The Concept, Project and Current Status of Virtual Power Plant: A Review

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Abstract. Due to technological advancements in recent years, distributed energy resources (DER) applications have become more prevalent in households and businesses, including various renewable energy applications. While the virtual power plant (VPP) can integrate energy storage, flexible loads and DER, etc., it can support the power grid operating stability and security. Therefore, more and more researchers give their attention to VPP and advise on their optimization. This paper states the VPP concept from other researchers' studies and provides a detailed explanation. Meanwhile, some typical VPP projects worldwide are also presented. In addition, some potential challenges and future development advice in the VPP studies are also presented.

Keywords: Virtual power plant, distributed energy resources, renewable energy, smart grid, energy storage facilities

1. Introduction
Nowadays, technology development is changing rapidly, and people's lives are becoming richer and richer, with various technological products applied to life scenarios, such as the internet of things, smart homes, etc. Under that situation, the energy demand is increasing throughout society. Electricity is critical to global economic progress and human well-being. Electricity demand has continued to expand over the previous decade, putting more strain on power networks and the global environment. Additionally, several nations have committed to presenting annual glasshouse gas reduction goals under the Paris agreement [1], which makes distributed energy resources (DERs) vital.

DER is attracting more attention from governments worldwide due to its enormous resource potential, low environmental impact, and long-term viability. Renewable energy development and utilization have been a critical component of many countries' energy strategies in recent years. The application of DER is also being vigorously developed with the support of national governments, and a wide range of renewable energy generation equipment, both household and business, are being deployed around the world. At the same time, how to efficiently use these renewable energy sources has got researchers' attention.

The distributed power generation technology represented by DERs has gained wide attention and rapid development because of its many reliability, economic, and flexibility advantages. The evolution of energy resources demonstrates a tendency towards clean and decentralized energy conversion [2,3].

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However, because distributed energy is stochastic, intermittent, and fluctuating, it creates issues to the grid's stability and reliability, such as tide changes, line congestion, voltage flicker, and harmonic impacts. Due to immature technology and expensive costs, economic issues also plague current grid-connected generation projects [4].

During the early years of the power system, conventional power generation was the primary component. Some conventional generating has been steadily phased out in recent years, driven by the energy shift. DER is gradually assisting the power grid and participating in the electricity market. If a large number of randomly DERs and high capacity loads are incorporated into the grid, and those DERs are controllable, therefore, the function of those DERs will be comparable to traditional generation or power plants. Additionally, some other technology like the microgrid has the same function, which can be used for distributed storage, load integration, and storage. However, microgrids are constrained geographically and in terms of size in both electricity systems and markets. As a result, the VPP concept has emerged.

The VPP is widely regarded as one of the most practical and potential power management solutions, allowing for unique functionality through the integration of embedded technologies and communication networks into power systems. Through a two-way energy flow, VPP enables tight collaboration and interaction amongst participants while also providing real-time monitoring and energy conservation. Without the participation of a third party, this strategy enables consumers to trade extra electricity on the market at the desired price. On the one hand, producers that install small DERs can sell excess energy to the market because the scheduling algorithm maximizes their surplus energy. On the other hand, customers without DERs or storage can participate through load shifting, peak shaving, and valley filling. Finally, VPP can help to strengthen network security by optimizing operational scheduling to ensure compliance with energy management regulations [5,6].

The following is the structure of this paper. Section 2 introduces the concept of VPP briefly. Section 3 describes some typical VPP initiatives from throughout the world and provides a brief overview. Section 4 discusses some potential issues with existing VPP research and gives some suggestions for future VPP. Finally, the conclusion is given. In addition, the year of publication was also considered in selecting references for this review, most articles published in the last decade. Figure 1 shows the number of publications and citations rapidly increased in the previous five years, indicating the interests and importance in the VPP field.

Figure 1. Paper publications and citations over the last decade
2. The main concept of the VPP
Awerbuch and Preston introduced the concept of VPP in 1997, although it lacks a clear definition [7]. Recently, with the rapid development of VPP, numerous definitions of VPPs have been given in the literature from a variety of angles, with DERs used for energy management being a mainstream choice. Some studies emphasize commercial and marketing considerations, while others emphasize technological perspectives such as IoE, energy management systems (EMS), aggregation of DER, autonomous microgrids, and information and communication systems (ICT) [7-13]. Research has found that VPP is characterized as a trading platform for DERs used in wholesale marketplaces for contracts [14]. In another study, VPPs operate as aggregators of DERs, synthesizing the network's impact on the output of DERs [15]. Likewise, VPPs are defined as information and communication systems that manage DERs, variable loads, and storage [13]. Also, a VPP is a cluster of power plants comprised of aggregated DERs, controlled loads, and storage units, with the EMS serving as the system's brain [10]. Meanwhile, VPP is the collection of numerous DERs dispersed across the distribution network's voltage levels [16].

The following paragraph summarizes the description of VPP in the paper, and Figure 2 depicts the fundamental configuration of a VPP. VPP is defined in this paper as "a cloud-based platform that connects DERs, flexible loads, and storage facilities in order to provide real-time monitoring via a two-way communication network, to establish a distributed and decentralized power plant for improved energy management, and to facilitate cross-system trading." VPP is among the most cutting-edge and new energy management approaches in the power system, allowing optimal energy trade through the use of intelligent tools and equipment [18]. As shown in Figure 2, the communication layer is in charge of data exchange between the VPP layers, such as generation, consumption, charging status, and transmission information. The network infrastructure, which consists of various DERs, flexible loads, storage facilities, and electric vehicles, transmits pricing suggestions to the decision centre and receives action signals to govern energy flow. Depending on the decision layer's action signals, including technical, economic, and processing sublayers, the surplus energy from the infrastructure layer can be traded on the internal market or external market. Meanwhile, in order to regulatory compliance, the external market and decision layers have to give the load estimations and bidding strategies to the independent power system operator (IPSO) [19].

![Figure 2. The basic layout of a VPP](image-url)
2.1. Classifications of VPP

A VPP is a scalable entity that is not constrained by distance, capacity, or resource type. It is connected via a collaborative system called the internet of energy (IoE), which is composed of multiple layers, including information and communication technologies (ICTs) and advanced metering infrastructures (AMIs). Commercial VPPs (CVPPs) and technical VPPs (TVPPs) are the two primary types of VPPs [17].

2.1.1. TVPP. TVPP is focusing on economic profitability and performance of the power system. In TVPP, the aggregator provides all relevant and accurate data about each DER unit's generation and future generation statistics. In TVPP management, the aggregator requires all information about the resulting power distribution and forecasting algorithms. For distribution system operators (DSOs), TVPP services and functions include local system management; for transmission system operators (TSOs), TVPP services and functions include system balancing and auxiliary services (TSO). TVPP not only monitors the status of various loads continuously but also provides statistics-based asset management. In addition, it can provide information about the location of a fault and assist in the recovery process following a failure. Additionally, it is capable of statistical analysis and portfolio optimization [4,20]. Sometimes TVPP provides local control and fast metering services for frequency support, including the control of battery systems and inverters.

2.1.2. CVPP. In commercial VPP (CVPP), aggregators start negotiating with the electricity market regulator for a fair price for their electricity production. CVPP is mostly based on economic rules to find the best deal among the different aggregators available. CVPP provides commercial aggregation in a network-agnostic manner. It provides visibility and value to the numerous DER entities operating in the energy market. Its purpose is to submit offers and quotes to the wholesale energy market while balancing its trading portfolio.

In comparison to isolated DER units, it mitigates capacity imbalances by the integration of numerous small-scale units. CVPP is not geographically constrained and can cover the rural areas far from the transmission grid and distributed networks. CVPPs also feature demand management during interruptions [4,20]. CVPPs also handle demand and generation forecasting, DER characterization, and submission of bids and generation plans to the market to achieve profit maximization.

2.2. Function and layout of VPP

The basic user schematic for VPP is depicted in Figure 3. The energy management system (EMS) is the central component of the VPP and serves as the brain of the system. The VPP sub-centres or sub-EMS, which include renewable energy and production users, are all connected to the central energy management system and regulated via a bidirectional information flow. This means that each sub-EMS collects and transmits data on the total number of distributed and connected energy resources, energy generation capacity, and energy demand, and then communicates this data with the central EMS [24,25]. By processing all the data from the local EMS, the central EMS determines the optimal operation of the VPP [10]. The sub-ems know the behaviour of each component connected to it and ensure the proper operation of the unit. It can be programmed to provide optimal results to minimize the cost of electricity and consider consumer preferences. The EMS needs to receive accurate data from the generating unit to the customer side [26]. The communication network should be fast and robust to send and receive information in real-time. The EMS should also maintain backup control and operation strategies in case of any communication network failure. In addition, it should be capable of covering new devices and expanding its network.
2.3. User Composition of VPP

As shown in Figure 3, Users can be classified into three types according to the size of the residual energy produced [27].

Standalone user: This kind of user meets the basic standards for energy generation and qualifies as a prosumer; but, it lacks the energy necessary to trade. It is incapable of purchasing or selling energy to other producers [27,28].

Energy purchasing user: This kind of user does not fulfill the basic standards for prosumer status; it requires additional energy. This user can transmit requests for energy purchases to nearby prosumers, thereby meeting the maximum demand for energy sales [27,28].

![Figure 3. Basic schematic of a VPP [21-24]](image)

![Figure 4. Three types of users in VPP](image)
Energy Selling user: This kind of user has excess energy accessible for trading and meets all of the standards for selling energy. It is not permitted to purchase energy from other producers; but, it may decline any request to sell energy to a neighbouring consumer, so operating as an independent producer [27,28].

3. Current status and typical projects
VPP is fast gaining traction as a critical necessity in the energy field. Due to significant improvements in power system durability and resilience, particularly in terms of peak demand response, VPPs have been widely embraced by utilities, aggregators, and the information and communication technology industry in recent years. From 2020 to 2027, the vpp market is predicted to increase at a compound annual growth rate (CAGR) of 21.3 per cent, from USD 1.3 billion in 2019 to USD 5.9 billion in 2027 [29]. The global VPP market is predicted to reach $1,187.5 million in value by 2023, and VPP is becoming an increasingly critical requirement for the industry, which will continue in the future [29]. In the United States, VPP handles the supply and demand-side challenges through DER and other load shifting frameworks, ensuring the effectiveness of power system operations in real-world scenarios.

Continental Europe is also changing its network to include more advanced capabilities and opportunities for new supply chains connected to innovative new market segments and energy transactions to maximize the value of scalable assets. The European Demand Response Center (EDRC) launched operations in March 2011 to assist, develop, and evaluate new revenue streams and technology for VPP systems. From the Australian perspective, the government is achieving its goal of establishing a large VPP program. This section will list some typical VPP projects worldwide, and some detailed data is shown in Table 1.

### Table 1. Typical VPP project in the world

| Name            | Start time | Country                  | Type of DERs                      | DER units       | Consumers | Capacity |
|-----------------|------------|--------------------------|-----------------------------------|-----------------|-----------|----------|
| FENIX           | 2005       | UK, Spain, France, etc.   | μ-CHP, PV, Wind Power             | 1000–1,000,000  | 169,000   | –        |
| EDISON          | 2011       | Denmark                  | EV                                | 52              | 27,000    | 125 MW   |
| WEB 2 ENERGY    | 2009       | Germany, Poland, etc.     | CHP, PV, Wind, Biogas, Hydropower | 16              | 200       | 40.5MW   |
| SA VPP          | 2017       | Australia                | PV, Battery Storage               | 1000            | 50,000    | 250MW    |
| CON EDISON VPP  | 2016       | USA                      | PV, Battery Storage               | 1000            | 300       | 100-300MW |

3.1. **FENIX**
This project is a joint European project sponsored in part by the European Commission's Sixth Research Framework Programme. It involves twenty partners and has a budget of 14.7 million euros. FENIX's purpose is to integrate DER costs efficiently into grid operation and development, focusing
on northern and southern applications [30]. The northern case study is based on an existing private
distribution network in Woking. It integrates approximately 4.3 megawatts of DER, 2.5 megawatts of
flexible DERs, and combined heat and power (CHP) with gas engines capable of rapid ramp-up and
ramp-down [29]. The Southern case study incorporates various technologies (CHP, wind, and so on)
based on existing Alava units. The southern region's total installed capacity is 150 MW, with around
half of that capacity being flexible.

3.2. EDISON
The EDISON project's objective is to use aggregators of electric vehicles (EVs), including plug-in
hybrid EVs, to provide the necessary balance of power to enhance wind energy's utilization on the
Danish grid [31]. Due to the intermittent and stochastic nature of DERs, EVs contribute to the grid's
health by charging and feeding back in a controlled fashion. EDISON can provide time-coupled
metering and billing systems that allow EV owners to benefit from their electricity bill, rewarding
owners to engage in the project [29]. This project was created to illustrate the ease with which electric
vehicles may be charged and discharged. If the VPP system is managed wisely, it will benefit EV
owners, the grid, and society as a whole. Edison began by focusing on intelligent charging. The time
delay associated with charging an electric car battery depends on a proper and standardized
information communication technology (ICT) architecture that considers factors such as energy costs,
grid limits, and renewable energy availability.

3.3. Web2Energy
The Web2Energy project's objective is to develop and validate the three pillars of "Smart Power
Distribution," smart metering, smart energy management, and smart distribution automation [32]. The
Web2Energy project approved the implementation of all three pillars of smart distribution in the HSE
AG's 20/0.4 kV network in Darmstadt, which is equipped with remote monitoring of nine x 20/0.4 kV
transformer terminals located across the network. In one-year demand-side response research, the
project brings together five combined heat and power plants, twelve batteries, twelve photovoltaic
plants, three wind farms, two hydroelectric plants, three big controlled loads, and 200 extra households
customers.

3.4. SA VPP
Beginning in 2019, Australia conducted a VPP demonstration in collaboration with the Australian
Energy Market Commission (AEMC), the Australian Renewable Energy Agency (ARENA), the
Australian Energy Market Operator (AEMO), and the Australian Energy Regulator (AER). The
demonstration examined the functionality and efficacy of VPPs in various ways, and it is expected that
by 2022, the total installed capacity of VPPs will reach 700 MW [33]. In addition, the largest VPP
project to date is being developed in South Australia, with Tesla Inc. The Asia-Pacific VPP market is
expected to grow at a compound annual growth rate of 25.54% from 2019 to 2028. The growth of
cities, increase in energy consumption, and favourable government spending is attributed to the
region's demand development.

3.5. ConEdison
The purpose of the ConEdison VPP is to test and validate the business case for integrating an
aggregated fleet of residential solar-plus-storage systems into the grid [29]. Hundreds of solar and
battery storage systems will be aggregated into a single VPP system installed behind the meter in the
customer's home. The project is controlled autonomously through intelligent software provided by
SunPower and Sunverge and can simulate a single, larger generation facility. The project is expected
to cost a total of $15 million over the next few years [29].
4. Potential challenges and future development

4.1. Potential challenges
As the sections mentioned above, the implementation of VPP does bring lots of benefits. It enables each DER unit to participate in the power system; however, numerous studies indicate significant obstacles: scheduling algorithms, technical and economic limitations, and uncertainty factors.

First and foremost, VPP is in charge of energy management, which includes multi-objective optimal resource scheduling that takes into consideration the runtime of major energy consumers. Numerous solutions have been developed too far for overcoming the difficulties associated with optimal scheduling problems in VPPs. However, researchers have mostly overlooked approaches that are based on learning. They took into account the complexity of smart grids and the massive amount of data generated across the system. Traditional strategies are insufficient to manage escalating issues. Machine learning-based approaches take advantage of generalization to sidestep the problems that other systems have in dealing with a lack of data characteristics and retrieving valuable information. These tactics not only improve accuracy based on prior experience but also uncover patterns and trends. Learning-based optimization algorithms achieve rapid convergence to approximation model solutions, resulting in strategies that are simple and low-effort. Additionally, deep learning-based systems are more scalable, which is critical for scheduling large-scale VPPs.

Meanwhile, there are significant technological and economic constraints on developing scheduling algorithms for VPPs, and the majority of published research on VPPs considers only one of these variables simultaneously. Only a few studies consider technological and economic restrictions, and no single approach takes into account all concurrent constraints. Only one method was tried for a specific situation in a small number of small systems. Additionally, network-related constraints such as the size of the network, the sort of infrastructure and time zone are ignored.

Lastly, uncertainty factors are divided into renewable energy resources, market and price, and power demand. Renewable energy sources produce significantly variable production depending on temperature and weather conditions, which means they are not always available during the peak demand periods and hence are associated with uncertainty. Uncertainty has a significant effect on wind and solar, and forecasting errors will increase. Volatility in prices and markets is a result of variable fuel, tool, and equipment prices, labour and maintenance costs, and weather conditions. These characteristics vary significantly by date of use, political issues, and global and local economics. And the unpredictability of load demand is intrinsically tied to weather conditions, peak times, etc. Along with permanent batteries, portable batteries, and electric cars, the popularity of small solar systems adds to the uncertainty surrounding demand.

4.2. Future development
To promote energy trading in a larger electrical market, the existing VPP aggregates the capacity of multiple diverse DERs and flexible loads and generates a centralized monitoring entity by combining the characteristics of each participant. On the other hand, the future VPP model incorporates a distributed control environment that enables a decentralized system to operate somewhat autonomously across all interconnected networks. Additionally, it aspires to include intelligent technology and self-control via artificial intelligence. The existing VPP makes use of a cloud-based platform for centrally integrating operational facility data. In the future VPP, local edge devices can be integrated into each DER and load side, connected to a central platform, and provide better response. Current VPP energy estimates are based on tariffs and load demand, which is complex and hard. Meanwhile, they utilize established intermediary energy trading methods to connect the wholesale and token markets. As a result, future VPPs are projected to benefit from blockchain-based smart contract market solutions that facilitate energy trading and forecasting. The present VPP project employs a conventional demand response strategy based on price and incentives. As a result, demand response based on reinforcement learning can be applied to generation and consumer compensation [34]. Smart metering technologies have the potential to improve VPP's active and reactive power control.
dramatically. VPP in the future is projected to incorporate more advanced and new technology and to be more cost-effective.

Nevertheless, the creation of next-generation VPP will necessitate the fulfilment of a number of conditions, including those associated with the present VPP. These essentials are required for the integration and maintenance of new technologies. The framework for future VPPs must be more robust, based on the IEC 61850 standard's communication protocols, and include capabilities such as reporting schemes, data transfer and storage, and commands [34]. Appropriate solutions must be investigated to ensure that the next generation VPP is resilient enough to deal with voltage and frequency stability problems in the event of a disaster. Moreover, improved and continuous power management must be provided. Concerns regarding renewable energy's environmental impact persist. Carbon emissions must be regulated through emissions trading schemes. Also, the attack surface of the existing VPP is enormous due to the fact that it consists of multiple layers. As a result, cyber security must be strengthened to prevent attacks, and severe regulatory requirements for the future VPP must be developed. VPP programmes are still needed to be established to guarantee that enough benefits are provided to customers, suppliers, and governments. To assure value proposition, more effective and profitable business models must be adopted. The capacity to operate under specific conditions and within a specified time period is constrained. As a result, it is necessary to maintain greater reliability and availability in order to avoid maintenance failures.

In conclusion, the future VPP will require an urgent entity that takes into account various evolving technological aspects, particularly those that will be implemented in power and communication systems, in order to overcome the shortcomings of the existing VPP from various technological and management perspectives. The future intelligence that could be deployed in the future VPP involves a variety of advancements in artificial intelligence control over the aggregation of heterogeneous DER and consumers. Additionally, it possesses numerous innovative technologies that facilitate the exchange of energy between consumers and aggregators and considerably increase energy production, transmission, distribution, and management.

5. Conclusion
The transmission, distribution, and control of electricity have all benefited from several advances brought about by scientific and technological progress. Numerous distribution networks have been linked into the power system, resulting in a shift in task methodologies. More effective approaches and upgraded computing devices are being used to forecast various expenditures. Smart grids and microgrids are two instances of power system modernization by advanced technologies. There is no doubt that the number of decentralized DERs will grow in tandem following the growth of renewable energy development. VPPs are required to aggregate, optimize, coordinate, and control distributed generation data from DERs, storage facilities, and controllable loads as intelligent dispatchable units in the operation of power systems and flexible tradable units in wholesale power markets. VPPs are a relatively new and attractive energy delivery technology, and existing various projects have proved their versatility, durability, convenience, and effectiveness. This paper summarises existing VPP principles, examines various representative VPP projects from around the world, and concludes by analyzing the issues and future development of VPP, thereby providing a theoretical foundation for the subsequent development and enhancement of VPP.

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