Virtual Power Plants (VPPs)

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A virtual power plants (VPPs) is an alternative for the management of Distributed Energy Resources (DER) in the electricity system, which operates based on the concept of the "virtual cloud". Its specific role is visibility and the technical and commercial integration of DERs in the power system. It is capable of grouping and managing the technical potential of different DERs (microgrids included), regardless of the voltage level at which they are interconnected with the network and without a geographical restriction between the elements. It is modeled as a single virtual element associated with the distribution network to guarantee a safe, efficient, cooperative and complementary operation between its elements, both in commercial and technical aspects. The VPP has the capacity to participate in the electricity market as a manager of controllable loads and as a provider of energy, power reserve and ancillary services.

Keywords: smart grid ; virtual power plant ; distributed generation

1. Definition and Scope of Virtual Power Plants (VPPs)

The concept of virtual power plants (VPPs) was firstly introduced in 1997 by Dr. Shimon Awerbuch with the term "virtual utility" [1], proposing the creation of small systems capable of taking advantage of the benefits of DERs. Since then, several studies have contributed to the maturity of this initial definition. In [2], VPPs are defined as a combination of storage devices and small renewable and thermal generating plants that serve to participate in the electricity market as a more robust and efficient power plant. Ref. [3] emphasizes the definition as a group of decentralized and grid-connected units installed in single and multi-family homes, small businesses and public buildings to provide heating, cooling and electricity production services, where a set of units can be controlled and managed as a single DER plant and with great flexibility in terms of fuel choice. In [4], the characteristics of the generator and controllable load parameters that can be aggregated and used to characterize VPPs are outlined, including frequency response characteristics, voltage regulating capability, active and reactive power loading capability schedule and profile of load, among others. In the European FENIX Project, a mechanism is proposed to manage DERs and make better use of its participation. It adds several small- and medium-capacity generation units to form a single virtual unit that behaves in a similar way to a large power station, and therefore with the ability to integrate DERs in the electricity market and provide technical services to the grid [5]. In the work developed in [6], VPPs are approached as a set of generating plants and controllable loads. The capacity of the generators is around dozens of MW, and they can produce electrical and thermal energy at the same time. Service supply is carried out through a smart management system. VPPs are part of the concept of DERs and medium/low-voltage distribution networks. VPPs are a fundamental element to participate in the active management of the system as a smart grid [7]. In [8], a VPP is defined as the set of DERs located in an electrical system, not limited in voltage level and grouped for cooperative operation as a single element that aims to obtain technical and economic benefits for all system participants. The flexibility of the management of DERs with VPPs to offer ancillary services to the system is analyzed in [9]. The DeMoTec laboratory was used for the control of active and reactive power through a VPP. In order to seek the proper interaction of DERs in the EPS, in [10], the participation of VPP as an "integrating agent" is proposed for small DERs to be power suppliers from distribution networks. The VPP operator would be in permanent communication with the system operator and in permanent interaction with small generating plants. As more studies have been developed in this area, the authors provided broader concepts of VPPs, allowing them to incorporate new elements and new operating strategies in the network. In [11], a VPP is a set of DERs, storage systems, electric vehicles and controllable loads, which are controlled, optimized and coordinated so that their operation is equivalent to an hourly dispatched unit and with participation in the electricity market. This VPP is a supplier of energy, capacity and ancillary services to the grid operations. The electric vehicle is also proposed as a fundamental part of VPPs. For example, in [12], various approaches are introduced to facilitate the integration of electric mobility through VPPs. Ref. [13] describes the implementation of a VPP as a means of coordinating the use of distributed resources by TSO and DSO operators for different control objectives. In [14], the concept of VPP is proposed to improve electrical systems and to integrate DERs in the electricity market as a single plant, basing its management on the concept of the "virtual cloud" and adding small-scale DERs. Another study proposes the concept of fog as a VPP (FaaVPP) to integrate DERs as services for community energy management [15]. Generating units are integrated in a power distribution hub, which is managed and controlled with fog-based service to form a VPP. This service provides a virtual trading system for prosumers. In the POSYTYF project, the concept of a dynamic virtual power plant (DVPP) is proposed [16]. The DVPP aims to facilitate the integration of dispatchable and non-dispatchable renewable energy sources into the electrical network by offering their combined flexibility. It is a new concept that considers the large-scale integration of only RES. The DVPP not only has economic advantages, but it also has the capacity to offer ancillary services to the system [17].

As a summary, **Figure 1** shows some important criteria that have contributed to the development of VPPs over time.

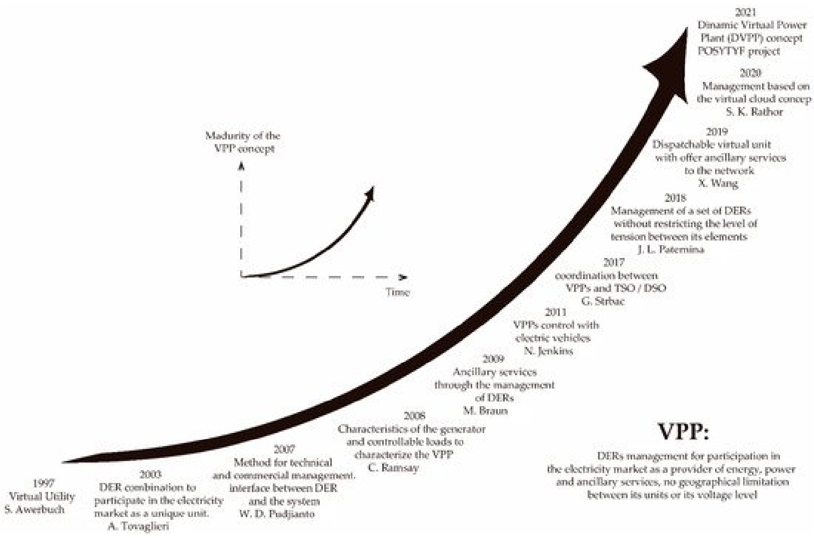

Figure 1. Time evolution of the concept and scope of VPP. S. Awerbuch [1], A. Tovaglieri [2], W. D. Pudjianto [18], C. Ramsay [4], M. Braun [9], N. Jenkins [12], G. Strbac [13], J. L. Paternina [8], X. Wang [11], S. K. Rathor [14], POSITYF Project [16].

Finally, bringing together the concepts formulated by multiple authors, an integral definition of VPP is proposed. This definition encompasses the different operating approaches and the services that can be offered to the EPS.

- *A VPP is an alternative for the management of DERs in the electricity system, which operates based on the concept of the "virtual cloud". Its specific role is visibility and the technical and commercial integration of DERs in EPS.*

- *It is capable of grouping and managing the technical potential of different DERs (microgrids included), regardless of the voltage level at which they are interconnected with the network and without a geographical restriction between the elements.*

- *It is modeled as a single virtual element associated with the distribution network to guarantee a safe, efficient, cooperative and complementary operation between its elements, both in commercial and technical aspects.*

- *The VPP has the capacity to participate in the electricity market as a manager of controllable loads and as a provider of energy, power reserve and ancillary services.*

Figure 2 displays the elements that support the proposed definition.

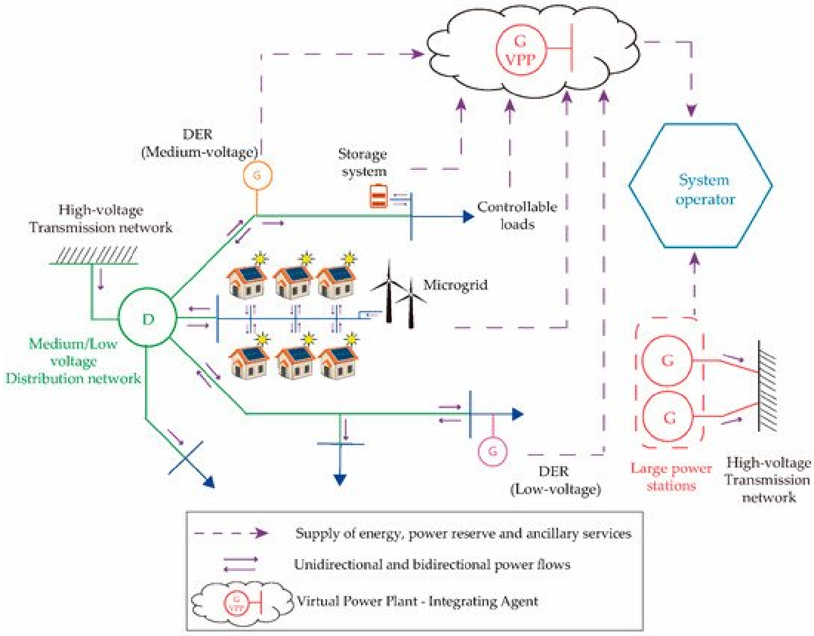

Figure 2. Scheme of the proposed definition of VPP.

Several authors use the term "aggregator" as a concept similar to VPP [18][19][20][21]. Therefore, here, when an aggregator is mentioned, it refers to the VPP. Depending on the political regulations and type of market used in different countries, the work of an aggregator could focus on managing a set of distributed elements, acting as an intermediary between DERs, consumers and the system operator [21].

It is important to mention that VPPs manage the services of the DERs through communication and coordination protocols between the aggregator and system operator. The power flows are supplied in the distribution networks and are controlled in real time. Finally, the economic flows are managed by the market operator. In summary, VPPs are responsible for three types of flows: communication and economic flows (virtual interconnection) and real power flows in the grid (physical interconnection between DERs and the grid). This concept is known as the "internet of energy" and has been mentioned in several works where VPPs play an important role [22][23][24]. To clarify the proposed concepts, **Figure 3** shows a diagram with the physical link between the VPP and the distribution grid.

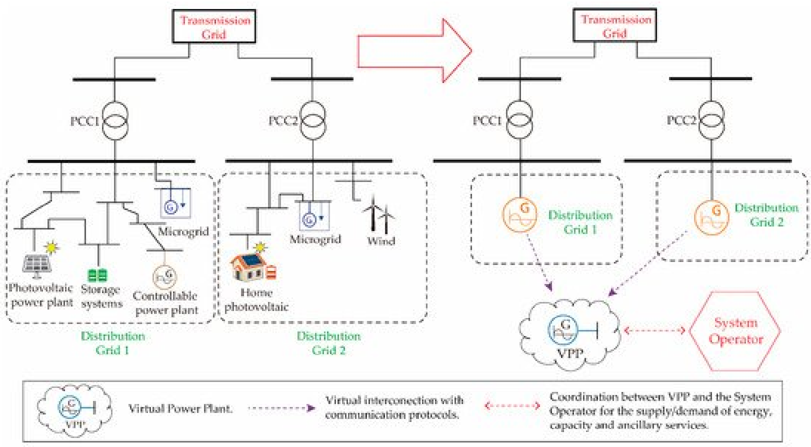

Figure 3. Physical link between the VPP and the distribution grid.

Figure 3 shows that the VPP functions as a suitable interface for DER management; however, it is important to note that a physical layer is required to perform any actual power flow transfer.

2. Classification of VPPs and Participation in the Electricity Markets

VPPs are usually classified in two groups: technical virtual power plants (TVPP) and commercial virtual power plants (CVPP) [18][25][5][26][27].

Technical Virtual Power Plant: The main objective of the TVPP is to grant the visibility of the DERs to the system operators. They contribute to the operation of the network in real time through the availability of capacity, energy supply and ancillary services, such as voltage regulation, secondary and tertiary frequency regulation, inertial response and black start, among others. TVPPs lead to the decentralization of the EPS, offering the technical characteristics of a traditional power station. Likewise, its flexibility allows it to manage the complementarity between its associated elements and to use storage devices to guarantee the stability required by the system.

Commercial Virtual Power Plant: The main objective of the CVPP is the commercial integration of DERs in the EPS, allowing participation in the electricity market with the supply of energy, power reserve and ancillary services. CVPPs manage their resources to find economic benefits for DER owners and for the system in general. The process gathers DERs and formulates a daily capacity and production plan, considering the costs of individual DERs. Finally, depending on the type of electricity market in the country or region, a service is offered at a specific price. This way, low-capacity DERs become visible in the electricity market and are more likely to be dispatched when combined with other technologies. Consequently, the CVPP constitutes a supply and demand subsystem between the DERs and the associated loads. The CVPP operator decides the dispatch of each element based on the cost and convenience presented in each operating scenario, according to the availability of the energy resource, hourly demand, marginal prices and the spot market. Based on these concepts, some authors have proposed new classification categories of VPPs. For example, in order to guarantee the flexibility of services offered by the TVPP and CVPP, in [7], management and control subcategories are established, which are called VPP with centralized (CCVPP) and distributed control (DCVPP).

The optimal operation of the electrical system depends on a technical operating structure and a commercial operating mechanism. First, the responsibility for the balance between generation/demand, power quality and system reliability rests with the technical operation. Second, the supply of these services is managed in different electricity markets. Worldwide, there are commonly three main electricity markets: Day-Ahead Market (DAM), Real-Time Balancing Market (RBM) and Futures Markets [28][29][30]. Although some concepts or regulations may vary according to each country, the main characteristics are common to all of them [28]. The DAM market allows trading electricity commodities the day before on a daily basis, while the RBM market closes shortly before the actual power delivery (usually at a higher price). Finally, futures markets allow transactions several weeks, months or years in advance (usually for contracts at an agreed price). DERs alone do not have the ability to dynamically participate in these markets and require an intermediary agent—in this case, the VPP. In this sense, the VPP aggregates the services of multiple DERs and benefits them from the economy of scale. In addition, it generates complementarity between DERs and increases their flexibility. The VPP also acquires reserve capacity and therefore can provide services in the Ancillary Services Market (ASM).

Since many DERs are renewable sources, participation in electricity markets becomes a problem of decision making under conditions of uncertainty. There are three main uncertainties: price, demand and availability of renewable resources. The solution to these problems is through stochastic programming optimization algorithms and robust optimization [31][32]. Renewable energies also pose a risk in electricity markets. CVPPs must face uncertainties and offer their services seeking maximum economic profitability. When considering risk in bidding, optimization algorithms are more complex and adaptive robust programming is recommended [31].

3. Demonstrative Projects

The potential of VPPs for the integration of DERs in explored through the development of several demonstration projects that seek to consolidate this alternative of DER integration in the EPS, generating new knowledge and solid experiences to support the energy transition. The projects developed worldwide have specific characteristics of architecture, operation, capacity, control systems, etc., according to the proposed scope and the set objectives to achieve. The most representative demonstration projects are summarized in **Table 1**.

Table 1. Worldwide developed projects' characteristics.

Project	Country	Year	Characteristics
FENIX [33]	**United Kingdom, Spain, France**	**2005–2009**	• Integration of DERs and maximization of their contribution to the EPS. • Implementation of a VPP and decentralized management. • Tests were carried out in real distribution networks in Spain and the United Kingdom.

Project	Country	Year	Characteristics
Edison Project [34][35][36]	**Bornholm Island, Denmark**	**2009–2012**	• Evaluation of the impact of smart management in the charging and discharging of electric vehicles. • Evaluation of the project in a system with high penetration of wind energy. • The management of DERs is carried out through a VPP.
PowerShift Atlantic [37][38][39]	**Canada**	**2010–2015**	• Implementation of a VPP that allows effective integration of wind energy. • Determination of whether demand control is an economical and effective alternative offer as an ancillary service. • Operation at 1400 interconnected clients and demands of around 17.3 MW.
WEB2 ENERGY [40]	**Germany**	**2010–2015**	• Implementation and testing of the three pillars of “Smart Distribution” (smart metering, smart energy management and automation). • Demonstration of the compensation of fluctuating deviations of renewable energies through the addition of conventional generators and storage.
Smartpool [41][42][43]	**Germany**	**2015**	• The company “Next Kraftwerke” developed a VPP that combines the flexibility of energy producers and consumers. • The additional power can be used to provide control and balance fluctuations in the network. • “Next Pool VPP” manages more than 2900 medium- and small-scale energy production and consumption units (1.9 GW).
Shanghai Huangpu District VPP project [27][44]	**China**	**2016**	• Implementation of a VPP for smart energy management in commercial buildings. • Energy storage systems are managed to execute operations with the distribution network.
Consolidated Edison [45][46]	**USA**	**2018–2020**	• Demonstrate that a set of photovoltaic systems with storage in residential buildings can offer resilience to distribution networks.
AGL Virtual Power Plant [47]	**Australia**	**2018**	• Implementation of a VPP with high penetration of batteries in the network. • Management will be through a cloud-based platform. • The AGL virtual power plant is a prototype created by installing storage systems in 1000 residential homes (5 MW).

Project	Country	Year	Characteristics
Virtual Power Plant Demonstrations [48][49][50][51]	**Australia**	**2018**	• Australian Energy Market Operator (AEMO), Australian Renewable Energy Agency (ARENA), Australian Energy Market Commission (AEMC) and Australian Energy Regulator (AER) manage a VPP in real time to evaluate its effectiveness to participate in ancillary service markets. • It is expected to execute the operation of a VPP (700 MW) to verify the potential of the storage systems for energy management and ancillary services.
Simply Energy Virtual Power Plant [52][53]	**Australia**	**2019**	• Implementation of more than 1200 batteries in homes in South Australia. • Management of up to 6.5 MW of residential energy storage. • Provision of ancillary services through a VPP.
POSITYF Project [16]	**Spain, France, Switzerland, Germany**	**2021**	• Development of a VPP adding only renewable sources (dispatchable and non-dispatchable). • Development of the dynamic virtual power plant (DVPP) concept. • Dynamic coordination is valid to provide ancillary services to the system.

Like the theoretical works, the demonstration projects have also experienced significant development over time. Each VPP is unique in relation to its technical characteristics and therefore, each demonstration project has specific objectives and different approaches.

If the technical characteristics of the Edison Project (2009–2012) are analyzed, the VPP is a set of electric vehicles and wind generation, while in the Simply Energy Virtual Power Plant project (2019), the VPP is a set of batteries and photovoltaic generators. Likewise, the specific objectives are different according to the interests of each project. For example, in the WEB2ENERGY project (2010–2015), a VPP was implemented to test Smart Distribution concepts, while in the Virtual Plant Demonstrations project (2018), the VPP is managed to offer ancillary services to the system. The different approaches between the FENIX (2005–2009) and POSITYF (2021) projects are evident. The architecture of the VPP of FENIX has a single point of common coupling (PCC) with the grid and DER management optimizes the maximum energy supply. On the other hand, the POSITYF project uses the concept of the cloud to control DERs at multiple PCCs with the grid. This project manages the energy and the capacity of the DERs to offer ancillary services to the system.

Another interesting example is Smartpool from the company Next Kraftwerke (2015). The implemented VPP manages more than 2900 DERs through the concept of the cloud and multiple PCCs. The management of each controllable DER as biogas power plants uses their flexibility to stabilize the system with secondary frequency regulation. It is observed in the demonstration projects that the level of penetration of DERs does not imply a limitation for VPPs. The Smartpool project manages 1.9 GW and is competitive in the German electricity market. In fact, the more DERs there are, the more flexible the VPP becomes, and its operation is more complex. On the other hand, the different technologies of the DERs do not impede the optimal operation of the VPP. For example, in POSITYF Project, the VPP manages only renewable sources (dispatchable and non-dispatchable), and in some simulation scenarios, they do not consider storage.

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