mobility. Collectively, these AI-driven approaches contribute to overcoming communication challenges in VPPs by enhancing the efficiency and reliability of data transmission. The integration of AI and the power grid holds significant promise for bolstering cybersecurity within VPPs. For instance, Kerem et al. [24] extensively explore the application of AI techniques to counter cyber threats, furnishing advanced security measures to safeguard VPPs from potential vulnerabilities. Venkatachary et al. [77] propose a security architecture grounded in edge intelligent computing to mitigate risks, enhance system security, and ensure privacy and data protection. These AI-driven solutions contribute to fortifying the security infrastructure of VPPs, addressing concerns related to authentication, access control, and protection against cyber threats. In recent years, numerous studies have extensively explored data interoperability across all service areas of VPPs, which is important for the seamless operation of these facilities. Adi et al. [29] presents a framework for analyzing IoT data derived from diverse heterogeneous sources. Such AI-driven solutions significantly contribute to ensuring rapid data transmission, aggregation, and interoperability, facilitating the efficient management of smart terminals and distributed energy resources within VPPs. Another study [33], conducted by Ali et al., introduces a real-time intelligent energy management model for VPPs. Utilizing multi-objective, multi-level optimization strategies, their model enhances data interoperability by enabling real-time exchange and coordination among different energy resources.

Grid data and energy utilization data are critical to advance in AI as most of the prediction is related to consumer use and distribution. However, several issues and challenges are associated with collecting electric grid data, including grid complexity, variety of data and volume, strict laws, cybersecurity risks, and privacy concerns. Despite the crisis of a large volume of data, the advancement of AI technology to build resilient grids continues at an incredible speed with limited available sources.

5 RELATED WORK

Academic Explorations in AI for Smart VPPs. Academic literature has extensively explored uncertainties associated with virtual power plants (VPPs), categorizing them into areas such as Uncertainty of Renewable Energy Resources, Market Price Uncertainty, and Load Uncertainty [65]. Various scheduling and optimization approaches have been proposed, ranging from a novel algorithm for enhancing the day-ahead thermal and electrical scheduling [43] to Mixed-Integer Linear Programming (MILP) models to maximize VPP profits [81]. Attempts using Deep Reinforcement Learning (DRL) methods have been made to address optimal scheduling challenges within VPPs, acknowledging limitations in managing non-linear, non-convex, and stochastic EV charging stations [51]. In the domain of demand response and consumer behavior, AI plays a pivotal role. Studies by Antonopoulos et al. [34] and Qaisar et al. [62] illustrate how machine learning models can predict and optimize electric vehicle charging schedules, contributing to grid stability. The application of AI in communication, security, and cybersecurity measures within VPPs has become crucial, with studies exploring blockchain, cloud-edge collaboration, machine learning, and ICT [24, 29, 33, 48, 77, 78]. In demand response and consumer behavior, AI has proven instrumental in predicting electricity demand, optimizing charging needs for electric vehicles, and analyzing and predicting consumer behavior [34, 53, 56, 62].

Industrial AI Effort for Smart VPPs. In the industrial domain, companies have actively applied AI to overcome challenges and enhance the functionality of VPPs. Evergen develops a Distributed Energy Resource Management System (DERMS) that advances renewable energy by integrating DERs [1]. H Energy, a South Korean startup, delivers power brokerage solutions for energy operators. Their cloud platform, DERShare, facilitates the management of numerous DERs, incorporating big data processing and real-time optimization, among other functionalities within a VPP context [1]. Logical Buildings, a U.S. startup, utilizes AI-powered VPP software for commercial real estate. The platform learns building habits to identify energy inefficiencies and cost-saving opportunities [2]. Another key player, Terhills, strategically incorporates AI in VPP operations to navigate uncertainties arising from fluctuating renewable energy inputs [10]. They achieve real-time adaptability through advanced algorithms, ensuring optimal energy resource allocation within their VPP network. AI-driven systems significantly improve energy storage efficiency and reliability of energy storage devices in VPPs [20]. Gridmatic, a power trading technology firm, showcases AI's role in autonomously optimizing power sales and reducing energy production risk [27].

6 CONCLUSION

A Virtual Power Plant (VPPs) integrates dispersed small-scale power production facilities, such as wind power, solar power, and fuel cells, with power demand endpoints through control centers, creating a flexible and manageable power system. This paper comprehensively examines the concept, historical development, evolution, and components of VPPs, delving into the key challenges and opportunities presented by the application of artificial intelligence in smart VPPs. Specifically, it categorizes and outlines four challenges encountered by current VPPs: energy sources and resource allocation, transactions and market prices, dynamic loads and demands, and communications and security. In addressing these challenges, the article explores the potential of AI to enhance the performance, efficiency, economics, and sustainability of VPPs. It delves into how AI can play a pivotal role in optimizing energy sources, streamlining resource allocation, managing transactions and market dynamics, accommodating dynamic loads and demands, and enhancing communication and security protocols within VPPs. This article also provides examples of existing VPPs and their AI applications in different aspects and summarizes related work on academic concepts and industrial applications.

ACKNOWLEDGMENTS

We are grateful to the anonymous reviewers for their comments and suggestions on this paper. This work was supported in part by U.S. NSF grants CPS-2103459, SHF-2210744.

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