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# Virtual Power Plant with Renewable Energy Sources and Energy Storage Systems for Sustainable Power Grid-Formation, Control Techniques and Demand Response

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**Abstract:** As the climate crisis worsens, power grids are gradually transforming into a more sustainable state through renewable energy sources (RESs), energy storage systems (ESSs), and smart loads. Virtual power plants (VPP) are an emerging concept that can flexibly integrate distributed energy resources (DERs), managing manage the power output of each DER unit, as well as the power consumption of loads, to balance electricity supply and demand in real time. VPPs can participate in energy markets, enable self-scheduling of RESs, facilitate energy trading and sharing, and provide demand-side frequency control ancillary services (D-FCAS) to enhance the stability of the system frequency. As a result, studies considering VPPs have become the focus of recent energy research, with the purpose of reducing the uncertainty resulting from RESs distributed in the power grid and improving technology related to energy management system (EMS). However, comprehensive reviews of VPPs considering their formation, control techniques, and D-FCAS are still lacking in the literature. Therefore, this paper aims to provide a thorough overview of state-of-the-art VPP technologies for building sustainable power grids in the future. The review mainly considers the development of VPPs, the information transmission and control methods among DERs and loads in VPPs, as well as the relevant technologies for providing D-FCAS from VPPs. This review paper describes the significant economic, social, and environmental benefits of VPPs, as well as the technological advancements, challenges, and possible future research directions in VPP research.

**Keywords:** virtual power plants; renewable energy; energy storage systems; sustainable power grids; energy management systems; demand-side frequency ancillary services



**Citation:** Liu, J.; Hu, H.; Yu, S.S.; Trinh, H. Virtual Power Plant with Renewable Energy Sources and Energy Storage Systems for Sustainable Power Grid-Formation, Control Techniques and Demand Response. *Energies* **2023**, *16*, 3705. https://doi.org/10.3390/en16093705

Academic Editor: Dimitrios Katsaprakakis

Received: 8 April 2023
Revised: 24 April 2023
Accepted: 25 April 2023
Published: 26 April 2023



## 1. Introduction

### *1.1. Renewable Energy and Distributed Power Grid*

Since the 1880s, centralized AC power grids have been extensively established and utilized in every corner of the world. Fossil fuels, such as coal and oil, account for 80% of the world's primary energy supply; however, their consumption results in greenhouse gas emissions that pollute the environment and lead to climate warming, which has led to the global climate crisis [1]. In the last 30 years, as the global economy has rapidly grown, the demand for energy has also increased significantly. From 2015 to 2040, global energy consumption is expected to grow by about 30% [2]. Therefore, renewable energy sources (RESs), such as solar, wind, and hydropower, should be considered as alternatives to fossil fuels in order to reduce their negative environmental impact [3]. In 2022, most countries implemented policies to promote the development of renewable energy. Globally, approximately a quarter of electricity comes from renewable sources. Hydropower is the most widely used RES globally, followed by wind and solar, which are also experiencing rapid growth [4].

RES is being integrated into power systems because of its environmental and economic advantages; however, its broader adoption will also have an impact on the reliability, stability, and economics of the grid [5].

- RESs are characterized by uncertainty as they are dependent on weather conditions and geographic locations, which makes these natural resources uncontrollable.
- The intermittent nature of RESs can lead to power imbalances, supply–demand mismatch, and power quality issues in the electricity system.
- The placement of large RES power plants (such as hydropower and wind turbines) is generally far from the power consumption centers, requiring long-distance or inter-regional transmission.

These factors have also driven the integration of RES with ESS. ESS offers flexible charging and discharging capabilities and reliable energy storage technology, making it useful in modern power systems [6]. By providing ancillary services, load-following, and other methods, ESS can help achieve supply−demand balance in the grid, thus enhancing power system stability [7]. ESS can also meet the growing reserve requirements, improve power system operation efficiency, and reduce investment costs and energy losses associated with long-distance power generation [8]. Furthermore, ESS can mitigate fluctuations and enhance power supply continuity and energy quality [9]. Previous studies have discussed ESS storage technologies and methods extensively [6,10].

The integration of RESs and ESSs has facilitated the development of DERs, which include small-scale generators and storage technologies located near the point of energy consumption. DERs can be used independently or in combination to provide value to the grid, and have significantly reduced power system costs and emissions, while improving reliability and safety [11]. However, while DERs present opportunities in power systems, they also bring new challenges. The increased use of DERs on the demand side aggravates the variability of load demand, leading to instability in the grid. Therefore, real-time monitoring and dispatch by distribution grid operators are crucial for safely operating the grid [12]. Additionally, the power system requires more flexibility, which can come from a variety of sources including demand-side management, generator output, and energy storage systems. Only through optimal coordination can these sources be effectively leveraged to enhance their contributions to the grid [13].

### 1.2. Virtual Power Plants

To better address the challenges mentioned above, extensive research has been conducted in recent years, resulting in numerous proposed solutions. Among them, VPPs are considered the most effective method for managing DERs, as they ensure an affordable, secure, and stable energy supply to the grid [14]. A VPP is a network of distributed energy resources, including distributed generators (DGs), ESSs, EV charging facilities, and adjustable loads. The typical structure of a VPP is shown in Figure 1 [15]. A VPP uses technology such as the Internet of Things and cloud computing to aggregate different power prosumers, energy storage, and power generators in order to achieve flexible power adjustment. Even a family using an electric car can be part of a VPP. The elements in a VPP system transmit data to the VPP communication system through the communication protocol. VPPs utilize software and communication technologies to aggregate and manage DERs, as well as adjustable loads, in order to provide reliable and cost-effective electricity to the grid [15]. VPPs do not significantly alter how DERs are connected to the power network, but instead aggregate different types of DERs through advanced control, measurement devices, and communication methods [16]. VPPs enable DERs to participate in various electricity market transactions as an aggregated entity. Clients of VPPs mainly include investors, power companies, and load aggregators. They participate in VPP projects by adjusting consumption in response to frequency fluctuations or load−demand imbalances. Some DERs can be connected to multiple VPPs through a smart energy management system, enabling optimal control and coordination of the resources [17]. They can increase the flexibility and efficiency of the system and enable VPPs to balance supply and demand in real time.

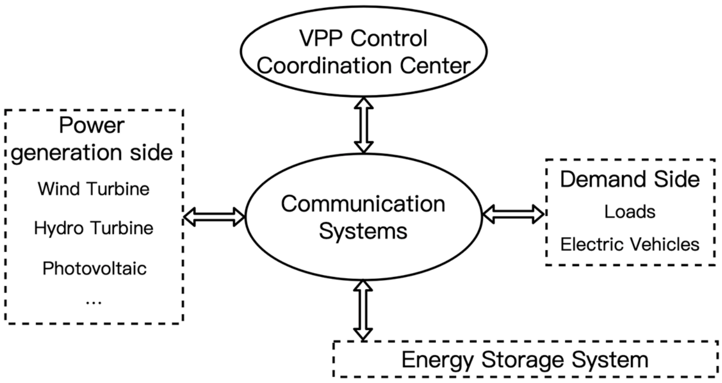


**Figure 1.** Typical structure of a VPP.

Despite the benefits that the emergence of VPPs has brought to the power grid, their development still faces numerous challenges. Although VPPs reduce uncertainty in the power grid, the continuous development of the power grid also increases its uncertainty factors, which can restrict the correct prediction of VPPs in the operation process and optimal dispatching. Therefore, uncertainty remains a challenge that VPPs need to face. Uncertainties in VPPs can be mainly classified into the following three categories [18]:

- Uncertainty in RESs: As the number of RES integrated into the grid increases, the periodic and stochastic power output will have a certain impact on the operation of the grid. The state-of-the-art day-ahead forecasting methods still have an error rate of 10% for RES output power prediction [19].
- Uncertainty in electricity market prices: In the energy system, market prices change with local policies and weather conditions [20]. Therefore, the price of electricity in the market has a high volatility, which may cause losses to VPP participants.
- Uncertainty in load demand: Load power mainly includes deterministic (affected by factors such as time) and stochastic elements (prediction and measurement errors) [21]. Load demands change with seasons and are related to consumers and unexpected events, making the uncertainty of load demands even more complex [21].

In addition, market models and regulations in different countries and regions vary significantly. Therefore, it is not feasible to use ready-made VPP solutions developed by other countries directly, and customized solutions must be designed for the given system and energy market; this is also one of the challenges that VPPs need to face [22].

There have been a fair number of literature reviews on virtual power plants, but they have primarily been focused on the concept of VPPs, optimal scheduling models, energy management, and future convergence technologies. For example, in [23], a comprehensive review of the concept of VPPs was conducted, including the definition, components, and framework, focusing on the technologies used for optimizing the operation of VPPs. In [24], the authors reviewed the components and models of VPPs and briefly classified and discussed VPP bidding strategies, VPPs with DR, and the participation of VPPs in the electricity market. In [25], the authors conducted a comprehensive review of the optimization scheduling of VPPs, studied and summarized their operational modes, described the concept of VPPs, and provided a mathematical optimization model for VPP participation in electricity market trading. These review articles focused primarily on the optimization operation model of VPPs. The review article in [26] considered load demand in VPPs and described the concept of managed controllable loads and the related management models and methods. Load characteristics, control strategies, and control effects were analyzed, focusing on the theoretical aspects of hybrid systems of RES with controllable electrical appliances, battery storage, and other related controllable loads. The authors in [27] conducted a comprehensive review of the application of VPPs in grid energy management and summarized the key methods and technologies for optimization scheduling in VPPs. Then, they proposed a scheduling method based on deep reinforcement learning for building VPPs that considered technological, economic constraints and uncertainties. However, these review articles aimed to identify research gaps in the operation and scheduling of VPPs. The review article in [18] detailed the uncertainties after VPPs are integrated into the grid and introduced methods, tools, target functions, and constraint conditions for improving the operational performance of VPPs. In [28], the authors collected important factors related to key strategies in VPPs and their consideration for use in power systems, and proposed considering factors such as uncertainty, reliability, DR, and reactive power when developing VPP models. The review article in [14] introduced recent applications of VPP models in different electricity markets. It summarized the formulation of VPP models, problem-solving methods, different electricity markets, and the application of VPP models in practical cases. However, these articles focused more on reviewing the completeness and practicality of VPP models. In [29], considering the development trends of power systems, the authors analyzed the concept of collaborative networks and VPP integration. Additionally, in [30], the authors described information and communication technology, control technology, energy storage technology, and strategic planning related to the smart grids used by VPPs. However, these review articles focused on planning for the development of future power grid systems.

Considering the above, a comprehensive review of VPPs and their formation, control techniques, and D-FCAS is still lacking in current review articles. Considering this research gap in the literature, this review paper focuses on the development and recent technological advances of VPPs, and aims to provide a comprehensive overview of the state-of-the-art VPP technologies for future sustainable grids. The main contributions of this paper are as follows:

1. Summarize the development process of the VPP concept from its introduction to the present, in chronological order, and draw a diagram of the evolution of VPP-related concepts from 1997 to the present so that readers can understand the whole process of VPP concept development.
2. Summarize and review existing control techniques for integrating VPPs into sustainable power grids so that researchers can better identify current research gaps.
3. The demand side auxiliary services of the VPP can reduce or increase end-user electricity consumption through incentives or price-based voluntary schemes. This enables VPPs to participate in the wholesale electricity market, improve the efficiency of the electricity market, and enhance system reliability. Finally, existing and new models related to D-FCAS are summarized and proposed for the development of VPPs.

The rest of the paper is arranged as follows. Section 2 summarizes the whole process of VPP conceptual development, as well and their difference from microgrids (MGs), in chronological order. Section 3 describes the social, economic, and environmental impacts of VPPs. Section 4 summarizes and reviews state-of-the-art control techniques for VPPs in sustainable power grids. In Section 5, based on VPPs as the source of D-FCAS, the relevant methods and technologies are summarized and proposed. Section 6 gives suggestions for future research directions. Finally, conclusions are drawn in Section 7.

## 2. Development of VPPs

### *2.1. Evolution of the VPP Concept*

Shimon Awerbuch first introduced the concept of VPPs in 1997 [31]. They were based on the definition of virtual public infrastructure, which describes a flexible collaboration between independent, market-driven entities to provide consumer-oriented energy services. Since then, researchers have conducted extensive studies on VPPs; Table 1 shows the evolution of the VPP concept in chronological order.

**Table 1.** Evolution of the VPP concept.

| Time | Brief Description | Reference |
|---|---|---|
| 1997 | VPPs were based on the definition of virtual public infrastructure, which describes a flexible collaboration between independent, market-driven entities to provide consumer-oriented energy services. | [31] |
| 2003 | The definition of VPPs was a combination of cogeneration units, small-scale RES, and EMS that effectively integrated VPPs into the electricity market. | [32] |
| 2004 | A new idea emerged involving clustering small generators near the load to provide heat and electricity. | [33] |
| 2007 | A widely accepted definition of VPPs was proposed as a flexible combination of DERs, which could aggregate many different DERs and create a single operational configuration file for control and management based on the parameters of each DER. | [34] |
| 2008 | VPPs and MGs were often mentioned together as the most effective solutions for integrating DERs into the power system, but they were different. | [35] |
| 2009 | Under the framework of an open electricity market, DG and controllable loads participated in real-time operation of the grid. The concept of VPPs included the integration of DERs, such as DGs, controllable loads, and EMS, into VPPs to make them more accessible and manageable in the energy market. | [36] |
| 2010 | Some definitions particularly emphasized the components of VPPs that rely on software systems for remote dispatch and optimization of the generation, storage resources, and demand-side services within a secure network system. | [37] |
| 2011 | Various methods were introduced to integrate electric vehicles into the power grid through the concept of VPPs. | [38] |
| 2014 | The concept of dynamic VPPs emerged, which reduced the operating costs of VPP by referring not only to market prices, but also to demand-side electricity predictions compared with traditional static VPPs. | [39] |
| 2017 | The concept of VPPs became more widely used as a power supplier for distribution networks, coordinating transmission system operators (TSOs) and distribution system operators (DSOs) to achieve different control objectives. | [40] |
| 2018 | VPPs were defined as a collection of DERs that participated as a single entity in the energy and reserve electricity market, aiming to benefit all system participants economically. | [41] |

Even now, VPPs do not have a fixed definition, but based on the above definitions, the definition of VPPs can be summarized as follows: A VPP consists of RESs, DGs, EMS, and controllable loads that can manage different DERs, without geographic limitations. VPPs have the ability to participate in the electricity market as demand-side managers or providers of energy, power reserves, and ancillary services. Moreover, VPPs can act as a single entity connected to the grid in the power system and can be either static or dynamic. Here, we summarized the evolution of VPP-related concepts over 26 years, from 1997 to 2023, as shown in Figure 2. In the figure, black represents high mention, blue represents middle mention, and gray represents low mention.

### *2.2. Difference between VPP and MG*

VPPs serve as energy clusters that bring together local generators and consumers to foster the development of RESs [22]. They consist of MGs in geographically close areas within a limited region that collaborate to minimize transmission costs for energy. VPPs also comprise selected remote areas or function as a large MG [42]. MGs are a nascent form of power system that boasts benefits such as better utilization of RESs with the aid of battery ESS, higher grid operational visibility, and augmented stability due to advanced control technology [43]. MGs can be regarded as an integrated energy system consisting of DERs and multiple loads. They operate as a smaller power system, which can operate in the grid-connected mode or islanded mode (independently), as depicted in Figure 3 [37]. The most obvious feature of an MG is its ability to isolate itself from the utility distribution system during brownouts or outages. This is achieved through the use of ESSs or other storage technologies, as well as the integration of RESs. By generating and storing its own power, an MG can continue to function, even if the larger grid experiences a disruption.

Another key feature of MGs is their ability to manage real-time power consumption and production using advanced control systems and algorithms. This allows them to balance supply and demand within MGs, optimizing energy use and minimizing waste. In addition, MGs can also provide a range of other benefits, such as improved resiliency and reliability, reduced energy costs, and increased energy independence.

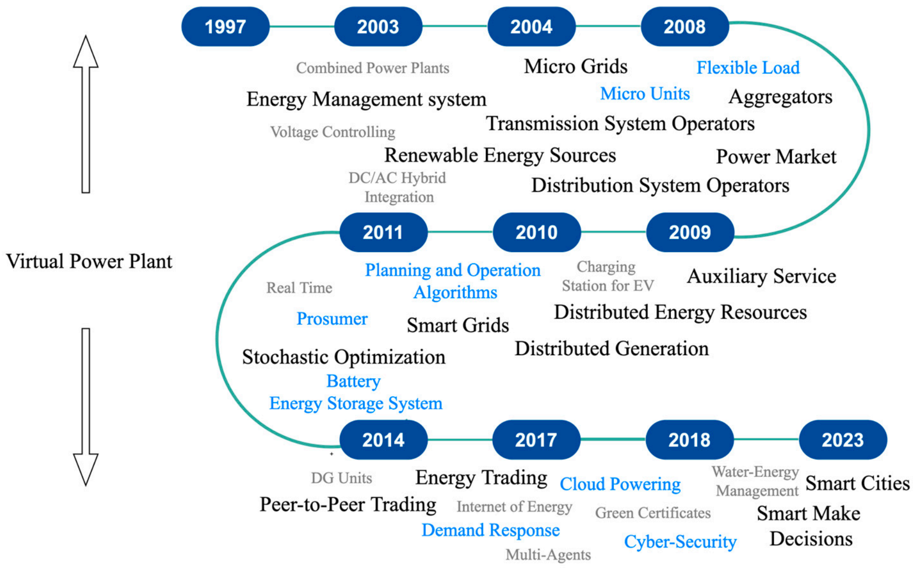


**Figure 2.** The evolution timeline of VPP-related concepts.

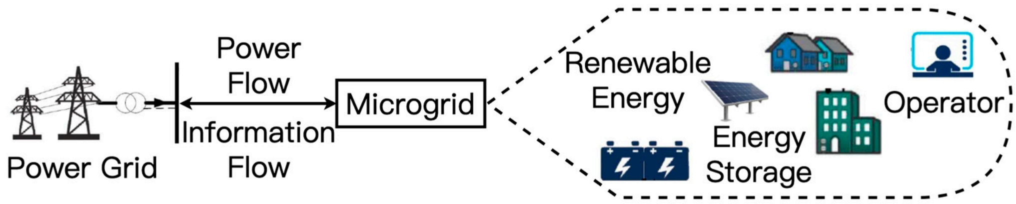


**Figure 3.** Structure of an MG.

Conversely, VPPs leverage software systems to remotely control and optimize power generation, storage resources, and demand-side management within a secure network infrastructure. Using the existing grid, VPPs deliver ancillary services to users, while maximizing value for consumers and distribution companies. The main advantage of VPPs is that they can respond quickly to changing user loads, provide value in real time, and optimize the entire system. This is achieved through advanced software that can analyze user data and adjust power generation and consumption accordingly. For example, during periods of high energy demand, VPPs can increase the generation of RESs. Conversely, during periods of low demand, VPPs can reduce energy generation and store excess energy for future use.

While MGs and VPPs offer solutions for ensuring reliable power supply in power systems, and share common features such as distributed renewable energy generation, storage systems, and the ability to integrate DRs, they still have differences [37,44]:

- VPPs always exist in grid-connected form (while MGs can be either grid connected or off grid). VPPs are always connected to the power grid and use advanced software to manage a group of DERs. VPPs can dispatch DERs to provide grid services or participate in energy markets. In contrast, MGs can operate in isolation from the grid, known as off-grid mode, or be connected to the grid, known as grid-connected mode. MGs are designed to provide reliable and resilient power supply, especially in remote or critical locations.

- VPPs may or may not have ESSs (while MGs typically require ESSs). A VPP is a cloud-based software platform that aggregates the distributed DERs. Instead of physically connecting them, a VPP manages them as a VPP to provide electricity to the grid in response to demand fluctuations. In contrast, an MG is a small-scale electrical network that can operate independently or in parallel with the main grid. They usually integrate various DERs with ESSs to ensure a reliable and resilient power supply. Therefore, while energy storage is optional for VPPs, it is an essential component of MGs.
- VPPs do not isolate themselves from the larger public grid as an emergency measure (while MGs can). In terms of VPPs and MGs, VPPs do not primarily function as an emergency source for backup power. Instead, they are a collection of energy resources that can be strategized and directed to the power grid in response to energy demand or sudden power fluctuations. On the other hand, MGs are designed to operate as self-contained units, generating and distributing power independently from the main power grid in case of emergencies or planned outages.
- VPPs primarily rely on smart meters and information technology (while MGs rely mainly on hardware such as smart inverters and switches). VPPs rely on smart meters and information technology to manage the energy supply and demand of a network of DERs. VPPs use algorithms and software to analyze data from smart meters and other sensors, which allows them to predict energy usage patterns and optimize the dispatch of energy resources. On the other hand, MGs rely mainly on hardware such as smart inverters and switches to manage the energy flow within a localized area.
- VPPs can combine and coordinate a variety of resources in a larger geographic area (while MGs only include a set of static resources in a limited geographic location). This means that VPPs can access and manage diverse sources of DERs across a wider region. VPPs can then dispatch these resources based on real-time grid conditions and customer demands to provide grid services such as peak shaving, load balancing, and frequency regulation. However, VPPs are difficult to connect in a larger geographical area with weak electrical supply. MGs operate on a smaller scale and typically manage a fixed set of DERs in a specific location. While both concepts involve managing distributed resources, VPPs have a greater ability to optimize a wider range of assets in real time for greater grid resiliency and flexibility.
- VPPs can establish connections with wholesale electricity markets (while MGs only conduct power transactions in a retail manner). This means that VPPs can sell the excess electricity generated by their DERs to the wholesale electricity markets, which can ensure a more cost-effective and efficient use of RESs. Additionally, VPPs can participate in DR programs and provide grid services to the utility, improving grid stability and reliability. In contrast, MGs are limited to retail transactions between DER owners and the end users.

The differences between a VPP and an MG are summarized in Table 2. MG models are interconnected and combined into a VPP model with new capabilities, as shown in Figure 4 [45].

**Table 2.** Main differences between a VPP and an MG.

| Brief Description | VPP | MG |
|---|---|---|
| Exist in grid-connected form only. | √ | × (Or off-grid) |
| May or may not have ESSs. | √ | × (Require ESS) |
| Can isolate themselves from the larger public grid as a contingency measure. | × | √ |
| Rely on smart meters and information technology. | √ | × (Rely mainly on hardware) |
| Combine and coordinate a variety of resources in a larger geographic area. | √ | × (Only include a set of static resources in a limited geographic location) |
| Trade power with retails and wholesalers. | √ | × (Only trade at the retailer level) |

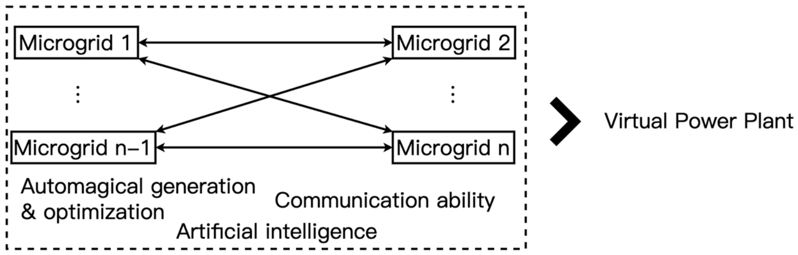


**Figure 4.** Transformation of an MG to VPP.

## 3. Benefit of Forming VPPs

Forming VPPs also brings significant economic, social, and environmental benefits.

### 3.1. Economic Impact

VPPs coordinate energy production, storage, and consumption entities and participate in the demand-side ancillary service market to reduce power consumption and operating costs [46]. For users, VPPs group users of different types and locations to bring greater flexibility to the market and benefits to users. VPPs participate in the electricity market and provide ancillary services to reduce violation costs from demand-side forecast errors [47]. VPPs are intended for utilities to maintain stability and economic balance, and they can also help governments maintain economic balance by lowering electricity costs [16]. In addition, VPPs can participate in the energy market in various ways to achieve a balanced energy market [14]. When multiple resources are used for generation and storage, implementing optimized energy management control technologies can help improve the efficiency and effectiveness of the power system, while meeting the demands of users [48]. Figure 5 shows a detailed overall layout of the VPP system [27]. The communication layer is responsible for data exchange between the various layers of the VPP, while the infrastructure layer consists of DERs, ESSs, and loads. The VPP sends bids to the decision-making layer and then conducts internal or external market transactions based on the energy flow signal adjusted by the decision-making layer. The external market and decision-making layer provide load forecasting and bidding strategies to the independent system operator (ISO), respectively [27]. Furthermore, VPPs have the potential to provide D-FCAS to enhance the stability of the system. Demand-side ancillary services are a form of demand response (DR) and an important means of demand management that can reduce or increase end-user electricity consumption through incentives or price-based voluntary plans. These services are intended to ensure the safety and reliability of the power system, help customers participate in the electricity market, and maintain a balance between supply and demand [49]. VPPs can benefit from DR or dynamic pricing plans by changing or re-planning energy demand, minimizing operating costs, and improving grid stability [50]. Overall, VPPs are a critical component of the future energy system, helping to improve efficiency, reduce costs, and integrate renewable energy sources.

### 3.2. Social Impact

VPPs foster better relationships between customers and utilities; increase utility and user participation in the electricity market; provide a safe, reliable, diversified market; and benefit society [16]. In addition, the emergence of VPPs aims to mitigate the uncertainty caused by RESs in the power grid, enhance the technology associated with EMSs, ensure the reliability and stability of the grid, and transform consumer behavior. Figure 6 illustrates the concepts of consumers and prosumers [45]. The main purpose is to demonstrate the difference between current consumers (called "prosumers", who can either buy electricity or sell their excess electricity) and traditional consumers (who can only buy electricity). For prosumers, incentivizing them to actively participate in power market trading based on pricing or incentive strategies promotes their engagement in energy consumption, production, and trading [51]. VPPs can also benefit vulnerable communities, such as lowincome households, by providing access to affordable, reliable clean energy sources and helping reduce energy poverty. Overall, VPPs have the potential to transform the energy sector, promoting a more sustainable, equitable, and responsive system.

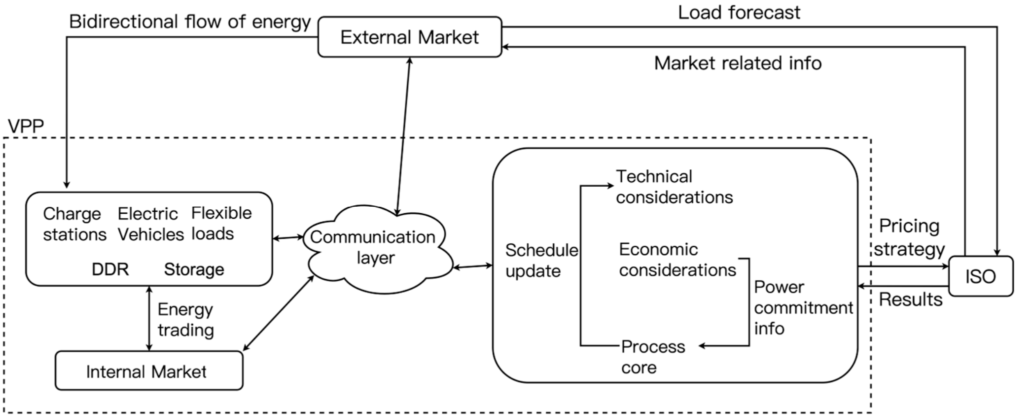


**Figure 5.** System layout of VPP.

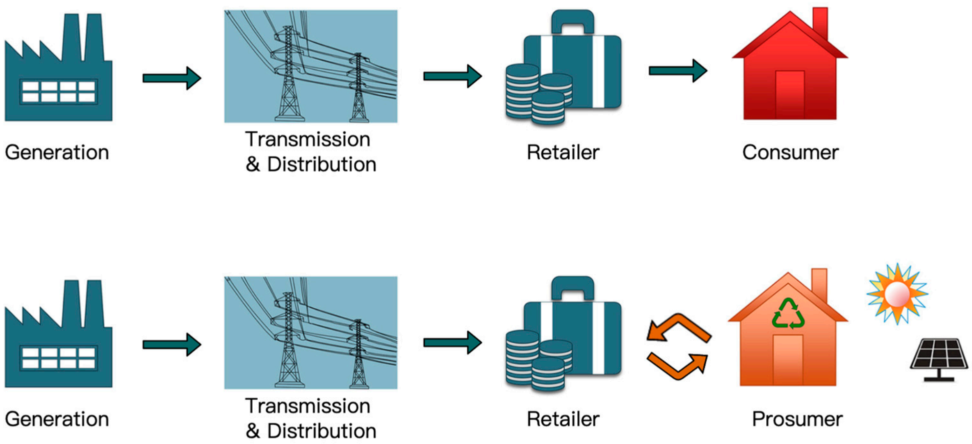


**Figure 6.** Consumer and prosumer concepts in the VPP.

### *3.3. Environmental Impact*

The integration of VPPs also increases the number of RESs integrated into the grid, reduces the carbon footprint and the use of fossil fuels, and builds a sustainable power network [52]. VPPs can aggregate different types of DGs, reducing environmental imbalances [16]. Moreover, VPPs eliminate geographical limitations, allowing prosumers to participate in the electricity market without considering actual distance, while adhering to safety regulations established by the independent system operator (ISO) [27]. Additionally, VPPs can also promote the integration of ESSs, which can help address the intermittent nature of RESs. By storing excess energy generated by these sources during off-peak hours, energy can be supplied to the grid during peak usage hours, reducing the strain on traditional power plants and promoting the use of clean energy. VPPs can also enable DR programs, which encourage consumers to lower their energy usage during times of high demand, ultimately reducing the need for fossil fuel-based power generation. Overall, the integration of VPPs into the energy grid can play a vital role in promoting a sustainable and environmentally friendly power system.

## 4. Cutting-Edge Control Techniques of VPPs

This article presents an overview of the cutting-edge control technology of VPPs, which falls into two categories: hierarchical control and control for ancillary services, as illustrated in Figure 7. Section 4 focuses on the former, while Section 5 delves deeper into the latter.

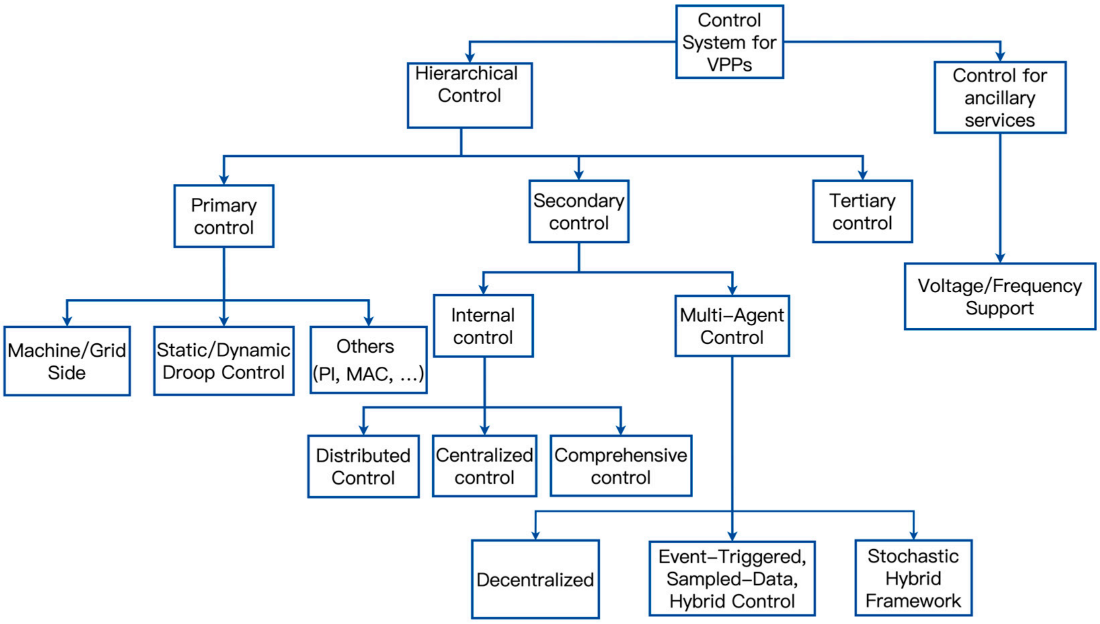


**Figure 7.** Control techniques for the classification of VPPs.

### *4.1. Control Framework and Systems of VPPs*

VPP aggregation entails the coordination of different dynamic energies, while ensuring the stability of the overall system. It requires careful design of the VPP control system, as depicted in Figure 8, which integrates the physical and digital layers into a closed-loop system powered by hybrid energy [53]. This framework is used to develop and analyze mathematical models for control design and is often simplified to obtain traditional multivariate linear models for discrete time, continuous time, or hybrid power systems [54]. To operate the DER and loads effectively in the VPP, we need to develop appropriate control strategies to meet various grid requirements and goals, including regulating and maintaining voltage and frequency stability, fault management, synchronization, and real-time optimization [53]. These goals are defined according to the VPP hierarchy and must comply with local standards or protocols. Different control system hierarchy structures are also defined based on hierarchical goals [16]. The control of auxiliary services (non-hierarchical control structure) follows the horizontal structure of the system time scale. The VPP control system considers the following factors:

1. Communication protocol: The communication protocol between the various elements of the VPP must be efficient, reliable, and secure. It should be able to handle large volumes of data in real time with minimal delay.
2. Resource management: The VPP control system should be able to allocate resources based on demand and supply. It should be able to balance the load across various energy resources, and ensure that there is always a surplus of energy.
3. Prediction and forecasting: The VPP control system should be able to predict the demand for energy and the availability of energy resources. It should be able to use historical data and current trends to forecast the future demand and supply of energy.
4. Security: The VPP control system should be secure and be able to prevent unauthorized access and cyber threats. It should be able to monitor the system for any potential security risks, and take appropriate measures to mitigate those risks.

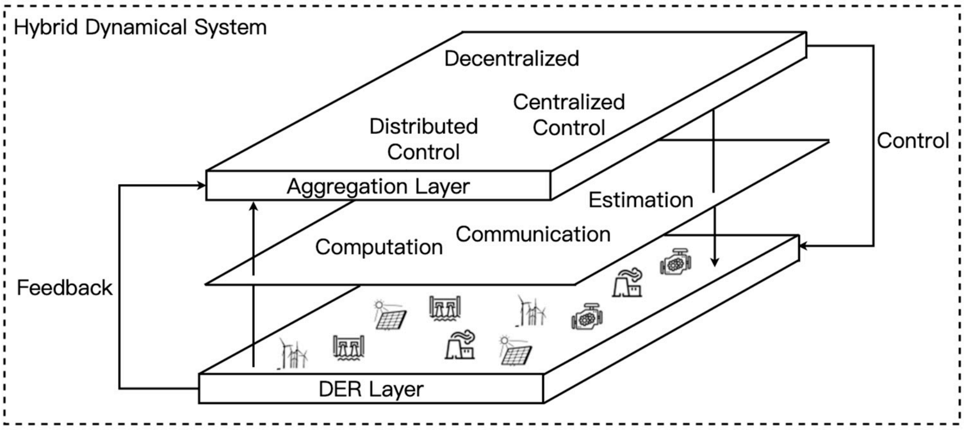


**Figure 8.** Control framework of VPPs (modified from [53]).

To further improve the utilization rate of RES, the VPP dynamic model has also attracted the attention of many scholars. The VPP dynamic model integrates the dynamics of various energy entities at all levels [55]. At the local level, the VPP dynamic model considers the individual characteristics and constraints of each RES, such as its available power output, current state of charge, and temperature. These parameters are continuously monitored and used to optimize the dispatch of power from each generator, ensuring that fluctuations in renewable energy production are minimized. At the global level, the model considers the integration of VPPs into the wider electrical grid, as well as the provision of ancillary services such as frequency control and voltage support. VPPs can also interact with other nearby VPPs, exchanging power and services to improve the overall stability and efficiency of the grid. Finally, the VPP dynamic model incorporates economic considerations, such as the current market price of electricity and the costs associated with operating and maintaining RES generators. It allows VPPs to participate in electricity markets, such as wholesale energy markets and capacity markets, as well as make sensible decisions to adjust its dispatch and output accordingly.

In essence, the VPP control system should be robust, efficient, and able to manage the various energy resources in a coordinated manner. It should be designed with the long-term objective of ensuring a sustainable and reliable energy supply.

### *4.2. Hierarchical Control*

In this paper, we mainly reviewed the relevant control techniques applied in the literature in recent years to primary and secondary control in VPPs. The main function of primary control is to ensure the stability of voltage and frequency, and the main goal of secondary control is to eliminate the deviation in the frequency and voltage of the VPP reference value [56]. Table 3 summarizes the hierarchical control techniques related to VPPs in the past five years.

**Table 3.** Hierarchical control techniques related to VPPs.

| Time | Brief Description | Reference |
|---|---|---|
| 2023 | A secondary frequency control strategy was proposed to offer emergency power support to systems in need through a high-voltage DC link of the voltage source converter. | [57] |
| 2023 | A VPP model was proposed to contain electric public transportation and distributed generator groups. A coordinated control strategy involving time-sharing planning and segmented execution was also proposed. | [58] |

**Table 3.** *Cont.*

| Time | Brief Description | Reference |
|---|---|---|
| 2022 | A distributed real-time multi-objective control strategy was proposed, taking multiple DERs in the DC distribution network as VPPs for multi-objective optimization control. The proposed strategy aimed to achieve optimal performance by minimizing power losses, improving voltage stability, and reducing the overall operating cost of the DC distribution network. | [59] |
| 2022 | A stochastic mixed-integer linear programming model about technical VPPs to optimize DERs scheduling in the current energy market and analyze the effects on volts and power was proposed. The model took into consideration the uncertainties associated with the availability of DERs, electricity prices, and demand, and minimized the overall cost of energy procurement and management. This model improved the system's ability to consolidate DERs, while enhancing some technical and operational indexes. | [60] |
| 2022 | A synchronous VPP framework for DERs based on grid-tied inverters was proposed to provide inertia support with parameter settings. The proposed VPP framework had several advantages over conventional generators for providing inertia support. | [61] |
| 2022 | A two-layer scheduling model for VPP was proposed to consider the interaction between the distribution company and VPPs. The upper layer reduced the associated costs of the distribution system by changing the electricity price traded with the VPP, while the lower layer VPP managed the quantity of electricity traded with the distribution system to increase VPP profits. | [62] |
| 2022 | A dual layer coordinated scheduling strategy for VPP was proposed as a comprise to electric vehicles and ESS. The VPP scheduled ESS using a direct control method. Furthermore, the interaction between VPP and electric vehicle owners was governed by Stackelberg games to maximize profit and minimize costs. | [63] |
| 2022 | A novel control method for dynamic VPPs was proposed utilizing an adaptive divide-and-conquer strategy. It involved obtaining dynamic VPP frequency and voltage control specifications for each device's behavioral decomposition or aggregation and optimizing the best matches. | [64] |
| 2022 | The efficacy of five control strategies for distributed energy storage in residential VPPs was evaluated. These strategies included VPP bill minimization, single-household bill minimization, peak shaving, daytime peak shaving, and load balancing. | [65] |
| 2022 | A data-driven and fully distributed voltage/reactive power control method for numerous VPPs was proposed, and its effectiveness was demonstrated. Each VPP corrected its control strategy by using feedback from the local system and exchanging partial information with adjacent VPPs. | [66] |
| 2022 | A two-stage deep reinforcement learning method was proposed to manage DER aggregators that offer frequency regulation services. In the first stage, the agent considered the current system frequency, the available resources, and the desired response time to adjust the power output of the DERs in real time. In the second stage, a deep reinforcement learning-based policy optimization algorithm was used to optimize the overall system performance. | [67] |
| 2022 | A coordinated control strategy for load frequency control of VPPs comprising a battery ESS and heat pump water heater was proposed. The final solution was obtained using a fuzzy policy based on user-defined conditions. Furthermore, VPPs participating in frequency regulation could reduce the frequency deviation caused by communication delay. | [68] |
| 2021 | A two-tier power system scheduling and control architecture was proposed based on grid-friendly VPPs capable of flexibly and safely accommodating RESs and participating in power system stability control. This VPP facilitated the full use of RESs under normal circumstances and power support when unexpected events occurred. | [69] |
| 2021 | A control framework for optimizing multiple markets, systems, and local network services was introduced, mainly coordinating three optimization problems: day-ahead energy scheduling, linearized power flow, and real-time scheduling. It was verified that the framework achieved flexibility of VPPs. | [70] |
| 2021 | An abstract dynamic control method for VPPs combined with computational intelligence was proposed, which was flexibly applicable to different VPP models and verified the feasibility of the control method. | [71] |
| 2020 | A coordination control framework integrating VPP, and electric vehicles was designed, and a coordination control strategy for electric vehicles and ESSs was proposed to optimize output and extend battery life using a new storage optimization method. | [72] |
| 2020 | The new mode of community based VPPs as a source of energy supply, co-constituted by five building blocks (two of which comprised of information technology systems control architecture aggregation and control of DERs) in community energy. | [73] |

As mentioned above, designing an appropriate control architecture for VPP and using appropriate control technologies or control methods can bring many benefits to the sustainable power grid and VPPs. One benefit is the ability to maintain a stable and reliable power system. With VPPs, multiple DERs can be integrated and managed as one system. This allows for better coordination of power generation and consumption to balance supply and demand and to prevent power fluctuations and blackouts. Another benefit is the optimization of energy usage, which can lead to significant cost savings and environmental benefits. By using real-time data and analytics, control technologies can optimize the performance of VPPs, ensuring that energy is produced and consumed efficiently and sustainably. Furthermore, VPP can enable the integration of more RESs into the grid, which can reduce reliance on fossil fuels and reduce greenhouse gas emissions. By using control methods such as energy storage and DRs, VPPs can maximize the use of renewable energy and minimize waste. In summary, designing an appropriate control architecture and using appropriate control technologies or control methods for VPPs can provide numerous benefits, including a stable and reliable power system, optimized energy usage, cost savings, environmental benefits, and the integration of more RESs into the grid.

### *4.3. Communication Protocols and Security*

The implementation, research, and development of the VPP concept aims to improve the performance of VPP operations. However, the system may face numerous vulnerabilities and network attacks without relevant security measures [74]. Therefore, the communication system is one of the core components of the VPP model, with the primary objective of ensuring real-time control information accuracy, sharing, and promoting communication facility instruction configuration [75]. This is achieved through the integration of various communication technologies such as wireless sensor networks, cloud computing, and the Internet of Things to facilitate data communication and information sharing between the different components of the VPP system. In addition to enabling real-time monitoring and control of DERs, the communication system also provides valuable insights into the performance of the VPP network, enabling operators to make informed decisions and optimize energy management. The implementation of VPP management and control is achieved through data transmission in the communication infrastructure. Real-time message transmission is mainly done bidirectionally, targeted at multiple entities [76]. Sufficient quality of service is essential to operate VPPs safely and effectively [77]. It is accomplished by tracking the necessary variables (such as transmission duration, frequency, loss rate, accuracy, and bandwidth) throughout the VPP service to limit the possibility of communication errors or failures [78]. VPP information exchange is implemented through signal requests sent from transmission or DSO to the VPP system or DER, as depicted in Figure 9 [16]. These requests contain information on the system's current needs, such as the requirement for additional capacity or frequency regulation. Based on this information, the VPP system or DER can dispatch the appropriate DER resources in order to meet the system's needs. VPPs can aggregate all types of DERs in the region, connect them to the power grid, and realize hierarchical demand reporting and reward-incentivized information interaction with the transmission and distribution networks during market operation. VPPs can work with DSO and TSO systems to optimize energy production, storage, and distribution and support grid stability, flexibility, and resilience. A framework was proposed in [79] that allows DSOs to participate in the balancing market as a central coordinator of the aggregator and as a balancing service provider. The framework also provides balancing services to TSOs. The framework enables DSOs to actively participate in the balancing market, supporting grid flexibility and stability while allowing RES integration. The authors presented a conceptual framework in [80] that includes different types of aggregators, under which specialized energy aggregators are coordinated to provide balancing services to system operators. The verification results showed how its control algorithm could effectively offer balanced services to different loads at different times. In [81], a service restoration framework was proposed for DSO and VPP coordination in active distribution networks, which ensures reliable and efficient power supply to customers while maximizing the use of RESs. The proposed scheme aims to maximize the utilization of DERs in both normal and post-fault conditions by dynamically adjusting the VPP scheduling and DSO restoration processes. The scheme also includes a communication and control framework for coordination between the DSO and VPP operators. The framework enables real-time data exchange and decision-making, which facilitates efficient coordination between entities. The VPP communication infrastructure comprises three types of networks: home area networks, neighborhood networks, and wide area networks [82]. Overall, the communication system is critical for the successful implementation of the VPP model and for ensuring its effective operation and maintenance.

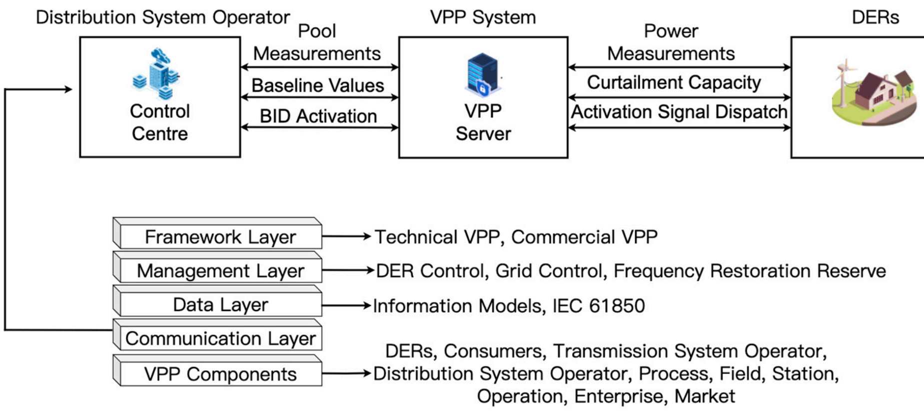


**Figure 9.** VPP communication system architecture with message exchange (modified from [16]).

To ensure effective and stable VPP operation, reliable, interoperable, secure, and standardized communication protocols are required [83]. IEC 61850 [84,85], IEC 60870-5-104 [86], and open automated demand response (OpenADR) [87] are some common communication protocols used in VPPs. These communication protocols should support real-time data transmission, event notification, and control commands between VPP components, such as DERs, EMSs, and grid operators. IEC 61850, based on standard communication, is the preferred choice for intelligent grid operation. It is a data format and architecture standard designed to achieve mutual communication within the structure of power utility processes [88]. VPPs can leverage IEC 61850 to perform advanced control and monitoring functions at the edge of the grid. OpenADR is a protocol used for DR programs, which allows VPPs to manage loads based on grid signals, price signals, or other parameters. The protocol provides an interface for energy providers and consumers to communicate and automate DR events. In conclusion, effective communication protocols are crucial for VPPs to operate efficiently, securely, and reliably. With standardized and interoperable protocols, VPPs can integrate various DERs and grid assets seamlessly, and optimize their operation in real time.

## 5. Ancillary Service Provision from VPPs

The purpose of auxiliary services in non-hierarchical control technology is to maintain the balance between electricity generation and demand [14]. Variants of power system auxiliary services include scheduling, reactive power, voltage control, load tracking, loss compensation, and system protection [16]. VPPs can partake in the energy market, furnishing auxiliary services via the aggregation of DG and loads. This aggregation provides a flexible and dynamic resource that can respond to real-time grid conditions, allowing for better system stability and reliability. Using VPPs to reduce losses in the distribution network, a local search algorithm for optimizing VPPs is proposed in [89], which is used for energy management in the distribution network, including the optimal selection and positioning of DERs. By strategically placing DERs, utility companies can reduce power losses during electricity transmission and distribution. In [90], a new method combining the interval optimization and deterministic optimization was used to solve the scheduling problem of VPP. The proposed combinatorial optimization increases the certainty of DG power generation and voltage profiles, reduces power loss, and increases revenue margins. As the involvement of VPPs grows, it can bolster the economic prosperity of the electricity market. Using VPPs can lead to a more resilient, efficient, and sustainable energy system.

### 5.1. VPPs as a Source for D-FCAS

VPPs can serve as a source for D-FCAS by utilizing their aggregative capabilities to manage and dispatch DERs. DERs can be controlled and coordinated through VPPs to respond to changes in frequency on the grid. This allows for effective demand-side management of power consumption and generation, helping to balance the supply and demand of electricity in real time. VPPs can bid into the ancillary services markets to offer frequency control services to grid operators, providing an additional revenue stream for DER owners who are part of the VPP. This incentivizes participation in VPP programs and can lead to increased adoption of RESs in the grid. Furthermore, utilizing VPPs for demand-side frequency control can also reduce the need for traditional power plants to regulate frequency, reducing emissions and the overall carbon footprint. This makes VPPs a valuable tool for transitioning to a more sustainable and equitable energy system. VPPs can participate in the energy market by purchasing energy at low prices, while storing it in ESSs and selling the surplus energy by adjusting demand and releasing energy from ESS when prices are high. For the balancing market, VPPs can offer the capacity to power plants that cannot fulfill their original commitments [91]. In the auxiliary services market, VPPs can provide almost real-time services [91]. Table 4 summarizes the literature related to VPPs providing D-FCAS control technology in the past few years.

**Table 4.** VPPs providing D-FCAS control technology.

| Time | Brief Description | Reference |
|---|---|---|
| 2023 | With the aid of a multi-stage stochastic mixed-integer linear programming with binary resources and a novel decomposition algorithm, the optimization of VPP operations for day-ahead scheduling and auxiliary services could be enhanced. | [92] |
| 2022 | A new computing architecture using cloud-based energy trading and DR for managing VPP was proposed, by buying and selling electricity through a cloud-based energy trading platform to maximize revenue. | [93] |
| 2022 | A data-driven approach was created to jointly optimize the battery ESS and DR, targeting the maximization of VPP profits, as per the resource planning of a VPP. | [94] |
| 2021 | As for a VPP in the combined FCAS and DR markets, a FCAS and a critical threshold discount strategy based on cumulative prospect theory was proposed. This result was achieved with both demand-side producers and retailers of the VPP profiting from the appropriate formulation of a pricing model. | [95] |
| 2021 | Devoting attention to the optimal bidding strategy of a VPP comprised of photovoltaics, battery ESS, and controllable loads in the FCAS market was proposed, seeking to maximize the associated interests. | [96] |
| 2020 | A hierarchical control strategy was proposed for ancillary services of an aluminum smelter load (controllable load). On the upper level, monitoring computers estimated the available power and allocated reserves to loads through optimization. The underlying level controllable load automatically responded to frequency deviations by changing its power consumption. | [97] |
| 2019 | A fog computing approach to shape and manage VPPs to render auxiliary services was proposed. This fog-layered collaboration model catered to local energy systems, considering local obstructions, service restrictions, frequency reserves, and profit optimization. | [98] |
| 2019 | An entirely novel scheme was proposed for optimizing VPP operations and bidding strategies by scheduling DERs and DR, making it possible for VPPs to supply energy and auxiliary services to the grid. | [99] |

**Table 4.** *Cont.*

| Time | Brief Description | Reference |
| --- | --- | --- |
| 2019 | A new framework for VPP energy control was proposed based on DR, which minimized VPP operating costs, with risk-based constraints on day-ahead and real-time electricity prices, RESs generation processes, and DR uncertainty. | [50] |
| 2019 | A coordinated operation strategy for an active distribution network based on a two-layer agent framework and considering the electricity price response of DER was proposed. DER made its own decisions based on operability and economics, while an active distribution network coordinated each participant through the interactive benefit prioritization. | [100] |
| 2019 | A mixed integer linear constraint programming model was presented for simulating a battery ESS in the Italian ancillary services market to verify the economic viability of the storage technology when providing network services. | [101] |
| 2018 | The industrial switch loads (quickly adjusting power consumption through switches) were proposed to provide regulation or load tracks with the support of ESS and to provide auxiliary services. | [102] |
| 2018 | A combination of RES and ESS to generate power consumption signals was proposed, in order to participate in real-time regulation and provide auxiliary services by tracking dynamic regulation signals, maintaining grid stability, and obtaining economic benefits. The proposed method was validated in factory scheduling. | [49] |
| 2018 | A method of using an artificial neural network to predict future prices of electricity in the auxiliary energy market was proposed. This information could be used by participants in the market to make decisions about when to buy and sell electricity, and to optimize the use of DERs. | [103] |
| 2018 | This innovative approach involved integrating thermal energy supply equipment with ESS in multiple VPPs to provide frequency modulation services to the auxiliary service market. | [104] |
| 2017 | A scheduling model based on a resource−task network formulation (represents the production process as a set of tasks that require specific resources, such as machines, equipment, and personnel) was proposed that incorporated the flexibility of electric arc furnaces to adjust their power consumption to reduce electricity costs during peak demand periods. | [105] |

The control of the power market and ancillary services is gradually transitioning from DERs to the demand side, leading to an improved overall power market economy. VPPs are aggregating DGs, ESSs, and flexible loads into a single virtual entity that can participate in energy markets. This aggregation of DERs can provide a range of ancillary services, including voltage support, frequency regulation, and spinning reserve. Therefore, implementing ancillary services in the distribution network era becomes more attractive with the continuous development of VPPs. It can help in the efficient management of the power grid, promote the growth of RESs, and provide benefits to prosumers in terms of reduced energy costs and peer-to-peer trading.

### *5.2. VPPs Consisting of Interconnected Microgrids for D-FCAS*

Most researchers conduct related studies on a VPP consisting of DERs and controllable loads. In our previous study, we proposed a two-stage two-layer optimization model of a VPP consisting of interconnected microgrids (IMGs) with RESs and ESSs to provide D-FCAS and considered the internal energy sharing within the VPP [42]. The overall flow of the model is shown in Figure 10. The first stage involves predicting the hourly power baseline for the next day and the adjustable power that can be rewarded, known as day-ahead scheduling. The second stage is divided into two layers, with real-time power control based on dynamic adjustment signals. The upper layer allocates DR signals from the main grid according to the electricity unit price of each MG. It then exchanges electricity between MGs via the new energy-sharing mechanism to reduce violation costs. The lower layer controls each MG's real-time power, minimizing operating costs. The overall goal is to maximize rewards in the day-ahead stage and to minimize violations in the real-time stage, thereby reducing the overall operating cost of the VPP. The experimental model is to divide the New England 68-bus test system [106] into four MGs, and the relevant input data comes from [107,108]. More details can be found in [42].

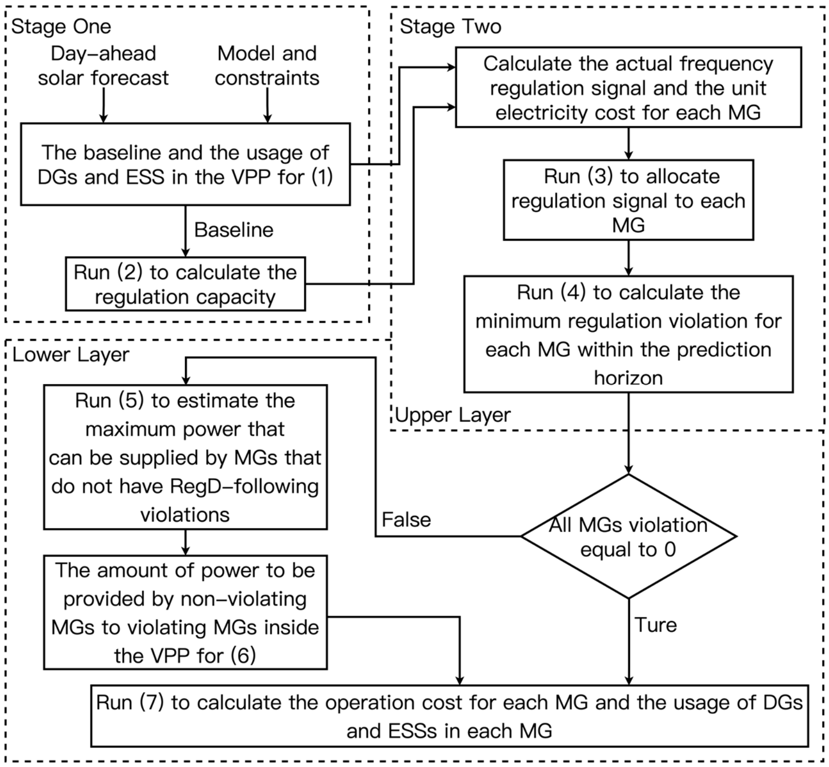


**Figure 10.** Flowchart of the VPP model.

### 5.2.1. Day-Ahead Scheduling

Here, we predict the hourly baseline and regulation capacity of the next day, and calculate the power that can be reserved. The verification experiment considers four interconnected MGs, and the experimental results are shown in Figure 11. The goal of this phase is to minimize the overall cost of the VPP:

$$\min \sum_{t=1}^{24} \left[ \alpha_s(t)\mathcal{B}(t) + \sum_{\text{DG}_k}^{k} C_k^{\text{DG}}(t) \right] + \sum_{\text{ESS}_i}^{i} \gamma_{\text{ESS}} D_i^{\text{ESS}} \tag{1}$$

where $\alpha_s(t)$ is the hourly main grid electricity price, and $\gamma_{\text{ESS}}$ is a positive real number and the cost coefficient of ESS. $\mathcal{B}(t)$ represents the baseline and regulation capacity at time t, $C_k^{\text{DG}}$ is the cost of the $k$th DG, and $D_i^{\text{ESS}}$ is the usage of the $i$th ESS over a 24 h period.

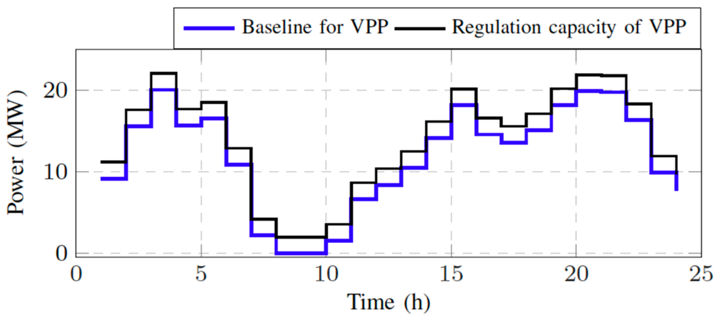


**Figure 11.** Hourly baseline and regulation capacity for VPPs.

The regulation capacity is calculated as,

$$\mathcal{R}(t) = min\{A - \mathcal{B}(t),\ \mathcal{B}(t)\} + \sum_{\text{ESS}_i}^{i} P_i^{\text{ESS,max}}(t) \tag{2}$$

where $A$ represents the maximum power consumption of all controllable loads and $P_i^{\mathrm{ESS,max}}$ is the maximum charging rate of the $i$th ESS. For a detailed overview of the other related parameters, constraints, and experimental results, please refer to [42].

5.2.2. Real-Time Power Control

Upper layer: the regulation signal received from the main grid is optimally distributed to each MG according to the following equation, and the experimental results are shown in Figure 12.

$$\min \sum_{j=1}^{L} \sum_{\mathrm{MG}_n}^{n} f_n^{\mathrm{MG}}\left(Reg_n^{\mathrm{MG}}(t+j\delta)\right) \quad (3)$$

where $Reg_n^{\mathrm{MG}}$ is the regulation signal for each MG, and $f_n^{\mathrm{MG}}$ represents the total cost of each MG. Term $j$ is the time step and $\delta$ is the sampling time.

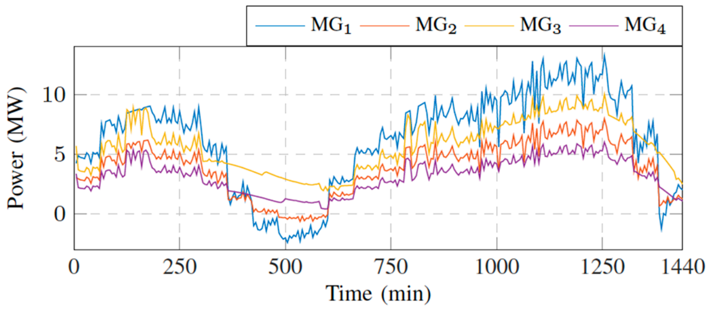


**Figure 12.** The assigned $Reg_n^{MG}$ for each MG inside a VPP.

Next, electricity is exchanged among MGs via the new energy-sharing mechanism so as to reduce violation costs, using to (4), and the experimental results are shown in Figure 13.

$$\min P_n^{\mathrm{vio}}(t+j\delta) = \left|\sum_{\mathrm{DG}_k}^{k} P_{n,k}^{\mathrm{DG}}(t+j\delta) + \sum_{\mathrm{ESS}_i}^{i} P_{n,i}^{\mathrm{ESS}}(t+j\delta) + P_n^{\mathrm{solar}}(t+j\delta) + Reg_n^{\mathrm{MG}} - P_n^{\mathrm{load}}(t+j\delta)\right| \quad (4)$$

where $P_{n,k}^{\mathrm{DG}}$ is the output power of the $k$th DG in the $n$th MG, and $P_{n,i}^{\mathrm{ESS}}$ is the $i$th ESS' charging or discharging power in the $n$th MG. Term $P_n^{\mathrm{load}}$ is the load consumption in the $n$th MG, and $P_n^{\mathrm{solar}}(t+j\delta)$ is the short-term solar power forecast.

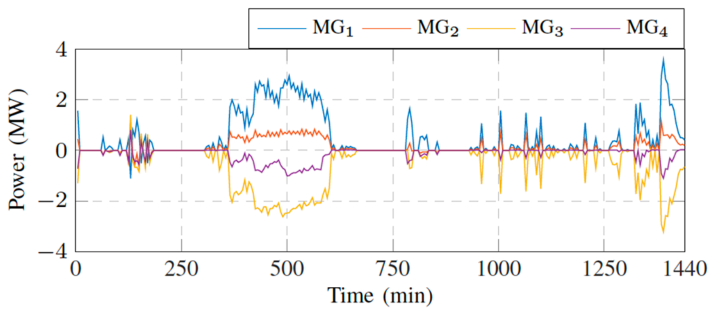


**Figure 13.** Energy sharing results in VPPs.

Then, we use $m$ and $q$ to represent the number of MGs with $P_n^{\mathrm{vio}}(t+j\delta) = 0$ and $P_n^{\mathrm{vio}}(t+j\delta) \neq 0$, respectively. The $m$th MG can provide excess energy for energy exchange:

$$\max P_m^{\mathrm{MG}}(t+j\delta) = \sum_{\mathrm{DG}_k}^{k} P_{m,k}^{\mathrm{DG}}(t+j\delta) + \sum_{\mathrm{ESS}_i}^{i} P_{m,i}^{\mathrm{ESS}}(t+j\delta) + P_m^{\mathrm{solar}}(t+j\delta) + Reg_m^{\mathrm{MG}} - P_m^{\mathrm{load}}(t+j\delta) \quad (5)$$

Allocate excess energy for exchange as follows:

$$P_m^{\mathrm{ex}}(t+j\delta) = P_m^{\mathrm{MG}}(t+j\delta) \times \frac{\sum_q P_q^{\mathrm{vio}}(t+j\delta)}{\sum_m P_m^{\mathrm{MG}}(t+j\delta)} \quad (6)$$

In the lower layer, minimize the operation cost of each MG according to (7), and Figure 14 shows the distribution regulation and load consumption curves against the regulation curve.

$$\min \sum_{j=1}^{L} \left[ \gamma_{\text{v}} P_n^{\text{v}}(t+j\delta) + \sum_{\text{DG}_k}^{k} C_{n,k}^{\text{DG}}(t+j\delta) \right] + \sum_{\text{ESS}_i}^{i} \gamma_{\text{ESS}} D_{n,i}^{\text{ESS}} \tag{7}$$

where $P_n^{\text{v}}$ is the violation power of the $n$th MG after energy sharing, and $\gamma_{\text{v}}$ is the cost coefficient of the penalty for regulation violation. For a detailed introduction of other related parameters, constraints, and experimental results, please refer to [42].

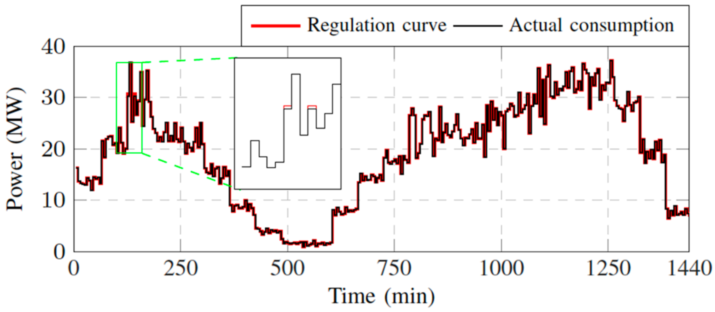


**Figure 14.** DR and actual power consumption.

### *5.3. Possible D-FCAS Paradigm Considering Grid Contingencies*

With the grid's dependence on and greater use of RESs, the number of conventional generators decreases, and contingencies in the grid increase [109]. This is because RESs such as wind and solar power are often intermittent and can only generate electricity when weather conditions permit. As a result, the grid must have backup generators to ensure a steady and reliable supply of electricity. However, with more RESs being added to the grid, the need for backup generators decreases. In addition, RESs may also require an additional grid infrastructure, such as energy storage systems, to ensure their stability and reliability [110]. The power system's source is mostly a rotating thermal generator, and the system inertia is relatively large. The traditional technical method uses 8–10% of a single machine's maximum capacity (or maximum power generation) as an emergency backup to automatically meet the frequency regulation requirements [111]. This means that in case of sudden load changes or generator failures, the system has enough inertia and reserve capacity to maintain its frequency stability. In recent years, more and more conventional units have been replaced by new energy units to meet the low-carbon goal of the power system, resulting in low system inertia [112]. There is a need to develop new reserve calculation methods that can account for the changing energy mix and the low system inertia that comes with it. Such methods need to take into account the different types of reserves that are available and the specific requirements of the power grid in different scenarios. By improving the classification of reserves, the power grid can better prepare for emergencies and ensure that the frequency of the system remains stable, even in the face of sudden disturbances. This is critical for the reliable operation of the power grid and for meeting the growing demand for clean and sustainable energy.

However, with the increasing penetration of renewable energy sources, such as wind and solar, the power system may experience larger and more frequent fluctuations in power output, which could lead to instability and blackouts if not properly managed. To address this issue, new technologies and techniques have been developed to enhance the power system's flexibility and efficiency. A robust optimization method based on budget uncertainty is proposed in [113]. Based on large-scale battery ESS power stations, a day-ahead scheduling optimization model is established to minimize the daily operating costs of dispatch and to utilize the advantages of battery ESS power stations. The model considers the uncertainty of RES generation and the load demand and uses a predictive algorithm to forecast the power output of wind for the next day. The forecast results are combined with the actual data of the previous day, and the scheduling optimization is performed based on the updated data. This ensures the accuracy of the dispatch plan and improves the economic efficiency of the battery ESS power station. In addition, it helps solve the power imbalance problem caused by wind power grid connection, and together with conventional generator sets, it can ensure the power system's safe, reliable, and economical operation. In [114], an economic analysis model of fast frequency response reserves considering risk preference was proposed to assess the risk of extreme events. The system operating state model is established based on the sequential Monte Carlo method. This model can be used to predict the behavior of the grid under different conditions, including extreme events such as blackouts or power outages. The fast frequency response reserve optimization planning and configuration method is then used to calculate the losses associated with such events. This method aims to optimize the allocation of fast-frequency response reserves across the grid to minimize the impact of extreme events on the system. A decomposed online calculation method for calculating the cycle life under different operating strategies is proposed in [115]. The method decomposes the cycle life calculation into two parts: the calendar life and the cycling life. The calendar life is estimated based on the storage duration and temperature, while the cycling life is calculated using the degradation model, which considers the depth of discharge and the state of charge. Using this method, the optimal bidding strategy can be determined by analyzing the trade-off between the revenue earned from selling energy and the cost of battery degradation.

Based on the above research, we consider a model for dealing with VPPs that is composed of IMGs providing D-FCAS to solve power grid contingency. The model is still divided into two stages. The first stage is day-ahead scheduling, which reserves adjustable power. In the second stage, when the system has contingency (randomly shut down any DR), the power of the day-ahead reserve is used to make up for the contingency. Through MG energy sharing, the VPP can consume less power. By optimizing energy usage and sharing resources, the VPP can help reduce the overall cost and environmental impact of energy production, while also improving the reliability and resilience of the energy grid.

#### 5.3.1. Day-Ahead Scheduling

The first stage predicts the next day's hourly baseline and regulation capacity and calculates the power that can be reserved. The objective function of this stage adds an item regarding regulation capacity, based on (1). The main goal remains to minimize the overall cost of the VPP:

$$\min \sum_{t=1}^{24} \left[ \alpha_s(t)\mathcal{B}(t) + \beta_{\mathrm{r}}\mathcal{R}(t) + \sum_{\mathrm{DG}_k}^{k} C_k^{\mathrm{DG}}(t) \right] + \sum_{\mathrm{ESS}_i}^{i} \gamma_{\mathrm{ESS}} D_i^{\mathrm{ESS}} \tag{8}$$

where $\beta_{\mathrm{r}}$ is positive real number and the cost coefficient of the regulation capacity. Refer to (1) for the definitions of the rest of the notations. The reserve power is calculated as,

$$P_{\mathrm{r}} = \mathcal{R} - \omega_{dl}\mathcal{R} \tag{9}$$

where $P_{\mathrm{r}}$ represents the reserve power and $\omega_{dl}\mathcal{R}$ is the regulation power.

#### 5.3.2. Real-Time Power Control

In the second stage, when the system has contingency, the power of the day-ahead reserve is used to make up for the contingency. Through MG energy sharing, the VPP can consume less power and minimize the amount of power drawn from the grid during a contingency event.

Step 1: the regulation signal received from the main grid is optimally distributed to each MG (the same as Equation (3)).

Step 2: if in the normal state, minimize the violation cost of each MG (the same as Equation (4)).

Step 3: use $m$ and $q$ represent the number of MGs with $P_n^{\text{vio}}(t + j\delta) = 0$ and $P_n^{\text{vio}}(t + j\delta) \neq 0$, respectively. The $m$th MG can provide excess energy for energy exchange (same as Equation (5)). Then, allocate excess energy for exchange (same as Equation (6)). If there is no remaining energy in any MG at a certain moment or are violations in a certain MG, reserve power is allocated:

$$P_q^{\text{r}}(t + j\delta) = P_{\text{r}}(t + j\delta) \times \frac{P_q^{\text{vio-r}}(t + j\delta)}{\sum_q P_q^{\text{vio-r}}(t + j\delta)} \quad (10)$$

If contingency occurs (a DG suddenly shuts down), recalculate the relevant data in step 2 and step 3.

Finally: minimize the operation cost of each MG (the same as Equation (7)).

### *5.4. P2P Energy Trading for Distributed Optimization*

Peer-to-peer (P2P) energy trading provides a promising solution to promote the efficient and safe operation of power distribution systems composed of multiple prosumers [116]. It is also one of the emerging concepts in power distribution networks. This technology allows individuals and businesses to trade the excess energy they produce with other consumers in their community. By creating a local energy marketplace, P2P energy trading can reduce the need for large, centralized power plants and transmission lines, which are vulnerable to power outages and natural disasters [117]. P2P energy trading can also lead to a more sustainable energy system by incentivizing the use of renewable energy sources. Furthermore, it encourages energy efficiency and conservation by creating a financial incentive for prosumers to produce and consume energy in a more sustainable way.

Here, we summarized the literature related to distributed optimized P2P energy trading. A security-constrained decentralized energy trading framework for P2P transactions and distributed optimization method based on the alternating direction multiplier method were proposed in [118] as a privacy-preserving solution. This framework allows direct energy transactions between adjacent prosumers in the distribution system, improving system efficiency and security without the need for traditional intermediaries. This method allows multiple parties to jointly solve an optimization problem without sharing their private data with each other. In [119], P2P multi-level energy trading is proposed, and a reliability credit allocation method is used for energy allocation. Users are encouraged to flexibly use the energy generated by local DER to reduce the uncertainty brought by RES and to maximize social welfare. This solution aims to promote the adoption of renewable energy sources and increase the reliability and efficiency of energy trading in a peer-to-peer network. A credit allocation method is used to evaluate the reliability of each participant in the network. The credit score is based on several factors: energy production, consumption, and trading history. Participants with a higher credit score will have priority and receive more energy allocation than those with lower scores. A two-layer P2P energy trading market is proposed, and a distributed market clearing method based on consensus and double decomposition is designed in [120]. The first layer of the P2P energy trading market consists of local energy communities, which consist of prosumers. The prosumers generate surplus energy that they can sell to other community members. At the same time, consumers can buy energy from the local community at a lower price than the grid. The second layer of the market consists of an overarching market that connects the local energy communities. In this layer, surplus energy from one community can be sold to another community with a higher energy demand. This layer also allows for integrating ESSs into the market. To clear the market, a distributed consensus algorithm is used, ensuring that all market participants agree on the prices and quantities of energy being traded. It is used for energy sharing among multi-region prosumers and protects the privacy of prosumers. In [121], a holistic P2P energy trading approach consisting of a distributed predictive control framework is proposed. The predictive control framework uses data analytics and machine learning techniques to analyze the energy demand and supply patterns of individual consumers and generators, and then optimizes the energy distribution to achieve system-level stability and efficiency. A new framework is developed for handling physical interactions of energy devices and determining pricing policies for energy transactions. A decentralized market framework supported by P2P energy transactions was proposed in [122]. The market equilibrium is achieved through the iteration of the alternating direction method based on the multiplier algorithm. This ensures that the market reaches an equilibrium point where the demand and supply of P2P energy are balanced and the market clearing price is found. This algorithm ensures that the costs and rewards of ancillary services are allocated fairly among the participants in the P2P energy trading network. In [123], a two-level network-constrained P2P energy trading for multiple MGs was proposed. In the upper layer, the DSO reconstructs the distribution network based on the results of P2P energy trading. The algorithm ensures that the DSO is aware of the energy flows and can take corrective actions if the network is overloaded or if there is a voltage violation. In the lower layer, multiple MGs use P2P energy trading to trade energy with each other and use the multi-leader and multi-follower Stackelberg game method to model the energy trading process among MGs. By using a P2P energy trading model, the proposed approach eliminates the need for a central authority, thus reducing administrative fees and improving the efficiency of the energy trading process. Furthermore, the proposed approach allows for greater flexibility in the trading decisions of individual MGs, thus enabling them to respond to changing market conditions and customer demands. The authors proposed a data-driven distributed robust collaborative optimization model for P2P energy trading and network operation of interconnected MGs in [124]. Energy management in MG uses the distributed robust optimization and alternating direction multiplier method as a pricing strategy, which is a distributed algorithm that allows the solution to be decentralized. The proposed model considers the individual local interests of MGs and provides a fair mechanism for energy trading among them.

Although P2P has brought many benefits to the power distribution system, the development of P2P energy trading is still in the early stages, and several technical and regulatory challenges need to be addressed, such as metering and settlement systems, data privacy and security, and the integration of renewable energy into the grid. Overall, peer-to-peer energy trading can transform how we generate, consume, and trade energy, creating a more sustainable and resilient energy system for the future.

## 6. Future Research Directions

Based on our review, the existing VPP research has opened a range of future research directions:

- Proposition of policy framework in the energy sector: This refers to the need to change and update the policies and regulations that govern the energy sector to accommodate the technological advances and changing trends in energy production and consumption.
- Hardware implementation of VPP control mechanisms: VPP control mechanisms are complex systems with power electronics devices and software control and communication protocols, which enable the aggregation, control, and dispatch of DERs within a VPP.
- New market regulations: Market regulations need to evolve to allow for the integration of VPPs into the energy market. This includes establishing new market structures and rules to support the use of VPPs.
- Secure communications: As VPPs rely on communication between various components, ensuring that these communications are secure is essential to prevent hacking and data breaches.
- Planning of infrastructure and necessary facilities for VPPs: The integration of VPPs in the energy sector requires strategic planning of next-generation infrastructure, such

as high-efficiency renewable generators, storage systems, standby generators, and flexible loads.

## 7. Conclusions

A VPP is a modern energy management system designed to address some of the challenges arising from integrating RESs into sustainable power grids. VPPs bring together multiple small-scale generation and storage units, such as solar PV, wind turbines, batteries, and electric vehicles, into a single flexible system. By using advanced information and communication technologies, VPPs can coordinate, monitor, and manage the output of DERs in response to changing grid conditions and market signals. VPPs can also provide ancillary services, such as frequency regulation, voltage support, and capacity reserves, which are critical for maintaining grid stability and resilience. VPPs have several advantages over traditional centralized power systems. Firstly, they reduce the need for expensive and complex transmission and distribution infrastructure, as well as the reliance on large, inflexible power plants. Secondly, they enable greater utilization of intermittent renewable energy sources by forecasting their output and integrating them into the grid more efficiently. Thirdly, they create new revenue streams for DER owners by participating in energy markets and providing grid services. Fourthly, they empower consumers to actively manage their energy consumption and production through real-time feedback and incentives. Overall, VPPs improve the flexibility, stability, reliability, and economic viability of power systems.

This paper reviews a large body of literature related to VPPs. Firstly, we summarize the development history of VPPs as well as related concepts. From the earliest definition based on virtual public infrastructure until the present, VPPs have become an innovative solution to balance energy supply and demand in modern power systems. Then, we compare the differences between VPPs and MGs, which are similar concepts in that they both involve the integration of DERs. However, MGs are designed to operate in isolation from the main grid, whereas VPPs are designed to be connected to the grid and provide support services. Next, we describe the benefits that VPPs bring to society, the economy, and the environment. Firstly, they reduce the cost of energy generation and distribution by optimizing the use of DERs and reducing reliance on fossil fuels. Secondly, they enhance the grid's stability and resilience by providing ancillary services such as frequency regulation and voltage control. Thirdly, they enable the integration of RESs by mitigating their variability and intermittency. Finally, they empower consumers to participate in the energy market by allowing them to sell their excess energy back to the grid. Here, we have detailed comparisons of the state-of-the-art research in VPPs, including VPP control models and systems, hierarchical control, ancillary service control, and market mechanism for VPPs as a source for D-FCAS, while explaining the communication protocols related to VPP. Hierarchical control is one approach that is being explored, where multiple levels of control are used to manage DERs at different time scales. Ancillary service control is another approach that is being implemented to provide grid support services such as frequency regulation and voltage control. Moreover, market mechanisms are being developed to enable VPPs to participate as a source of distributed frequency control ancillary services (D-FCAS). Communication protocols are also important for enabling the coordination and control of DERs in VPPs. Finally, we also propose a possible VPP control and trading paradigm for grid contingency support as a means of DR.

In conclusion, VPPs are a promising concept with the potential to transform the way we generate, distribute, and consume energy. The offer numerous benefits for the environment, the economy, and society, by promoting a more decentralized, democratic, and resilient energy system. However, implementing VPP requires careful planning, collaboration, and innovation to overcome the barriers and leverage the opportunities that arise from the integration of renewable energy and smart technologies.

**Author Contributions:** Conceptualization, J.L. and S.S.Y.; methodology, J.L. and H.H.; formal analysis, J.L., H.H., S.S.Y. and H.T.; resources, S.S.Y. and H.T.; writing—review and editing, H.H. and S.S.Y.; supervision, S.S.Y. and H.T. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The authors declare no conflict of interest.

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