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# Virtual Power Plant Operational Strategies: Models, Markets, Optimization, Challenges, and Opportunities

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**Abstract:** High penetration of distributed generation and renewable energy sources in power systems has created control challenges in the network, which requires the coordinated management of these resources. Using virtual power plants (VPPs) on a large scale has solved these challenges to a significant extent. VPPs can be considered systems consisting of distributed generations, energy storage, controllable loads, electric vehicles (EVs), and other types of resources to provide energy and ancillary services. VPPs face various challenges such as energy management, operation, resource uncertainty, participation in electricity markets, etc. This paper discusses an overview of the basic challenges of VPPs, including control and communication issues, electricity markets, its different models, and energy management issues. The main purpose is to investigate the performance of VPP in different markets, energy management of VPP in different operating conditions and strategies, and compare different planning methods for VPP. Note that the application of blockchain to control and improve VPP performance has been investigated, taking into account the different layers of this technology.

**Keywords:** virtual power plant; energy management; resource uncertainty; electricity market; blockchain

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## 1. Introduction

The need for higher electricity demand and increasing environmental concerns, on the one hand, and the complexity of energy distribution networks, on the other hand, have led to the focus of many distribution network designers on MGs as a source of electrical energy with high reliability [1]. The available challenges in environmental issues and recent advancements in the field of power electronics increase the penetration rate of distributed energy resources in distribution networks [2]. In the last decade, RESs have been considered the closest alternative to the current power systems due to their high flexibility of operation. However, the high penetration of these resources may provide great challenges for the power grid [3]. The VPP is an effective solution to solve this problem. VPPs can be a combination of sources such as WT, PV, MT, ES, interruptible loads, etc. [4]. Although the outputs of DERs may be intermittent and have uncertainty, the total behavior of a VPP is more certain [4]. The VPPs have several advantages such as reducing the number of outages, reducing network recovery time, integrating DGs, reducing line congestion, reducing peak demand, etc. [5,6].

With the expansion of DERs in distribution networks, new ideas for using these resources have been reviewed in various papers; one is using VPP. The challenges in VPPs have caused different VPP modes that must be evaluated. These challenges could be control and operation, power exchange, and required communication and telecommunication systems. Reference [3] proposed a completely distributed control strategy for several DGs so that DGs can easily form a VPP. Reference [4] has proposed a general method to investigate the effect of combining energy storage elements in a VPP model. This study tries to increase generation power based on existing storage devices. The communication systems and protocols that could be used in VPPs are investigated in [5]. In this study, a new method for two-way communication in VPPs has been proposed. The control aspect of VPP as a basic challenge has been discussed in [6] and various control strategies have been proposed. The authors in [7] investigated the impacts of the uncertainty of PV and WT sources using the Monte Carlo method and evaluated the control strategies related to these resources within VPP. The operation of VPP in a disconnected mode from the main grid has been evaluated in [8].

The authors in [9] evaluated the challenges that VPP faced in telecommunication and system operations. The reference [10] has three main parts: optimization, generation planning, and VPP classification. In the optimization part, the main objective is to reduce pollutant emissions and planning costs. In the generation planning part, the main purpose is to satisfy load and generation balance constraints. The authors in [11] presented a novel solution to solve the problems related to energy deficit and excess. In this regard, the VPP communicates with different available resources, such as PVs and battery energy storage, to respond to power deviations. The authors in [12] provided a new approach for the simultaneous management of responsive loads and EVs in an industrial VPP (IVPP) to reduce the load of industrial centers to enhance the system's profit and reliability. The objective function assigns to short-term generation scheduling of IVPP with the aim of profit maximization, taking into account DERs, conventional resources, DR, and EVs.

Uncertainty management is one of the most important issues affecting the optimal scheduling of DERs [13]. The VPP brings together different ENs to enable them to participate in energy markets in an integrated manner. The VPP manages the generation of each DER and encourages the DER owners to participate in the electricity market. Penalties and incentives have also been considered for DERs, even those with a low-power generation capacity. Today, business models are lacking in achieving win-win benefits for all stakeholders [14]. This study described the structural models of energy markets, market services, and future market mechanisms in the design of VPP. The authors in [15] presented a new model to use a large number of distributed energy resources in rural areas with rooftop PV resources and distributed wind turbines. This new structure has been designed in order to absorb the carbon emission of the gas power plant. Revenue maximization and carbon emission minimization are the objective functions, eventually leading to stakeholder satisfaction. A new approach for the investment planning of a VPP in the market environment has been presented in [16]. In [16], different VPP models and structures have been evaluated with multiple resources. Investment decisions have also been made under the long-term uncertainty of the energy market. The authors in [17] analyzed various VPP models taking into account carbon absorption devices and a comprehensive, responsive load mechanism. The paper used a risk-based model considering the uncertainty of the electricity market price as well as the price of natural gas through the value of the risk index.

The large-scale VPP (LSVPP) concept has been proposed in [18] so that different generation resources, loads, and storage devices are distributed in a wide geographical area while each of them could have a separate connection point. It is noteworthy that although the mentioned resources may have separate owners, all resources are managed through one VPP. A price-based unit commitment model has been developed in [19] in order to determine an optimal strategy for VPP in the electricity market. The presented model takes into account the constraints such as generation and load balance, technical limitations of DER units, security constraints of VPP, and network constraints. In the proposed model, it is possible for VPP to participate in the market as a producer or consumer. According to the direction of power exchange within the main grid, the VPP could play different roles in the market. The VPP model presented in [20] aggregates the available DGs installed in a wide geographical area, and the output power of the aggregated DGs can be controlled like a large central power plant. The paper has employed a distributed control strategy to optimize the VPP output and converge to an optimal operating point.

The current paper intends to analyze the behavior of VPPs in different structures of energy markets. In addition, the power management of VPPs and their challenges are also analyzed. Finally, the utilization of blockchains is examined in the context of VPP. Therefore, the contribution of the paper can be summarized as follows:

- To analyze different VPP models for different market mechanisms. In this regard, this paper describes different energy market structures and thoroughly explains the role of VPP in each market.
- To address different energy management algorithms within VPP considering various resources such as renewable-based/conventional DGs, battery energy storage, responsive loads, and EVs.
- To compare different planning methods of VPPs in terms of solution methods to optimize VPPs.
- To examine the use of blockchain in the structure of VPPs and the benefits of using this technology.

The rest of this paper is organized as follows: the concept of VPP is fully investigated in Section 2. In Section 3, the uncertainties in the context of VPP are explored. In Section 4, the energy management approaches in the VPP are reviewed. Section 5 assigns to the planning of VPPs in the power system. Section 6 addresses the participation of VPP in the electricity markets. Section 7 is related to the basic challenges of VPP and the application of blockchain in VPP. Finally, Section 8 concludes the paper and remarks on future directions.

## 2. VPP Definition

Awerbuch firstly defined the concept of VPP as a "virtual distribution company" that creates attitudes about changing the paradigm in distribution companies. Since then, the concept of VPP has been extended by various researchers. Recently, various definitions have been presented for VPPs, and in all these definitions, there is a common point that VPP is a set of conventional DGs and renewable (RES) resources that could be controlled as a single power plant in order to perform better in a supplying load [21–29]. The authors in [24] have defined VPP: "A set of DG units, controllable loads and energy storage system are integrated, which act as a power plant with less uncertainty". This study also emphasizes that the generators in the definition of VPP can be renewable-based or fossil fuel-based. The heart of a VPP is an EMS that coordinates generators, controllable loads, and storage devices. In [25], VPP is defined as "A set of DERs that include DER with different technologies, responsive loads and storage elements, which by integrating these sources, flexibility, and controllability similar to large conventional power plants are obtained." In [26], VPP is defined as an information and communication system with a focus on a set of DGs, controllable loads, and storage elements. In [27], VPP refers to a set of DERs mutually connected and controlled through a central entity. This study further explains that a VPP can be replaced with a conventional power plant to achieve greater efficiency and flexibility. A set of different DER types that may be dispersed at different points of the distribution networks is called VPP [28].

From the definitions presented for VPP, a more comprehensive and complete definition can be defined as follows: a set of controllable and uncontrollable DGs, energy storage systems, and flexible loads, together in the presence of information and communication technologies to form a single imaginary power plant. The VPP could schedule and monitor the performance of its elements and coordinate their operation in order to minimize the generation costs, minimize the production of greenhouse gases, or maximize profits within the electricity market. The conceptual schematic of a typical VPP has been illustrated in Figure 1.

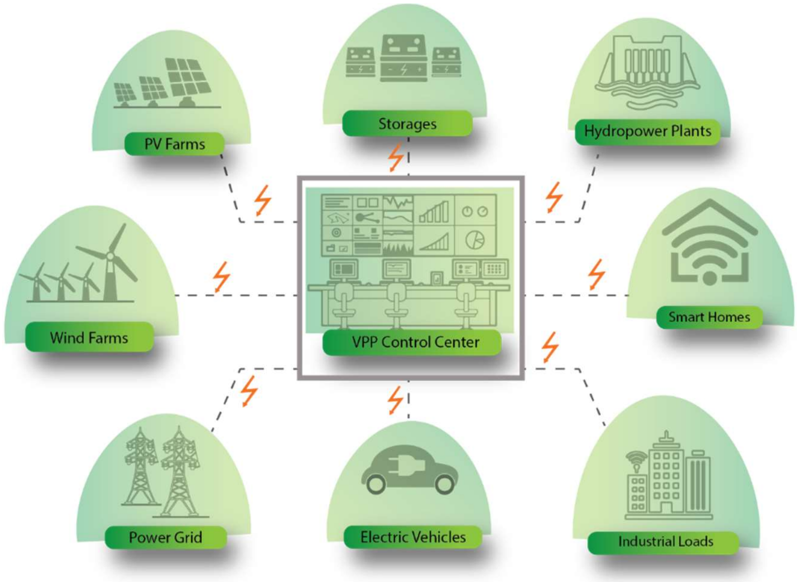


**Figure 1.** Conceptual model of VPP.

*Operating Strategies of VPPs*

VPP is a new power generation entity that aggregates and optimizes the scheduling of DGs, energy storage, and loads. The VPP can significantly improve the power system's flexibility, help to better use distributed demand-side resources, and promote the development of the electricity market [29,30]. To facilitate the application and deployment of VPP, powerful and reliable VPP platforms are essential. However, currently, VPP is still in the early stages of its development [31]. There is still no systematic and comprehensive participation mechanism, control algorithm, or supporting software for VPP. In this section, practical applications of VPP are reviewed. The practical worldwide applications of VPP are shown in Table 1.

**Table 1.** Completed projects of VPP in the world.

| Targets | Construction Time | VPP Name | Type of DER | Country/Countries |
|---|---|---|---|---|
| Development, implementation, and testing of the VPP as well as whether fuel cells can be installed in residential areas | 2001–2005 | VDCPP | Fuel cell | Germany, Netherlands, Spain |
| Provide market mechanism | 2005–2007 | PM VPP | µCHP | Netherlands |
| Choosing DER-based systems in order to choose a solution for EU electricity supply with low cost, safety, and high reliability | 2005–2009 | FENIX | µCHP, PV, WT | GB, Spain, France |
| Providing the balancing power needed to increase the use of wind power | 2009–2012 | EDISON | EVs | Denmark |
| Active power supply and small-scale generation | 2010–2013 | FLEX POWER | WT | Denmark |
| Implementation of "Smart Distribution" | 2010–2015 | WEB2ENERGY | CHP, PV, WT | Germany, Poland |
| Advanced integration of wind turbines | 2012–2015 | TWENTIES | WT | Belgium, Germany, France |
| Providing network support services, helping to secure demand, and saving customers' energy costs | 2016–2018 | SA VPP | PV, battery | Australia |

In recent years, many VPP projects have been deployed around the world, including the European FENIX project [32], the Danish Edison V2G/VPP project [33], the Shanghai Huangpu Commercial Building VPP project [34], and the South Australian Tesla VPP project. Table 1 shows the completed projects of VPPs around the world. DG technologies in VPPs currently offer a wide range of active and reactive power generation options. The final structure and operation strategy of a VPP depends on the interests of stakeholders and owners of different resources involved in the electric power supply, such as system operators, DG owners, energy suppliers, customers, and supervisory centers [35]. Therefore, the optimal operation of VPPs can have economic, technical, and environmental goals. Figure 2 summarizes VPP operation strategies.

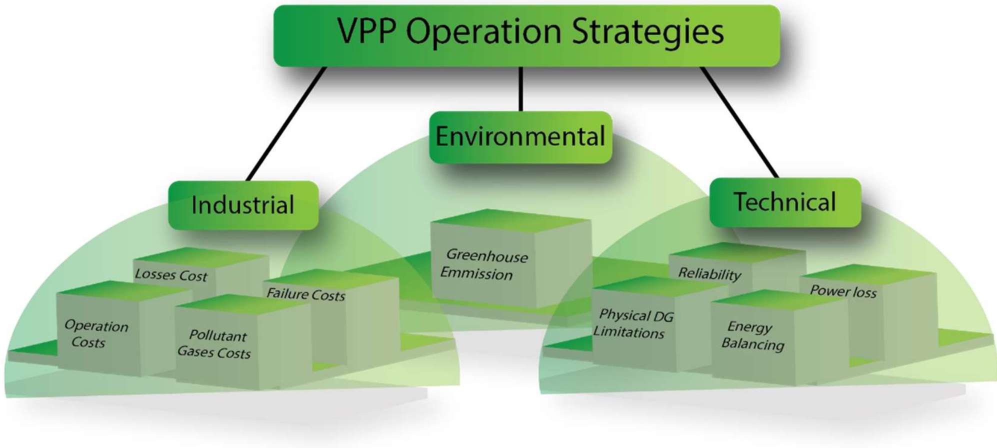


**Figure 2.** VPPs operation strategies.

Depending on the stakeholders involved in the planning and operation of VPP, four objectives have been identified in the operation of VPP [36]. The economic, technical, and environmental goals of VPP are the three important purposes of VPP operation, while the fourth objective is a combination of the previously mentioned goals [36].

- In the economic objective, the objective function is to minimize the total costs with respect to less impact on the network. This option may be considered by DG owners or operators. The main limitations in the economic viewpoint are the physical limitations of DGs which may affect the economic dispatch. The impact of VPP on reducing losses cost is because of the elimination of the transmission lines since these resources are close to the load location. In fact, when transmission lines are removed, power is generated near local loads, which can reduce losses. In this case, the network operator can also benefit from this issue. As a result, electric power can be delivered to the customer at a lower price due to reduced losses. Exploiting VPP could also reduce the failure cost and the number of emission pollutants that enter the air; therefore, the cost of these items will be avoided or will be very low.
- From a technical point of view, the network performance is improved. The purpose of network performance is to minimize power losses and improve voltage fluctuations and network congestion without considering resource costs or revenues. This option is mostly considered by system operators [37].
- The environmental objective function is considered regardless of the economic or technical aspects and only based on the need for reducing greenhouse gases. This option is fully supported by regulatory schemes.

## 3. Uncertainties in the VPP

By increasing the share of large-scale grid-connected RESs and the emerging electricity market, the uncertainties in the power system are gradually increasing, making the power grid's safety and stability more challenging. Therefore, it is necessary to identify the uncertainty sources and choose the appropriate solution to describe these sources [38]. In this section, we will examine the available uncertainties for VPPs. These uncertainties are categorized in three different sections as follows:

### 3.1. Uncertainty of Renewable Energy Resources

The uncertainty of RESs is mainly reflected in the time-varying characteristics of wind and solar energy. In order to enable the VPP to operate in a steady state, various characteristics of RESs must be fully considered in the design process. Currently, the accuracy of forecasting the output of renewable resources is still not satisfactory and the error of forecasting wind and solar energy is around 20% to 30% [39]. The uncertainty of wind power generation is mainly due to the randomness of wind speed, which is influenced by environmental factors such as location and climate. Similarly, solar radiation is the most important factor affecting solar energy production. Seasonal and daily modes characterize solar radiation. These sources are also affected by sudden weather changes, especially cloud changes. When the installed capacity of RESs to the grid increases, the output power increases randomly, which will have a special effect on the grid's safety, stability, and economic performance. This special effect could be categorized from the consumer and producer's points of view. For example, by installing high-capacity energy sources, the manufacturer will generally eliminate the transmission lines and save costs. From the consumer's viewpoint, purchasing energy from renewable energy sources is cheaper than conventional units. Finally, RESs could affect the system reliability so that in a blackout situation, these units can operate separately from the main grid and supply the load.

### 3.2. Market Price Uncertainty

The market price is another uncertain resource when dealing with VPP. During the lifetime of the energy system, market prices, for example, power prices, gas prices, and oil prices, do not remain constant and will change with changes in energy markets, weather conditions, and global and local policies [40]. Market prices can be determined only after the market clearing procedure. It should be noted that the prices are also affected by the transmission network, the demand elasticity, and the supply capacity. Therefore, the electricity market prices are different from the price of physical goods and have strong fluctuations. According to the Department of Energy of the United States report, the fluctuations in electricity prices in the United States can reach up to 359.8% [41]. Under such extreme volatility, market participants may face huge losses. In addition, the crisis in the electricity market may impose great losses on both consumers and resource owners.

### 3.3. Load Uncertainty in VPPs

Load uncertainty is one of the main factors in VPPs. The load amount is composed of two parts, including deterministic and stochastic parts. The deterministic part can be repeated and depends on factors such as time and geography. The stochastic part is obtained from measuring and estimating information. Uncertainty in the VPP environment increases with the appearance of controllable loads such as EVs. At the same time, VPP motivates customers to change their electricity consumption and actively participate in smart electricity distribution. However, load demand fluctuates not only with seasonal changes but also with consumer habits, economic situations, production activities, and emergency conditions. These characteristics make the load demand uncertainty more complicated [42].

In general, the three main groups of uncertainties in the VPP decision-making problem and the factors affecting them are summarized in Figure 3. In fact, the factors affecting uncertainty tend to present in more than two characteristics in the VPP optimization scheduling process, and these characteristics are subject to real physical features. For instance, the output of DG units is affected by the external system [43]. Therefore, familiarity with uncertainty modeling and its impressive factors, along with combining multiple uncertainties with physical limitations, is one of the essential subjects in the field of VPP uncertainty. In addition to modeling an uncertainty factor, in some cases, the relationship between the uncertainty coefficients should also be considered. For example, the coefficients affecting multiple uncertainties in the wind turbine, which work together as a couple, have a high impact on the turbine's power and should be taken into account.

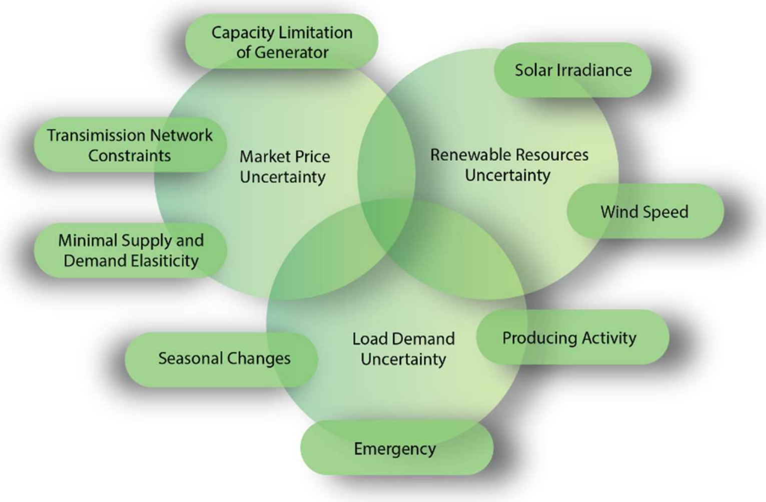


**Figure 3.** Uncertainty resources in VPPs.

### *3.4. Modeling Uncertainties*

In order to measure the effects of uncertainties in VPP, many explanations have been given in recent research [44]. Here, we divide the explanations related to uncertainty modeling into two different parts.

(A) Probability distribution: The probability model is a classical method. The most important part of this approach is to extract characteristics of coefficients affecting uncertainty [45]. In modeling random parameters of VPP, probability density function (PDF) as well as normal PDF, uniform PDF, and exponential (logarithmic) PDF are used to identify the input parameters. For example, the Weibull PDF is used for modeling wind speed uncertainty as in Equation (1).

$$\mathrm{PDF}_{(v)} = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{\left(-\left(\frac{v}{c}\right)^{k}\right)} \tag{1}$$

where k is the shape, c is the scale coefficients of the Weibull PDF, and v represents the wind speed in the area where the study was conducted [43]. The normal distribution is used to describe the uncertainty of electricity market price and its PDF can be expressed as in Equation (2).

$$f(x) = \frac{1}{\sigma\sqrt{2\,\pi}} \exp^{-\frac{(x-\mu)^2}{2\,\sigma^2}} \tag{2}$$

where x is the market price, μ is the position parameter, and σ is the size parameter. It should be noted that the expressed PDFs are the input variables of probability distribution description (PDD). If this situation is not acceptable, i.e., PDFs are not PDD input variables, the following explanation can be considered [46].

(B) Feasibility description: In many cases, due to incomplete information, it is difficult to extract the PDF of the uncertainty resource, and only its approximate value can be predicted. Therefore, a different linguistic category with fuzzy boundaries is used to describe uncertainty [44]. Assume that the function Y = f(X), where X is the input vector of uncertainty coefficients and Y is the output vector. Many MFs, such as the trapezoidal MF, can be applied to describe the membership degrees of probabilistic uncertainty coefficients. The MF of a fuzzy set is a generalization of the characteristic function in classical sets. In fuzzy logic, this function represents the degree of truth as an extension of evaluation. The degree of truth is often confused with probabilities. However, these are two separate concepts because fuzzy truth refers to membership in vaguely defined sets rather than the probability of certain events or conditions. In addition, the historical database and relevant forecasting tools are also used to obtain the minimum, maximum, and most probable range of load demand and output power.

## 4. Energy Management of VPPs

Electric energy is essential in humans' economic development and social life [47]. In recent years, the need for electrical energy has increased by 1.3% throughout the year [48]. According to the American EIA, 62% of the electric power produced in America is generated from fossil fuels [49]. Buildings are a significant producer of greenhouse gases (GHG) due to the fact that more than 50% of the electrical energy consumed in different countries is consumed in buildings. The sharp increase in demand should be addressed through an intelligent EMS, especially for residential loads, as the growth rate of household consumption is above average. In addition, according to the Paris Agreement, many countries have agreed to reduce their GHG emissions. Therefore, reducing pollutants is achievable by using RESs and EVs [50]. In addition to the benefits of distributed and renewable resources, the high penetration of these energy generation units in smart grids brings new challenges due to the uncertainty in their nature. Conventional EMSs are no longer effective due to new grid topology and different generation and consumption patterns combined by RESs and EVs. On this basis, it is vital to develop an optimal scheduling algorithm for integrating RES resources by considering geographic distribution and uncertainties [51]. The concept of VPP is one of the most practical solutions for energy management which enables new features by integrating communication networks in the energy system. The VPP facilitates the necessary interaction among all participants (energy producers and consumers), performs real-time monitoring through a bidirectional energy flow, and improves energy efficiency. This concept helps consumers to trade their surplus electrical energy in the market without the intervention of a third party.

On the other hand, consumers who have installed RESs or storage devices (such as batteries, EVs, etc.) can sell their excess power in the market. Consumers who do not have RESs can also participate in load shifting. Finally, VPP can assist energy management policies by optimal planning and enhancing the security level against physical cyber-attacks [52,53]. Building a centralized renewable-based power plant requires significant investment while transmission losses and other costs are still present, making the development of small-scale RESs widespread [54,55]. On the other hand, a comprehensive management solution is required to overcome the three main challenges of a renewable-based grid: high risk of market participation due to the uncertainties of RESs, energy pricing, and the complexity of energy trading. The VPP, MG, ADN, and load aggregators are four main concepts that have been used for energy management purposes in smart grids [56]. The VPPs do not face geographical restrictions based on operating conditions; rather, these power plants are suitable to supply consumers considering economic, technical, and security issues. In VPPs, the RESs also appear to determine the energy price (price maker). In addition, MGs and ADNs are limited according to the network topology, and only centralized control is accessible in this manner. Figure 4 shows the diagram of energy management approaches at different levels.

VPP is the only flexible alternative allowing the consumer to act simultaneously as a price maker and price taker. Accordingly, as an organized platform, the VPP can implement EMS to deal with the discussed challenges. The VPP activates an energy management mechanism and analyzes information collected from all power system components to control and coordinate supply and demand among all energy elements. Subsequently, an EMS aims to improve the load curve as much as possible and reduce costs for either providers or users. In fact, VPP is a suitable solution for EMS because of its particular features such as real-time monitoring, energy transfer controlling, and operational planning from the viewpoints of electricity producers and consumers, simultaneously. With the EMS of VPP, all consumers can benefit. In addition, power companies can reduce their operating, transmission, and maintenance costs and delay the need for new investments. It should be noted that EMS plays an important role in reducing GHG emissions since it leads to declining fossil fuel use and makes RESs more useful and affordable.

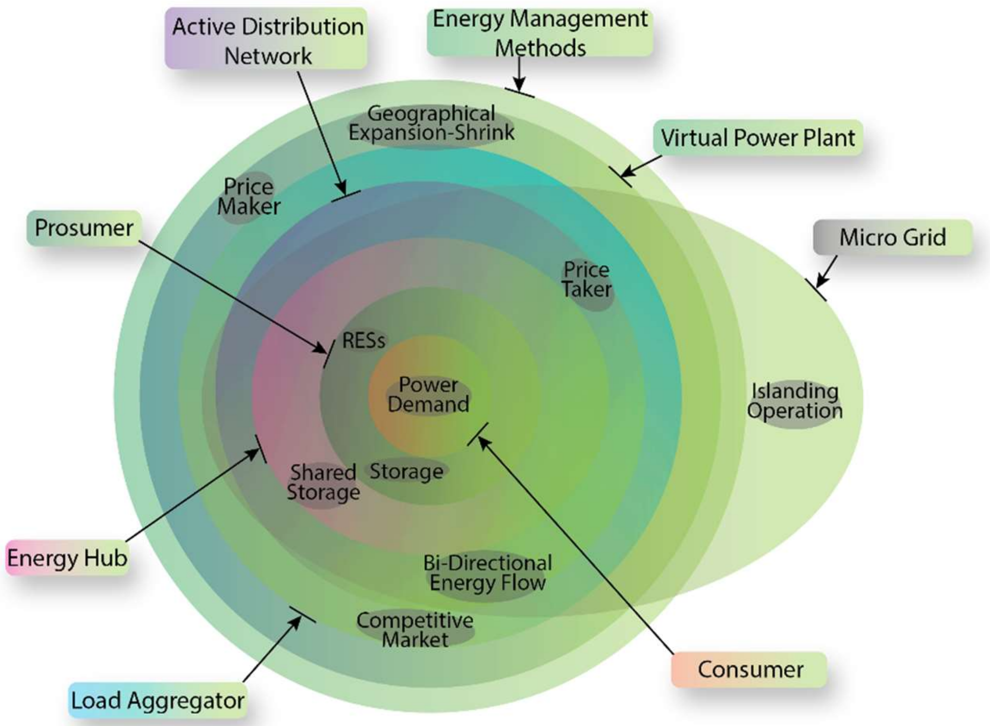


**Figure 4.** Energy management approaches.

## 5. Planning of VPPs in the Power System

Electric energy can be supplied in different ways, but consumers want it with the highest quality, lowest cost, and highest reliability. MGs and VPPs are two important solutions for reliable power supply in a power system. Since these structures include DERs, planning these resources is very important and should be considered [57]. MGs and VPPs share some important features, such as the ability to integrate DERs at the distribution level. These two platforms (MG and VPP) are active players in energy markets, but they have some differences [58,59]:

- MGs can be operated connected to or disconnected from the main grid, while VPPs can only operate in a grid-connected manner.
- MGs usually require some level of energy storage. However, the presence or absence of storage in VPPs is not very important.
- MGs depend on hardware changes such as inverters and smart switches, while VPPs heavily depend on smart metering and information technology.
- MGs include a fixed set of resources in a limited geographic area, while VPPs can combine a wide variety of resources in large geographic areas.
- MGs are usually traded in retail markets, while VPPs can also be traded in wholesale markets.
- MGs may face legal and political obstacles, while VPPs could be implemented based on the current structure and legal tariffs.

For the planning of VPPs in the power grid, EMS is needed. Figure 5 shows a VPP energy management system. According to Figure 5, EMS is associated with the electricity market, load/DER/price forecast, consumers, and distribution network. EMS also receives forecast information on energy resources, loads, consumers, etc., and creates its planning policies based on this information.

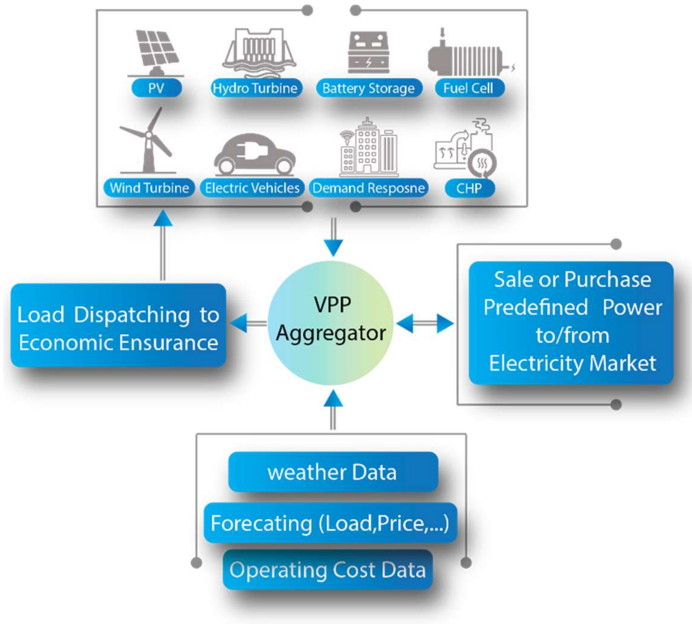


**Figure 5.** Intelligent management system of VPPs.

Table 2 has examined various modeling approaches for the planning goals of DERs in the context of VPP. The planning of VPPs is a multi-objective problem its goals are to maximize profit and, at the same time, minimize the cost of power generation, considering all the constraints. Two important aspects of VPP planning are technical and economic perspectives, as addressed in [60]. From the economic point of view, the operation of DERs must be done to minimize costs or maximize revenues considering the environmental aspects. From a technical point of view, all elements' physical constraints must be considered to ensure secure and reliable network operation. There are different methods for VPP planning, and we will evaluate three of them in this paper.

**Table 2.** Optimal planning methods in VPP.

| Reference | Solution Method | Description |
|---|---|---|
| [56] | MINLP | Presenting a new strategy for providing ancillary energy services |
| [57] | MILP | Maximizing profits and minimizing pollutant emissions in VPP |
| [58] | LP | Optimum scheduling of VPP with battery regardless of cost |
| [59] | MINLP | Planning industrial VPPs |
| [60] | LP | Linear programming of market optimization |
| [61] | MILP | Optimum planning of day-ahead markets |
| [62] | Mathematical programming | Optimal planning of VPP considering battery failure |
| [63] | Mathematical programming | Maximum profit in the market and reduction in pollution |
| [64] | Monte-Carlo | Optimum planning to increase profit by considering DR |
| [65] | MINLP | bi-level planning of VPPs |
| [66] | Scenario-based PSO optimization | Reserve planning and VPP energy |
| [67] | Point Estimation (PE) | Planning resources in the day-ahead market for VPP |
| [68] | Interval optimization | bi-level optimization of VPP |
| [69] | PSO | Multi-objective optimization stochastic programming for VPP |
| [70] | Combination of genetic and Monte Carlo algorithms | Planning VPP uncertainties |

### 5.1. Classical Method in Optimal Planning of VPPs

The Linear Programming (LP) method is the simplest classical mathematical optimization method that is applied when all objectives and constraints are linear or assumed to be linear because the real relationships may be very complex [61]. The IP and MILP are linear algorithms where all or some variables are integers. Based on the number of objectives and constraints, and type of variables, classical optimization methods in VPPs are formulated as follows [62]:

$$\text{objective function} = \begin{cases} \text{minPP},\ x_{n,t} \in \mathbb{R} \\ \text{minCC},\ R_t \in \mathbb{R} \\ \text{maxSS} \ \in N,\ x_{n,t} \in \mathbb{R} \end{cases} \tag{3}$$

$$\text{constraints} \ = \begin{cases} \sum x_{n,t} \leq L \ \forall t \ \in \mathcal{H},\ n \in \mathbb{Q} \\ \sum P_n \times \text{rate} \ \leq C \ \forall t \in \mathcal{H} \\ \sum \xi_{n,t} \times k \ \leq \theta \ \forall t \in \mathcal{H},\ k \in N \end{cases} \tag{4}$$

$$x_{n,t},\ P_n,\ \xi_{n,t} \geq 0 \tag{5}$$

In (3), the variables p, c, and s stand for power consumption, cost, and safety, respectively. x is a set of functions and n is the number of elements. Different time periods can be specified based on the nature of the problem. For example, $x_{n,t}$ means the electric power consumption of device n in the time period t. Variables L, C, and θ in Equation (4) represent the maximum power consumption in peak load, cost, and security limit, respectively. However, $\xi_{n,t}$ shows the security factor of device n at time t. k shows the priority of using any device. Equation (5) also shows the non-negative limits. The LP has been used in [63] to optimize the electricity market considering electricity price, renewable energy generation, and EV constraints.

The MILP is also used for a wide range of optimization problems. For instance, the planning of VPP and MG has been formulated in [64] by a MILP model. Moreover, developing a business framework [65] and modeling VPP considering battery failure cost [66], as well as profit maximization and GHG emission minimization [68], are a number of proposed models based on MILP. Mixed integer nonlinear programming (MINLP) is also used to solve nonlinear optimization problems. The MINLP model is used to develop a planning model for VPPs in order to aggregate RESs and controllable loads [69]. Mathematical programming is one of the most basic approaches to planning and operating VPPs. The allocation of limited resources is very important to achieve technical and economic goals.

### 5.2. Heuristic and Meta-Heuristic Methods in VPP Planning

Heuristic methods aim to achieve a specific result for a problem that balances the solution's accuracy and the computational cost by performing various tests. Although the final answer cannot be confirmed as the optimal solution in heuristic methods, the computational load is reduced compared to mathematical methods [69]. Meta-heuristic approaches are high-level procedures designed to solve various optimization problems without requiring specific knowledge about the problems and combine multiple heuristics to reach an optimal or near-optimal solution. The PEM, one of the heuristic methods, uses random samples to discover the estimated value of the population factors, as discussed in [70]. The interval optimization, in contrast to PEM has been used to optimize the operation of a VPP, including wind, PV, and storage systems [71].

The PSO algorithm has been used in [72] to schedule the operation of a VPP as a single objective optimization considering costs and GHG emissions. In this method, solutions are particles that move to the best location in a search region (taking the last position), where location refers to the optimal solution. When all the particles have been completely moved, it means that one iteration has been completed to find the optimal location.

The authors in [73] used a combination of genetic algorithm (GA) with Monte Carlo simulation for daily scheduling of VPP. Due to the uncertainties arising from the nature of

RESs, the stochastic formulation has been studied more than the deterministic formulation in the last few years since this method can estimate probability distributions.

*5.3. VPP Planning Methods Based on Learning*

Artificial intelligence and machine learning are interesting and attractive methods that are used in different branches of science because, unlike conventional optimization methods, significant expertise is not required to use these approaches [74]. Due to many information challenges in modern power systems, in addition to the complexity, speed, and computational load of conventional optimization methods, learning-based optimization approaches are widely used in scheduling and planning problems of VPP. Three main categories of machine learning methods, so-called supervised, unsupervised, and reinforcement learning (RL) can be formulated as optimization problems in the machine learning method. The objective of supervised learning is to minimize the loss function by finding the optimal mapping function f(x). Equation (6) shows the objective function of a supervised learning optimization problem, where N is the number of available samples, $x^n$ and $y^n$ are the feature vector and function of sample n, respectively. In addition, l represents the loss function [75].

$$\frac{\min}{a} \frac{1}{N} \sum_{n=1}^{N} l(y^n, f(x^n, a)) \tag{6}$$

Unsupervised learning usually uses dividing samples into multiple groups for clustering purposes and ensures that the difference between samples in a cluster is as small as possible. For example, the k means optimization algorithm is formulated, as shown in Equation (7) that minimizes the loss as the main objective function [76].

$$\min_{\beta} \frac{1}{N} \sum_{n=1}^{N} \sum_{x \in \beta_n} x - C_{n2}^2 \tag{7}$$

x is the feature vector of samples divided into N clusters. $C_{n2}^2$ and $\beta_n$ are the index of the center and sample of cluster n. The RL technique aims to find an optimal function that can control the output changes with any change in the environment and choose the best response for each given state. The RL optimization formula is shown in Equation (8).

$$RL = \begin{cases} \frac{\max}{\pi} V_\pi(s) \\ V_\pi(s) = E(\sum_{p=1}^{\infty} \alpha^p r_{t+p} \mid S_t = s) \end{cases} \tag{8}$$

In this equation, $\pi(s)$ and $V_\pi(s)$ are the value function and policy function of state S, respectively. Finally, a penalty coefficient is also defined so that a $\in$ [0, 1]. Table 3 summarizes the advantages and disadvantages of all the mentioned programming algorithms. In general, the components of RL are [77]:

- Policy determines how to deal with each action and how to make decisions in different situations.
- The reward function determines the goal of the learner function. The purpose of this function is to give a reward for each action of the agent so that the reward increases as the goal gets closer.
- The model of the RL problem is probabilistic and stochastic, and its states are non-deterministic. For one action, it can go to all states but with one probability.

Deep learning and RL have recently become popular in VPP operation planning optimization. Techniques based on deep learning, including CNN and RNN, have shown significant capabilities in feature extraction, approximation, and learning [78]. The RL is a subset of machine learning that provides a mathematical structure for experience-based learning to achieve optimal control of an MDP in which each agent interacts with the environment in a trial-and-error manner to learn optimally.

**Table 3.** Advantages and disadvantages of VPP scheduling algorithms.

| Algorithm | Advantages | Disadvantages |
|---|---|---|
| IP and LP | - Simplicity<br>- ease of use<br>- Place of reassessment<br>- Improving the quality of decision-making | - Inability to deal with uncertainties<br>- Necessary need for objective function and constraints |
| MILP | - Flexibility in model development<br>- Accurate modeling capability<br>- Convergence to the final solution | - Difficult to understand<br>- Hard implementation of the algorithm<br>- Slow solving speed—high cost for large-scale issues |
| PEM | - Low cost<br>- Proper accuracy<br>- Balance between speed and accuracy | - Low accuracy for multidimensional environments<br>- Recognizable pattern of restriction<br>- Weakness in handling samples with high distribution |
| PSO | - Easy implementation<br>- Parallel computing capability<br>- Fast and easy convergence<br>- Low computational cost | - Lack of a precise theoretical basis<br>- Instability in solving scattered problems<br>- Convergence to local optimality in complexity problems |
| Algorithms based on machine learning | - Fast and cheap generalization<br>- Data analysis<br>- Production and extraction of problem features | - High knowledge is needed for implementation |

## 6. Participation of VPPs in Electricity Markets

VPP can enable intelligent energy consumption in a distributed environment through optimal electricity generation and load management. This means that users produce and consume their own energy, which leads to the consumer's active participation in decision-making. In addition, VPP is a useful tool for renewable energy integration to ensure grid balance. These small-scale power plants better compensate for the possible generation and demand fluctuations. In addition, they reduce the prediction errors and the penalty of power fluctuations. The generation resources within the VPP have better access to the electricity markets because it is difficult for them to enter the market alone. Another important advantage of VPP is using the potential of EV management [79]. An important point in the electricity market is the pricing strategy. There are different methods in pricing strategy. Some pricing strategy methods are explained below [80–83].

- Penetration pricing or pricing to gain market share: Some power companies adopt this pricing policy to penetrate the market and gain a part of the market for a short period of time. These power companies offer some of their services for free or at a low price for selling energy for a limited period of several months.
- Economic price or no low-frill price: The pricing strategies of these products are considered as no low-frill prices where the cost of marketing a product is minimized. Economical pricing is determined for a certain period when the company does not spend more on advertising products and services.
- Using psychological pricing strategies: Psychological pricing strategies are an approach to elicit the consumer's emotional response rather than their logical response. For example, a company prices its product at $99 instead of $100. The product is priced at $100, making the customer feel that the product is not too expensive. For most consumers, price is a factor in whether or not to buy a product.

An important advantage of VPP is that it sells energy and increases its profits when accessing wholesale and retail markets on behalf of DER owners. In this section, we examine the performance of VPP in different electricity markets. The aim of this section is to examine the characteristics and performance of VPP in different markets.

### *6.1. Bilateral Contracts*

In electricity markets, bilateral contracts could be used to directly trade power between the buyer and seller. The energy price, the amount of power, and the contract's validity period are agreed upon in this contract.

The growth of RESs in recent years has strengthened this type of contract that avoids price uncertainty, and thus, ensures price stability in the long term. This contract offers a strong opportunity to guarantee VPP income due to market price fluctuations and possible limitations of the transmission system operator [84].

### *6.2. VPP in the Day-Ahead Market*

The day-ahead market is designed to carry out power transactions on an hourly basis for the next day through market agents' buying and selling offers [85]. The VPP allows power producers to access the electricity markets to sell their generated power directly. Moreover, it allows consumers to produce their energy and sell their surplus in the market. When the price in the market is high, the strategy of VPP is to produce with its maximum capacity and sell its excess power at a higher price in the market. Many papers have used this feature of VPP in futures markets [86,87]. The VPPs usually act as price takers in the electricity markets [88,89]. However, they act as price makers due to the wide use of DERs in the structure of VPPs.

### *6.3. VPP in the Ancillary Services Market*

This market aims to increase the reliability and security of the power grid. This market provides a balance between generation and consumption at each moment. From the technical point of view, the gradual growth of RESs in current power systems can weaken the system's performance in terms of stability and worst case, lead to power system collapse. Therefore, the authors in [90,91] have included the possibility of frequency control through VPP to guarantee power quality and system security.

### *6.4. VPP in the Reserve Market*

The reserve market is a mechanism that ensures system security. Usually, producers who submit their offers for this market are subjected to incentive programs. A Reserve market is necessary for locations where RESs exist to enhance grid reliability and security. Based on the obtained results, reserve markets are highly important when the network demand is maximum. Furthermore, when DERs generate at their full capacity, VPP can sell the excess power in the day-ahead market or charge the energy storage devices so that they can participate in the reserve market [92]. Table 4 summarizes the different characteristics of the markets mentioned above.

### *6.5. Virtual Powerhouse in Daily Markets*

Intra-day markets are designed to regulate the energy traded in the day-ahead market more precisely because there is more information than the mechanism of the day-ahead market. A smaller volume of power and energy is traded in this market compared to the day-ahead market. Intra-day markets have become more important due to the increase in RESs and their unpredictable nature. This market can also be very useful for the agents participating in it. For example, suppose a power generator fails for any reason and cannot generate power. In this case, the owners of the resources can repurchase the energy they sold in the day-ahead market mechanism in the intra-day market [93].

**Table 4.** The main characteristics of market types.

| Reference | Market Type | Characteristics |
|---|---|---|
| [87,88] | Day-ahead | Offer to buy and sell energy for every hour of the next day<br>Increasing the flexibility of the power system—high operating profit |
| [90,91] | Ancillary services market | Increasing security and reliability of power generation and transmission—the balance of generation and demand at any time |
| [94] | Reserve market | Management of excess power generation to ensure supply of demand and security of power supply |
| [95] | Daily market | - Adjusting the price of energy trading in the future market—reducing the cost of supply and demand imbalance |
| [96] | Real-time market | - Management of power fluctuations between supply and demand and network security |

### *6.6. VPP in Real-Time Market*

The real-time market is the last chance to balance supply and demand. This market usually operates between 5 to 30 min and closes the market during this period. In other words, in this market, the time to provide electric power services is between 5 to 30 min and the electric power is provided according to the required demands. Although the intra-day markets allow the VPP to adjust its scheduled energy after the day-ahead market, it is still possible that the VPP could not be able to supply the required power of consumers at the power delivery time. Therefore, the real-time market compensates for the lack of power supply. Figure 6 shows different steps for market mechanisms.

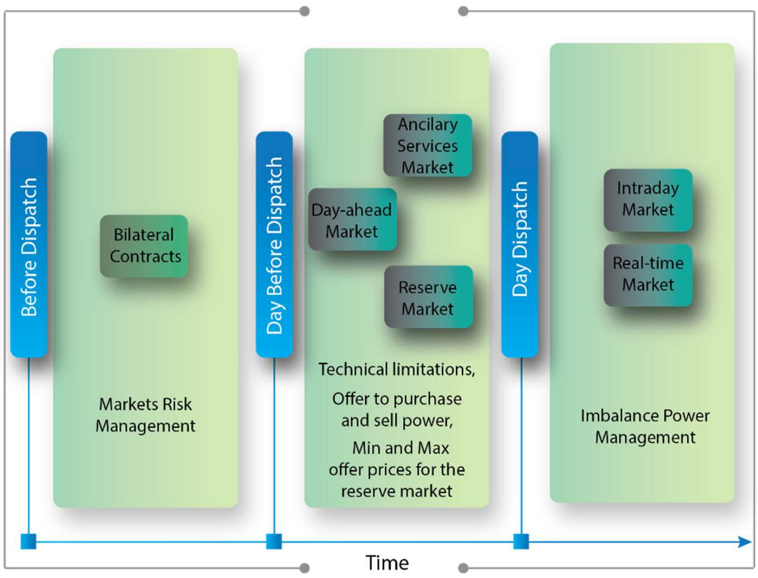


**Figure 6.** Stages of various energy markets.

## 7. Challenges of Using VPPs

VPP enables each DER unit to participate in power system operation and wholesale markets. However, several challenges in resource operation, control, communication technologies, and power transactions within VPP need to be addressed. Therefore, in this section, the challenges of VPP in the power system are investigated.

### 7.1. Challenges of Control and Operation System

Due to different adjustment factors, range, and stable time of the energy resources within VPP, the actual control results cannot be exactly what is expected. In order to accurately control DERs in VPP and obtain detailed information about the operation of these resources, it is essential to provide a variety of ancillary services in multiple time frames that need some requirements and control elements. Therefore, the system cannot be controlled by a unique method. The control system needs to use different features of DERs and interacts with the power grid. Therefore, using different algorithms to control each element (resource) in VPP may negatively affect other resources, and the desired results may not be achieved [97].

### 7.2. Communication and Information Challenges of VPPs

Based on modern smart technologies, 4G/5G wireless networks, and other technologies, such as information compression, communication, intelligent computing, measurement, and control technologies, more advanced platforms supporting VPP can be developed. In general, for communication and telecommunication information exchange, the presence of four security and communication layers could be included in VPP. Figure 7 shows the basic layers of the communication mechanism in VPP. The communication layer is the basic infrastructure for the integration of DERs in VPP. The communication technologies and hardware outputs ensure the access of the power system to the VPP resources. The performance layer in VPP is a module that considers all basic functions and components, including load forecasting, information monitoring, risk assessment, etc. Another layer of VPP is the service layer. This layer is developed based on the performance layer and the decisions made by that layer. It complements the functions of the VPP suite by coordinating the elements of the function layer. This service can include auxiliary services such as peak load reduction, energy arbitrage, DR, market trading, etc. The service layer modifies these things and cannot limit them.

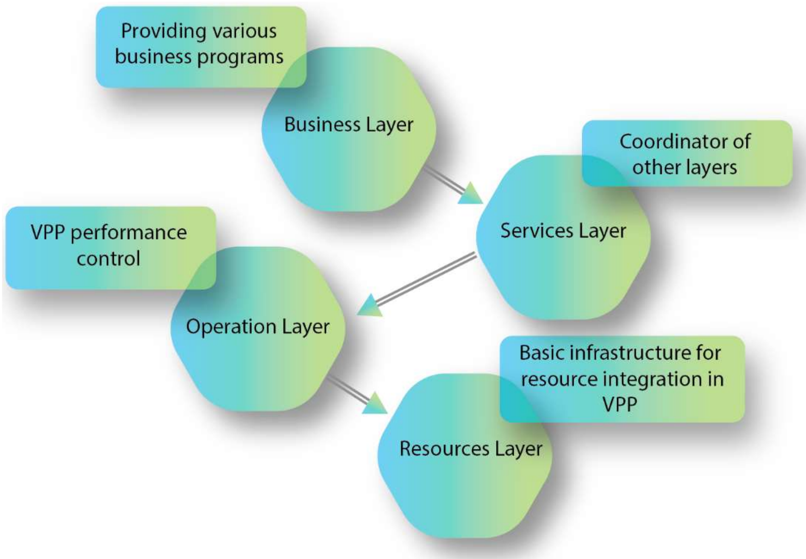


**Figure 7.** Communication mechanism for different layers of VPP.

Another important layer in intelligent communication with VPP is the business layer. The business layer can provide various business programs for consumers in VPP, such as energy generation management, generation safety management, electricity market transactions, optimal energy utilization, optimal energy resource integration services, etc. In addition, it provides a smart web page and mobile app for VPP users.

A new concept of IoT in the VPP is presented in [96]. The main goal of providing the IoT in VPP is the intelligent control of power transmission in high voltage lines at a low cost. Although smart devices have been used in the telecommunication and communication structure of VPP; however, the main thing in using these devices is security checks. Therefore, it is necessary to use the latest technologies to enhance the security of VPP.

### 7.3. Power Exchange Challenges

One of the basic challenges of VPP is related to the uncertainty of DERs. On this basis, the power balance should be met in the VPP. Therefore, power exchanges in VPPs with more wind turbines and photovoltaic resources may create serious challenges for the grid-connected mode. In other words, due to the uncertainty in the output power of WT and PV resources, the best idea is to trade in the electricity market using the potential of these resources or to have large batteries in the VPP structure. The most important challenge of VPPs is the uncertainty that was fully examined in the previous sections. However, other issues such as maintenance, resource failure, and resource lifetime can also be other important challenges for the energy exchange issue. It is very important to consider this issue in order to increase reliability, as well as to supply the critical and large loads that are connected to VPP.

### 7.4. Blockchain Applications in VPPs

Blockchain is basically an online ledger that securely stores information and makes it available to everyone as an immutable source of information. This technology is not controlled by one particular entity but is distributed among many computers and uses a specific and secure format to record data so that other people cannot change or tamper with the information. Using methods such as data decentralization and protecting them against manipulation has facilitated transparency and information exchange in the blockchain. Thus, this particular data recording method has provided a great capacity to shape the new wave of technology and the ability to interact with it. Many start-up companies are trying to use blockchain as a tool to develop accessible and sustainable energy networks by developing instant information-sharing methods. The idea behind the creation of blockchain-based energy networks is relatively simple. As long as consumers have complete control over how to supply their consumed energy and complete information based on how it is produced, effective competition and sustainable energy development will be possible [98,99]. Using a blockchain-based smart grid, consumers will be able to compare their energy suppliers better and purchase directly from them. In Estonia, a blockchain-based smart grid called WePower has been piloted, which is actually a kind of customer-choice energy market that operates based on data provided by a set of energy generators. With the help of how to manage this program, consumers can enjoy more freedom of action in choosing their energy supply source (according to the exact requirements of instantaneous production and its price). Decentralization of energy systems will help the process of democratizing information and empower people to make better decisions. Blockchain-based smart grids, as a powerful tool, can reduce inequality and provide cheaper and cleaner energy in all areas (both developed power grids and energy-deprived areas) [100]. Therefore, blockchain can be one of the most important solutions to reduce carbon emissions in the long term and contribute to sustainable development worldwide.

The growth of the use of VPP in recent years is due to the need for higher reliability, lower cost, and participation of small generators in the electricity market. In the previous section, the challenges of using VPPs were explained. The most important challenge is assigned to communication and telecommunication issues within VPP. The idea in this paper to improve this case is to use blockchain in a decentralized manner. In other words, a decentralized blockchain-based communication solution should be provided for each DER. Today, the exploitation of VPP requires coordination among the different small-scale generation units. Blockchain is one of the most important topics related to every source in VPP.

Blockchain technology can be a suitable method to ensure transparency between integrated DERs in the VPP. The basic concept of blockchain is to improve information transparency between interacting parties [101]. In the electric energy sector, blockchain technology has played an essential role in solving communication challenges in the context of VPP and improving the efficiency of current energy control processes. There are various sets of papers regarding utilizing blockchain in power systems for a wide range of applications such as peer-to-peer (P2P) energy trading, electrical dynamics, network operation and management, monitoring of RESs, and demand response.

When VPP operators apply a control command to each DER, this control command is completely recorded in the blockchain. The recorded data in the blockchain are the traded power, the time intervals, fluctuations, and all other information related to the contract between DER and VPP. Finally, after the end of the event and the control command, the smart contract that has been set up is published, and based on the recorded data in the blockchain, payment is made to the DER owners [102].

Three types of transactions are provided in blockchain for energy management. The first type of blockchain transaction for VPP is network services, which include Feed-in tariffs (FIT) information or guaranteed electricity purchase policy, information related to ancillary services, and information related to the demand response. The FIT service allows VPP users to sell their generated energy to the grid and receive a guaranteed tariff for their electricity production. The FIT service is the fee that the owners of electricity generators (solar and wind) receive for selling their electricity to the main grid. This cost is in addition to the cost of power sales and is considered an incentive to encourage these owners to sell their generated power to the government or large private sectors. Note that the amount paid as FIT varies between different retailers. This type of transaction provided by blockchain is between VPP users and the network.

Another type of transaction that blockchain has provided is the P2P strategy that is between VPP users. This strategy allows the VPP user to communicate with each other and buy/sell energy directly. The third type is the token-based transaction since the blockchain offers the token as a digital currency to facilitate online payment [103].

There are many potential applications for blockchain technology in the energy field, and most of them target P2P energy trading. However, in power systems, the performance of both sides may be different, and this difference is also due to the presence of EVs or prosumers. Other applications of blockchain in the electrical energy sector can be classified into the following two categories:

- Exchange of electrical energy
- Effectiveness in responding to the load and checking RESs

The first category includes all the programs that two different users do in order to exchange power. The P2P strategy is included in this category. These transactions can be managed centrally under the supervision of the network operator (TSO or DSO) to obtain the maximum benefit for both network and users. The second category includes renewable and loads response units. The reference [104] has investigated the connection between VPP and MG using blockchain. This reference stated that blockchain could be useful in the connection between the MG and the VPP. The authors in [105] also presented the blockchain application of a distributed algorithm. The blockchain energy exchange plan among VPP users has been addressed in [106].

## 8. Conclusions and Future Directions

This paper presented a relatively comprehensive review of the VPP concept. The paper mainly discussed existing definitions, general components, basic challenges, operational planning methods, market participation, energy management tools, and energy transactions in the context of VPP. As a novel aspect, the paper has concentrated on blockchain applications in VPP. In this paper, various uncertainties of VPP, including load, renewable generation, and market price uncertainty, were fully investigated. The energy management of VPP is another important topic in this review paper. This paper explains that each VPP allows the resources within its structure to exchange freely with the energy markets. Classical and heuristic methods were also investigated to optimize VPP operation in the power system. Moreover, different markets were discussed, and the impacts of these markets on VPP have been evaluated. The last part of the review paper is about the challenges of VPP. Communication challenges are among the basic challenges in VPPs. Another challenge is system control and operation, which must be solved using different algorithms to facilitate coordination between VPP control and operation. Despite examining the advantages and disadvantages of VPP, there are still fundamental challenges to the wide use of VPP, so appropriate infrastructures and solutions must be provided. Therefore, the following suggestions can be made for future research.

- To use neural networks for VPP in the electricity markets and the overall modeling of these power plants in the power system.
- To propose novel control methods in the context of VPP.
- To present an appropriate protection scheme for VPP.

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## Abbreviations

| | |
|---|---|
| ADN | Active Distribution Network |
| CNN | Convolutional Neural Network |
| DR | Demand Response |
| DERs | Distributed Energy Resources |
| DG | Distributed Generation |
| DSO | Distribution System Operator |
| EV | Electric Vehicle |
| EIA | Energy Information Administration |
| EMS | Energy Management System |
| EN | Energy Nodes |
| FIT | Feed-In Tariff |
| IP | Integer Programming |
| IoT | Internet of Things |
| LP | Linear Programming |
| MDP | Markov Decision Process |
| MF | Membership Function |
| MG | Micro-grid |
| MINLP | Mixed Integer Non-Linear Programming |
| PSO | Particle Swarm Optimization |
| PV | Photovoltaic |
| PEM | Point-estimate Method |
| PDF | Probability Distribution Function |
| RL | Reinforcement Learning |
| RES | Renewable Energy Source |
| RNN | Recurrent Neural Networks |
| TSO | Transmission System Operator |
| VPP | Virtual Power Plant |
| WT | Wind Turbine |

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