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# Applications, Operational Architectures and Development of Virtual Power Plants as a Strategy to Facilitate the Integration of Distributed Energy Resources

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**Abstract:** In this article, we focus on the development and scope of virtual power plants (VPPs) as a strategy to facilitate the integration of distributed energy resources (DERs) in the power system. Firstly, the concepts about VPPs and their scope and limitations are introduced. Secondly, smart management systems for the integration of DERs are considered and a scheme of DER management through a bottom-up strategy is proposed. Then, we analyze the coordination of VPPs with the system operators and their commercial integration in the electricity markets. Finally, the challenges that must be overcome to achieve the large-scale implementation of VPPs in the power system are identified and discussed.

**Keywords:** aggregator; distributed energy resources; electric market coordination; smart management system; smart grid; virtual power plant



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## 1. Introduction

### 1.1. General Context

The traditional electric power system (EPS) has been developed according to a top-down operational structure, with unidirectional power flows. However, the traditional centralized operation of the EPS is beginning to become obsolete as a result of the large-scale incorporation of distributed energy resources (DER), which are gradually displacing traditional plants [1]. According to data from the International Energy Agency (IEA) [2], in a number of countries around the world, the electricity sector maintains a trend of progressive increase in the production of DERs. For example, in Australia, consumer-owned generation could account for 45% of annual electricity consumption in 2050 [3].

The operation and control of the EPS are being altered by the growing presence of DERs in the distribution networks. When the aggregate capacity of the DERs is low in comparison to the total capacity of the system, its impact is negligible. However, the large-scale connection of DERs in the distribution networks will produce significant technical impacts, such as bidirectional power flows and incorrect operation of protection relays, among others. DERs are generally invisible to the distribution system operator; therefore, they are uncontrollable and unable to provide stability and balance to the network. Furthermore, they do not participate in the management of the ancillary services (AS), which are exclusively provided by conventional plants [4].

However, the adequate management and coordination of DERs may provide multiple benefits to the system, such as reduced grid losses [5], increased flexibility [6], reduced power congestion on transmission lines [5], peak load shaving [7], reactive power contribution [8], demand management [9] and system resilience [10], among others. Currently, the challenges of the electricity sector are no longer sustained exclusively in the search for new models of systems that are capable of guaranteeing efficiency, firmness and flexibility in the power grid [11]. The search for mechanisms to facilitate the large-scale integration of DERs must also be considered.

The coordinated and aggregated management of DERs in the distribution network would facilitate the integration of these units. For this purpose, an alternative has been proposed, known in the scientific literature as virtual power plants. The concept is schematized in Figure 1.

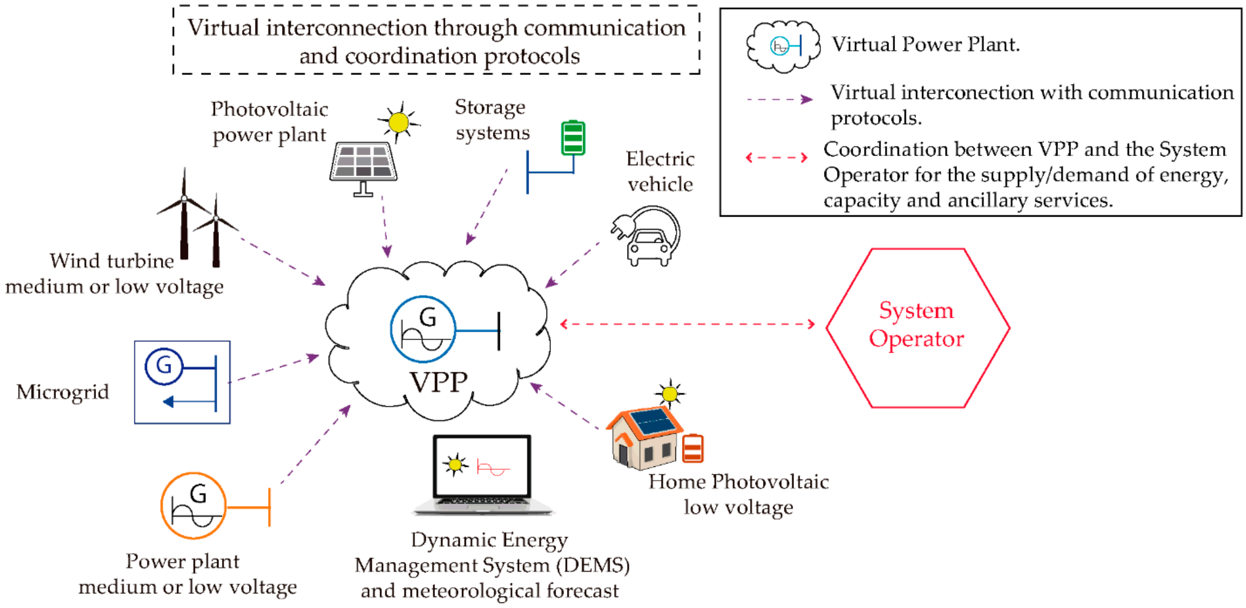


**Figure 1.** Virtual power plant as a strategy to facilitate the integration of DERs in the power system.

The virtual power plant is a mechanism that aggregates multiple DERs. It was developed for the technical and commercial management of DERs, giving the system operator visibility and control of multiple distributed elements. It works as an interface between DERs and the system operator [12]. Its main objectives are to facilitate decentralization [13], to improve the complementarity of the resources available from different sources and to participate in the electricity market as a single virtual element associated with the system [10,14,15]. Some publications conclude that the most representative strength of VPPs is the geographical independence between its elements, because the DERs that constitute the VPP do not require physical interconnection between them [16–18].

According to what is indicated in [16,19–21], Table 1 describes some characteristics of VPPs.

**Table 1.** Characteristics of VPPs.

| Criteria | Characteristics |
|---|---|
| Geographic expansion | It does not depend on physical interconnection between its elements. Geographic expansion is limited to regulatory and economic criteria. |
| Operation | Always works synchronized into grid. |
| Interface | Through communication and coordination protocols between the DERs and the system operator. |
| Coordination | With TSO and DSO. |
| Composition | Conventional and renewable-based generation. |
| Enabling technologies | Smart metering, information and communication technologies (TICs); smart energy management systems; and development of artificial intelligence. |
| Objectives | Energy and economic efficiency. |
| Market | Energy, power reserve and ancillary services offers in wholesale markets. |

### 1.2. Previous Studies and Current Gaps

As DERs continue to expand in the distribution network, there is a need for stronger integration and coordination strategies to address the challenges introduced by uncertainties in renewable generation and the technical challenges created by DERs [22]. VPPs are proposed as an alternative for the integration of DERs, where their operation is presented in the system as a single controllable unit [1]. With this same trend, in [23,24], it is indicated that distribution networks can be structured as a composition of subsystems (set of DERs) with increasing autonomy, promoting the need to interact and complement each other in order to give functionality to a complete system made up of several subsystems. In effect, these subsystems could interact with each other, work cooperatively and supply AS to the main network [8]. Consequently, the scope of operation and control of a VPP adjusts to these scenarios and offers great flexibility to the system, being even able to work cooperatively between multiple DERs.

In order to maintain technical security in the distribution network due to the incorporation of DERs in the grid, the concept of VPPs has become the focus of many works in recent years [25]. For example, in [20], the authors propose the transformation of a microgrid into a VPP to efficiently manage DERs and maintain the stability of the system. Other approaches have focused on VPPs to manage demand through controllable loads [25]. This way, in [9], the capacity to respond to demand in the energy market and the role of the controllable load to support the intermittency of renewable generation are analyzed. In the same vein, [26] evaluates the flexibility obtained by demand management as a strategy for the integration of DERs.

The benefits that VPPs grant to the system facilitate the integration of DERs in the distribution networks. According to [27], the optimized management of distributed elements could dispatch resources outside its own local grid to provide services to the DSO and TSO. For example, in order to provide better management for the integration of DERs, in [28], a coordinated operation strategy is proposed for a VPP that offers regulation services to the system. The management of DERs through smart energy management technologies has been studied in several works [29–31], and this is considered a necessary strategy for the integration of DERs. However, making the management of DERs operate adequately is not an easy task, and it also requires coordination strategies with the system operators. Other studies [11,32–34] discuss the coordination between the TSO, DSO and DERs to guarantee the technical and commercial integration of DERs. These works analyze the responsibilities of each participant in the energy system and provide guidelines for the safe participation of DERs.

In conclusion, there are many approaches aimed at promoting the integration of DERs through VPPs. However, these works do not propose integration strategies that begin with the individual management of each distributed element, nor do they describe which benefits are progressively added to the rest of the system through adequate coordination with the network operators. The existing gaps are due to the lack of studies that systematically address the implementation stages of a VPP and define its scope, limitations, management of DERs and finally, its coordinated operation with the system operator to facilitate real integration (technical and commercial) of DERs. Therefore, it is necessary to know the most important criteria to define a comprehensive management strategy that ensures the best solution from technical and economic points of view.

### 1.3. Novelty and Contributions

The effective integration of DERs involves two important approaches: integration with the system (technical) and integration with the market (commercial). To achieve this, it is necessary to manage and control each distributed element through a smart and efficient system. Additionally, coordination between virtual power plant operators and the system operator is necessary. Once the control of each distributed element and coordination with the system operator has been achieved, multiple services can be offered to the system, such as energy supply, power reserve and ancillary services. This way, the set of distributed elements will facilitate the displacement of large conventional generators and the participation in the wholesale market.

Regarding the role that VPPs play in facilitating the integration of DERs, the key novelties and contributions of this paper are the following:

- We present a review and discussion of the most relevant literature on the development of virtual power plants, as well as an analysis on the general concepts and applications. A definition of VPP is proposed and argued.
- We present and review the main projects around the world with practical virtual power plant implementations.
- The general structure of a smart grid with virtual power plants is proposed, based on an operational bottom-up scheme, through smart energy management systems. In this proposal, the virtual power plant acquires the specific role of "integrating agent" and participates, in a fundamental way, in the management of DERs.
- As an energy management mechanism, the general architecture for the operation of a "Net Zero Energy Grid" is proposed, seeking to achieve neutrality between the energy produced and required through virtual power plants.
- The virtual power plant concept is adapted to the coordination architecture between system agents for participation in five market models for energy, power reserve and ancillary services.
- Finally, the current challenges that must be overcome for the large-scale implementation of these systems are identified and discussed, to achieve an energy transition towards a new smart system that is decentralized, safe and efficient.

The rest of the paper is organized as follows. Section 2 reviews theoretical concepts of VPPs, analyzes the development and practical applications of VPPs around the world and proposes a new definition of VPP. Section 3 analyzes the management of each distributed element and its integration in the virtual power plants. The importance of smart grids in DERs is analyzed and an operation scheme is proposed through smart energy management systems. In addition, a possible application for energy balance in distribution networks is formulated. Section 4 reviews the coordination strategies between the virtual power plants and the system operators to facilitate the integration of DERs in a safe and efficient manner. Section 5 identifies and discusses the challenges and barriers that must be overcome to achieve a mass deployment of virtual power plants in the world. Section 6 contains the conclusions.

## 2. Applications and Development of VPPs

This section reviews the different approaches to the concepts, classification and applications of VPPs. A new integral definition is proposed and the main projects around the world with practical VPP implementations are reviewed.

### *2.1. Definition and Scope of VPPs*

A review of the literature shows that there is currently no official definition of the concept of VPP. This concept has evolved over time and is strongly related to the characteristics offered by technological developments.

The concept of VPP was firstly introduced in 1997 by Dr. Shimon Awerbuch with the term "virtual utility" [35], 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 [36], 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. [37] 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 [38], 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 [39]. In the work developed in [40], 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 [41]. Although in this paper, the level of low voltage operation is limited, most authors do not restrict this characteristic. In [42], 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 [43]. 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 [19], 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 [44], various approaches are introduced to facilitate the integration of electric mobility through VPPs. Ref. [45] 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 [46], 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 [47]. In this work, 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 [48]. 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 [49].

As a summary, Figure 2 shows some important criteria that have contributed to the development of VPPs over time.

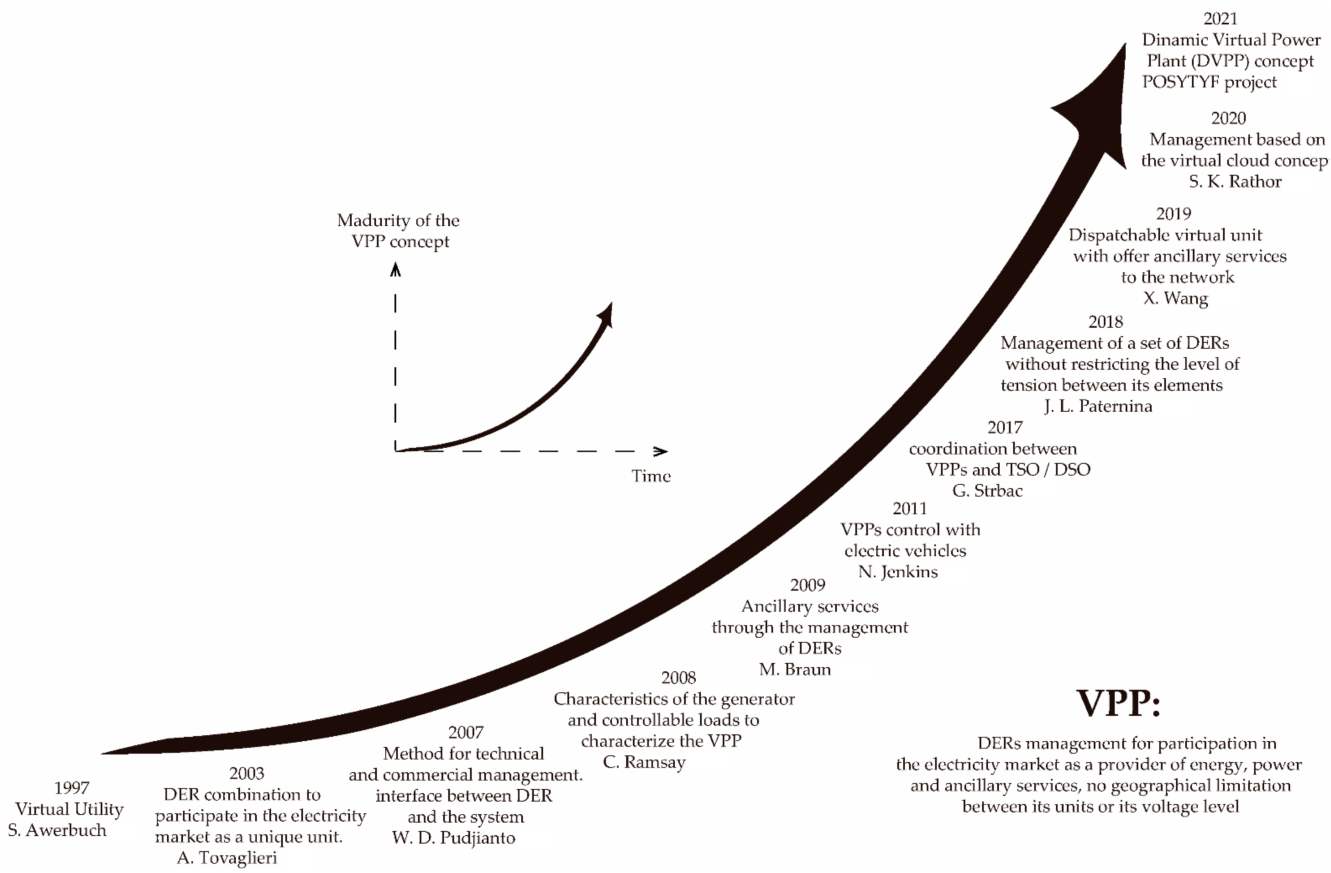


**Figure 2.** Time evolution of the concept and scope of VPP. S. Awerbuch [35], A. Tovaglieri [36], W. D. Pudjianto [12], C. Ramsay [38], M. Braun [43], N. Jenkins [44], G. Strbac [45], J. L. Paternina [42], X. Wang [19], S. K. Rathor [46], POSITYF Project [48].

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 3 displays the elements that support the proposed definition.

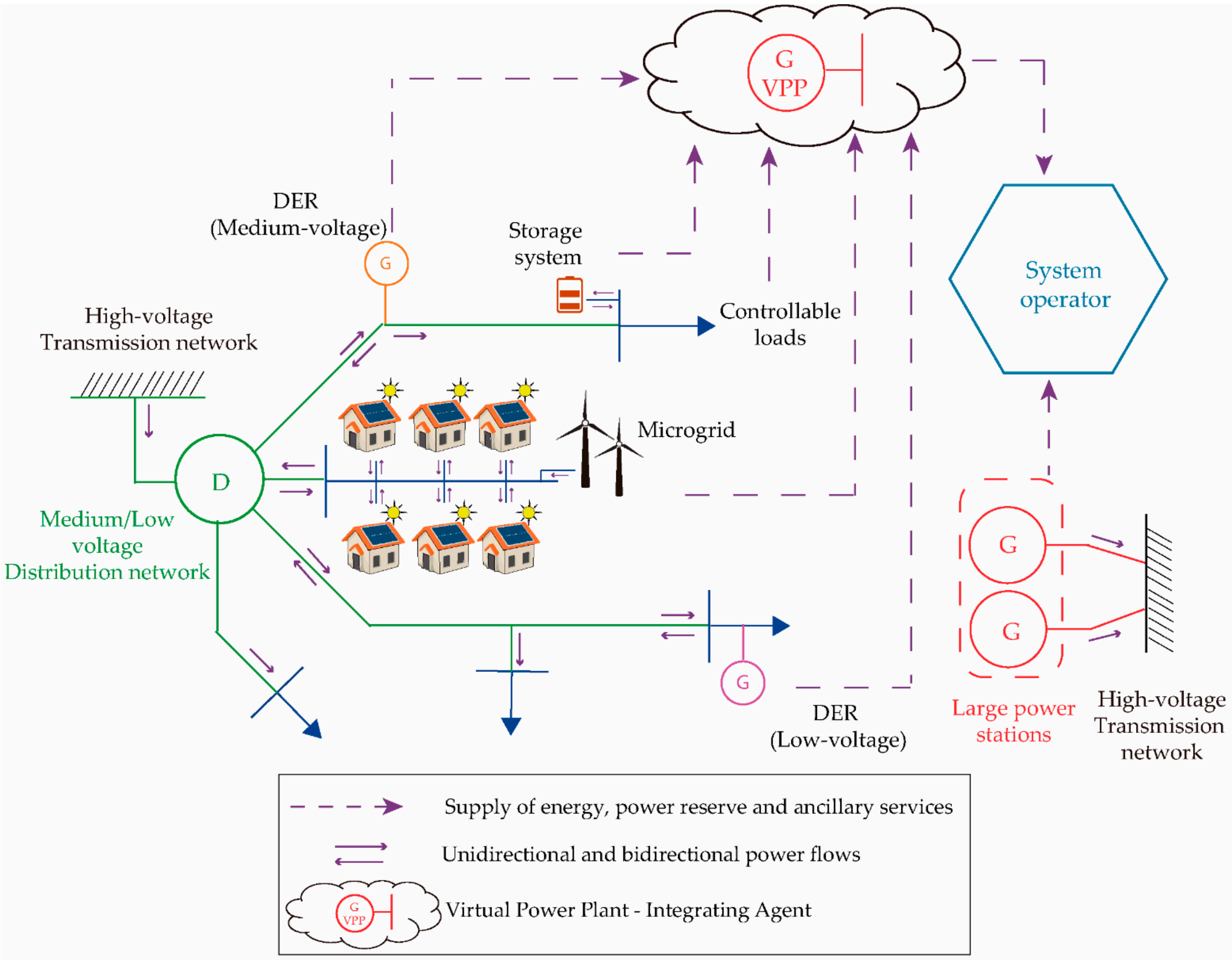


**Figure 3.** Scheme of the proposed definition of VPP.

Several authors use the term "aggregator" as a concept similar to VPP [12,50–52]. Therefore, in this paper, 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 [52].

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 [53–55]. To clarify the proposed concepts, Figure 4 shows a diagram with the physical link between the VPP and the distribution grid.

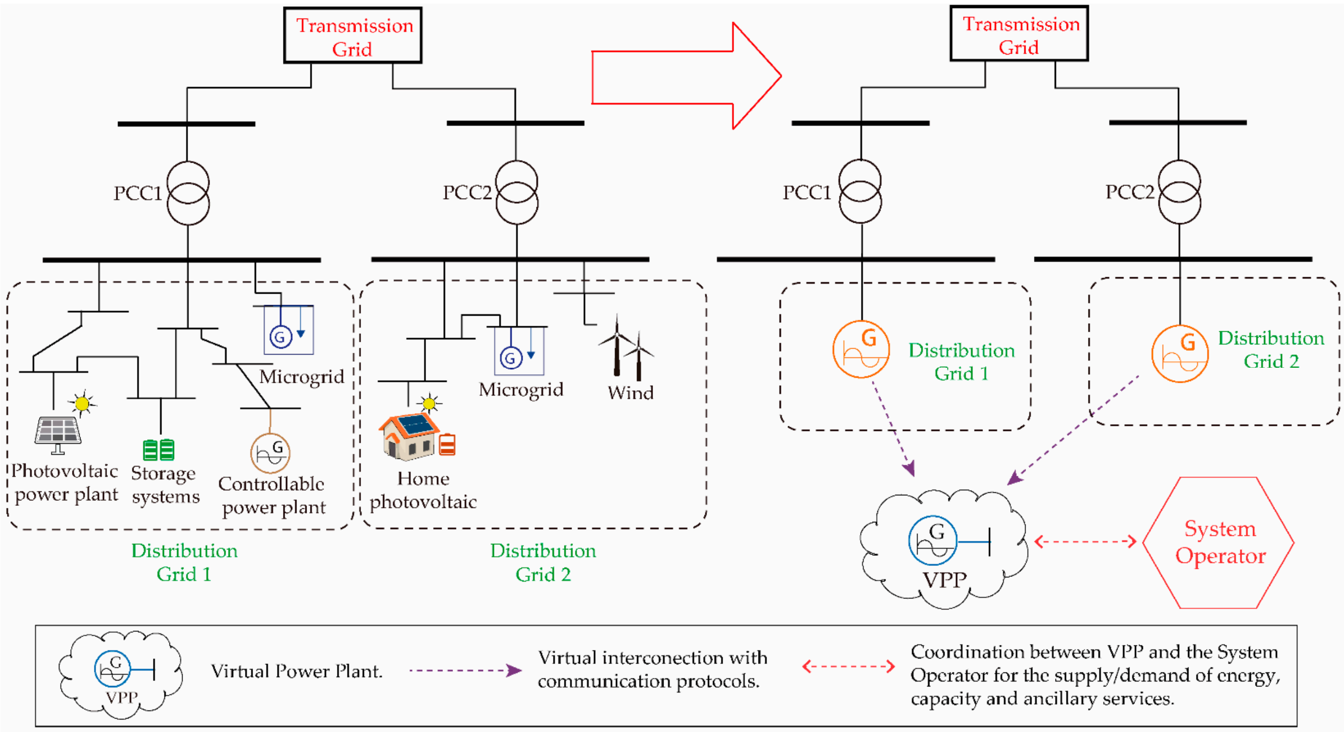


**Figure 4.** Physical link between the VPP and the distribution grid.

Figure 4 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.

### 2.2. 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) [12,20,39,56,57].

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 [41], 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 [58–60]. Although some concepts or regulations may vary according to each country, the main characteristics are common to all of them [58]. 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 [61,62]. 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 [61].

### *2.3. 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 2.

**Table 2.** Worldwide developed projects' characteristics.

| Project | Country | Year | Characteristics |
| --- | --- | --- | --- |
| FENIX [63] | United Kingdom, Spain, France | 2005–2009 | • Integration of DERs and maximization of their contribution to the EPS.<br>• Implementation of a VPP and decentralized management.<br>• Tests were carried out in real distribution networks in Spain and the United Kingdom. |
| Edison Project [64–66] | Bornholm Island, Denmark | 2009–2012 | • Evaluation of the impact of smart management in the charging and discharging of electric vehicles.<br>• Evaluation of the project in a system with high penetration of wind energy.<br>• The management of DERs is carried out through a VPP. |

**Table 2.** *Cont.*

| Project | Country | Year | Characteristics |
|---|---|---|---|
| PowerShift Atlantic [67–69] | Canada | 2010–2015 | • Implementation of a VPP that allows effective integration of wind energy.<br>• Determination of whether demand control is an economical and effective alternative offer as an ancillary service.<br>• Operation at 1400 interconnected clients and demands of around 17.3 MW. |
| WEB2 ENERGY [70] | Germany | 2010–2015 | • Implementation and testing of the three pillars of "Smart Distribution" (smart metering, smart energy management and automation).<br>• Demonstration of the compensation of fluctuating deviations of renewable energies through the addition of conventional generators and storage. |
| Smartpool [71–73] | Germany | 2015 | • The company "Next Kraftwerke" developed a VPP that combines the flexibility of energy producers and consumers.<br>• The additional power can be used to provide control and balance fluctuations in the network.<br>• "Next Pool VPP" manages more than 2900 medium- and small-scale energy production and consumption units (1.9 GW). |
| Shanghai Huangpu District VPP project [57,74] | China | 2016 | • Implementation of a VPP for smart energy management in commercial buildings.<br>• Energy storage systems are managed to execute operations with the distribution network. |
| Consolidated Edison [75,76] | 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 [77] | Australia | 2018 | • Implementation of a VPP with high penetration of batteries in the network.<br>• Management will be through a cloud-based platform.<br>• The AGL virtual power plant is a prototype created by installing storage systems in 1000 residential homes (5 MW). |
| Virtual Power Plant Demonstrations [78–81] | 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.<br>• 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 [82,83] | Australia | 2019 | • Implementation of more than 1200 batteries in homes in South Australia.<br>• Management of up to 6.5 MW of residential energy storage.<br>• Provision of ancillary services through a VPP. |
| POSITYF Project [48] | Spain, France, Switzerland, Germany | 2021 | • Development of a VPP adding only renewable sources (dispatchable and non-dispatchable).<br>• Development of the dynamic virtual power plant (DVPP) concept.<br>• 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.

In conclusion, the practical projects analyzed have demonstrated the viability and great potential of this technology.

## 3. VPPs as a Strategy for the Management of DERs

In accordance with the concepts discussed in Section 2, a VPP groups several DERs and manages this set as a single virtual element associated with the system. The technologies used for the management and operation of each DER are reviewed in Section 3.1.

Because DERs are interconnected in distribution grids, bidirectional power flows emerge, modifying the traditional top-down approach. Section 3.2 discusses the role of VPPs in a new bottom-up operational approach to facilitate the integration of DERs into EPS. Finally, this new operational approach could present advantages in the balance of distribution networks, and this is analyzed in Section 3.3.

### *3.1. Management and Operation of DERs*

The efficient operation of many DERs requires smart and safe systems. VPPs are part of a modern electrical system called smart grids (SG). An SG works through an advanced communication and control system to ensure efficient distribution of electricity, reduce grid losses and maintain a high level of quality and security of power supply. At present, interest in smart grids is increasing with technological development, which facilitates the application of strategies for the integration of DERs in the EPS. Coordinating DERs with EPS participants requires robust and innovative control systems and new operating models that promote the implementation of the next-generation electrical systems [84]. This new concept of smart management operates with bidirectional power and communication flows, and takes advantage of the development of Internet of Things (IoT) devices [85], cybersecurity [86], big data [87], TICs [88] and artificial intelligence [89], among others.

This new system is based on the adequate integration of different generation sources, advanced communication devices, modern technologies and complex control systems [90,91]. Smart grids can automatically manage bidirectional flows of power and communication. At the same time, they motivate the development of new market models, operating schemes and organizational structures [23,85,92]. The SG is the final evolution of the traditional EPS. Therefore, VPPs play an important role in this concept and in the modern electricity sector. The organization, management and operation of DERs are carried out through the application of smart energy management systems.

Energy management system (EMS) technologies were initially developed for the management of the generation–transmission system, but currently, digitization allows the development of these systems for power flow management in the distribution grids, called distribution management systems (DMS). Finally, these systems have evolved in smart grids for the smart management of DERs and are known as dynamic energy management systems (DEMS). DEMS can be defined as an intelligent module capable of monitoring multiple supply and demand signals of a system in real time. This system can efficiently control the power flows between the different power plants, storage systems and the electrical grid, for the purpose of finding economic benefits and optimizing available resources [93–96]. These systems are the "brain" of the managed electrical system [97], which guarantees its optimal functioning without jeopardizing stability. The operation algorithms are based on multiple variables, such as supply/demand in the electricity market, weather forecasts, spot price of energy and DER availability. In [98], various optimization techniques and algorithms as well as their objective functions and the types of mathematical formulations that are used to manage the DERs and VPPs are discussed and systematically categorized. According to their architecture, these systems can operate centrally or be distributed [46,99].

The large-scale incorporation of DERs into the EPS and the development of DEMS technologies allow for energy consumers to become dynamic participants in the electricity market. In this new model, consumers have the ability to commercialize energy, reserve power and ancillary services to the system, motivated by economic and energy efficiency benefits [100]. The literature identifies this concept as "prosumer", and it is described as a fundamental element in the economic transactions of future smart grids through the management of demand and small generation [101].

Therefore, to meet the technical and economic objectives of a smart grid, an adequate DEMS is required. This system should be capable of efficiently managing the available resources and converting energy management into a profitable business by monitoring, controlling and optimizing system performance [102]. The algorithms implemented in each DEMS work with similar sequences. However, depending on the predetermined objectives and the associated DER management system, each DEMS is unique, and its capacity to supply energy, power reserve and ancillary services is different.

DERs are important energy resources interconnected with the grid. However, to provide flexibility to the grid, they must be aggregated and controlled according to the needs of the system operator. The literature classifies smart energy management system technologies according to their application as follows:

- Home Energy Management System (HEMS) [29,46,103–105]

They are smart systems, formed of specific software and hardware that control storage systems, electric vehicles, controllable loads and small generating plants. The HEMS monitors the demand and production of the homes in real time and allows manual or automatic control of its elements. It is a system to optimize the use of energy according to economic parameters of the electricity market.

- Building Energy Management System (BEMS) [106–108]

They are smart technologies with the purpose of optimizing the energy resources in commercial and residential buildings. Its operation algorithms can be framed under the concept of prosumers for energy, power reserve and ancillary services supply. A BEMS seeks to reduce energy consumption in buildings and to improve efficiency without compromising the comfort of their occupants.

- Microgrid Energy Management System (MGMS) [109–111]

They are management units integrated by hardware and complex software algorithms. The MGMS is the enabling technology that will allow the integration of MGs into smart grids through more advanced and efficient operational systems. Its function is based on processing information from a set of DERs and controllable loads for making decisions. These smart technologies seek to economically benefit the system without jeopardizing the stability of the MG. It uses consumption and meteorological forecasting models to evaluate the production and demand of the system. The MGMS can use artificial intelligence systems to integrate into a VPP and participate in the electricity market with offers such as the supply of energy, power reserve, ancillary services and demand management.

- Energy Management System Aggregator (EMSA) [31,46]

The EMSA is a complex control system of a VPP. The main purpose of this smart unit is to bring together and manage the potential of every DER to form a virtual element that provides flexibility services to the system.

The EMSA can optimize the resources that have been made available by the HEMS, BEMS and MGMS. Its function is to manage the supply and demand of this group through a collaborative approach between the associated elements. Finally, it offers flexibility services with demand management and services in the electricity market.

In conclusion, to provide flexibility, DERs must be integrated and managed as fundamental parts of the distribution network. In this way, the smart energy management system [30] is an enabling technology for the integration of DERs and for the development of VPPs.

### *3.2. VPPs for Energy Management through a Bottom-Up Operational Scheme*

The more DERs and prosumers that need to be managed in the system, the more complex the network becomes. The aggregator must process historical information of demand and weather to guarantee security and firmness in the offers submitted to the system operator. It is also important to know the restrictions of the distribution network to make technically possible offers. To maintain better control over DER management, a bottom-up operation scheme is proposed. This DER management concept modifies the top-down operating mode of a traditional EPS and facilitates the technical and commercial integration of DERs.

The bottom-up operating scheme seeks to supply the energy requirements in collaboration with other associated DERs, starting from its own local network, then the progressive supply of the distribution network and finally, the rest of the system.

The management of DERs can be conducted in various subsystems of the distribution network. In these cases, two or more distributed VPPs may participate, offering their services to a centralized VPP. The VPP organizes each element, verifies the technical availability of each DER, supplies local requirements and builds the best economic offer to participate in the wholesale market. In the bottom-up scheme, the distributed aggregator has the responsibility of guaranteeing the security and firmness of its controlled subsystems and the centralized aggregator, acting as an integrating agent with the system operator.

Figure 5 shows a set of DERs interconnected in the distribution grid. These elements are managed by several smart energy management systems and integrated into the EPS by distributed VPPs and by a central VPP (integrating agent). The proposed operational architecture not only controls power flows in a bottom-up manner—in this proposal, the management of each distributed element and even the electricity markets can be managed in a bottom-up scheme. For example, bottom-up management meets the technical needs of each subsystem of the distribution network through the supply of active and reactive power. Similarly, a bottom-up market could manage service offers directly between the aggregator and the DSO, without the need to participate in a centralized market.

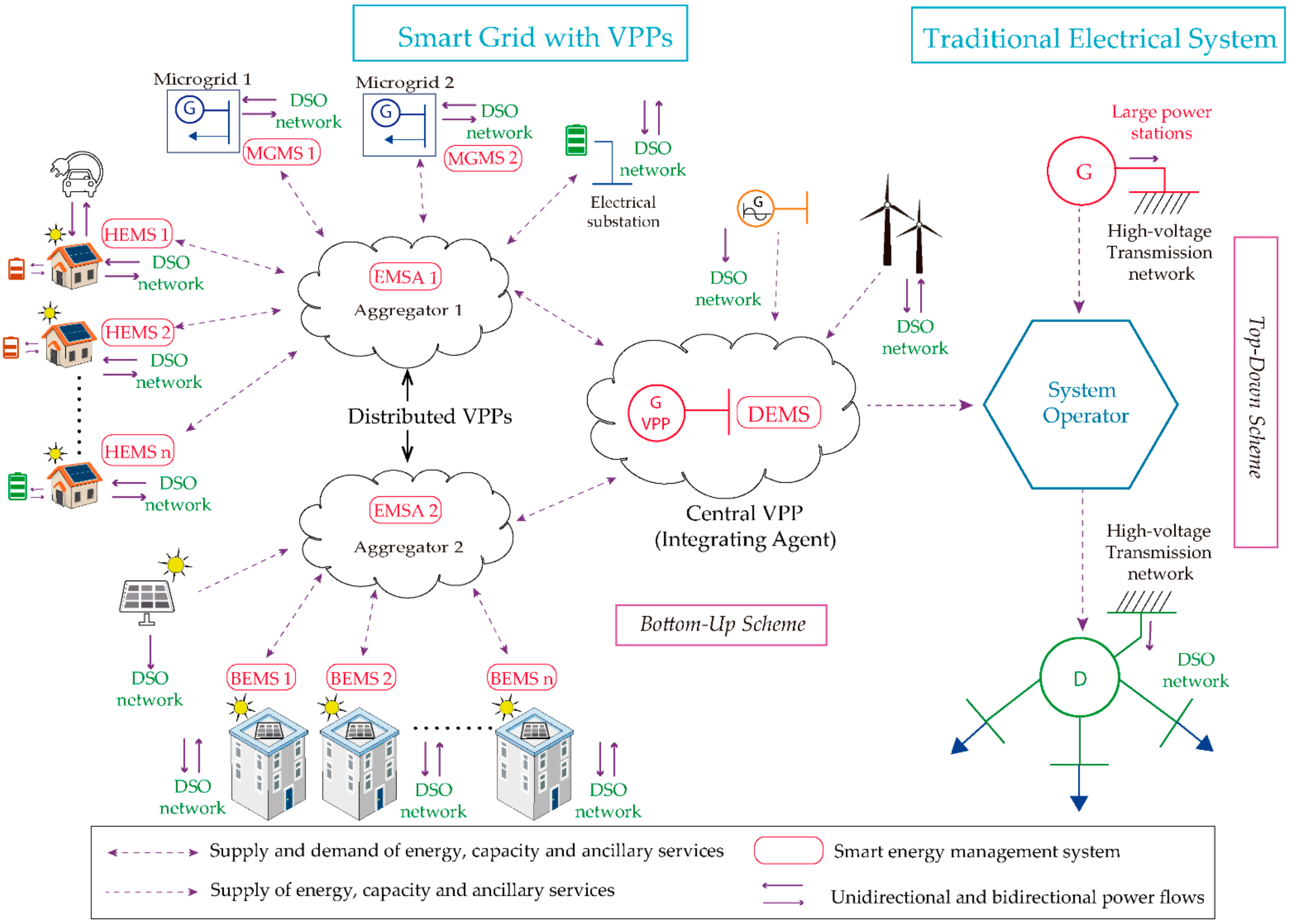


**Figure 5.** DERs bottom-up management through DEMS, distributed VPPs and central VPP.

The bottom-up operational scheme presents some benefits for the system, such as optimized resource management, complementarity between DERs and technical and commercial integration of DERs. This management allows better control of each element and offers flexibility to the system. In addition, the distribution network does not depend exclusively on the services provided by conventional power plants, being also supplied by ancillary services from the DERs of its own grid.

Finally, the proposed operational architecture also makes possible the identification of the engineering challenges that must be overcome for the large-scale implementation of smart grids. These barriers are currently of great interest for the research, for example, of information and communication technologies; cybersecurity; control and operation algorithms for HEMS, BEMS, MGMS and EMSA; meteorological forecasting; DER control and coordination; artificial intelligence; demand management; control and coordination of microgrids; electricity markets for the supply of ancillary services; smart grid regulatory issues; management and optimization of storage systems; and coordination schemes between EPS participants. Once the management and control of each DER are guaranteed, the operation of the VPP must be coordinated with the system operator and with the distribution operator. The coordination strategies and specific responsibilities of the aggregators, TSO and DSO are analyzed in Section 4 of this paper.

To clarify the differences between the traditional top-down operating approach and the bottom-up operating approach, Table 3 indicates the most relevant characteristics.

**Table 3.** Comparison between top-down and bottom-up operational approaches.

| | Top-Down Operating Approach | Bottom-Up Operating Approach |
|---|---|---|
| Reduced operational complexity | ✔ | |
| Facilitation of DER integration | | ✔ |
| Visibility and control of DERs by the SO | | ✔ |
| Management of large-capacity power plants | ✔ | |
| Management and control of bidirectional power flows | | ✔ |
| Contribution with ancillary services for the system | ✔ | ✔ |
| Provision of flexibility to the system | ✔ | ✔ |
| Motivation of dynamic markets with DERs | | ✔ |

According to the table, in recent years, VPPs have been proposed for the participation of ancillary services in the system, such as voltage control, frequency response, active power ramp control and contribution to black start. Likewise, the technical DER visibility of the system operator and the management and control of DERs such as batteries or controllable loads contribute to the flexibility system.

Without proper management, DERs provide power to the system exclusively when the resource is available. However, through the VPP concept and the bottom-up operational approach to the management and operation of DERs, the technical and economic integration of DERs are facilitated. The VPP not only manages the energy of the DERs—it also participates dynamically in the operation of the power system, and it can use its flexibility to offer capacity and ancillary services to the system operator. This dynamic operation of VPPs is currently under development and is known as a dynamic virtual power plant (DVPP) [49,112]. In summary, the bottom-up operating scheme promotes decentralization and facilitates the participation of DERs, providing flexibility and reducing the absolute dependence on large power plants, but in a more complex system.

### *3.3. Application of the Bottom-Up Operational Scheme for the Management of Net Zero Energy Grids*

In recent years, several authors have promoted the implementation of an energy management approach called Net Zero Energy (NZE), which has been popularly developed in the construction field and sustainable cities [113,114]. Its principle is based on encouraging the use of renewable energy sources to reduce the consumption of fossil energy and the emission of greenhouse gases [115]. The NZE concept seeks energy neutrality (zero or nearly zero imbalance between total generation and demand). It analyzes the energy consumption of homes and buildings in a predefined period of time and establishes energy efficiency strategies through the reduction of losses, efficient management of resources and satisfaction of demand with DERs [116,117]. Technically, an NZE system is formed by a DEMS with real-time monitoring, a smart energy meter and several DERs interconnected with the distribution network to provide energy purchase and sale services. In [118], a diagram of NZE is shown, detailing its elements.

The European Union (EU) has established the necessary requirements so that new buildings from 2020 and all existing buildings from 2050 will have NZE guidelines [119]. Any neighborhood that is dimensioned with adequate criteria for renewable generation and storage will be an appropriate start to achieve the objective set by the EU.

According to [117], existing electricity infrastructures and generation and operation strategies must be modified towards smart grid concepts, which go beyond just the implementation of DERs. In this way, the NZE objectives and the technical proposal of smart grids with VPPs are adequately complemented to contribute to the development of a new concept proposed in this paper, called Net Zero Energy Grid (NZEG). This concept is based on the premise of minimizing the electrical losses, DER boost and energy efficiency strategies. NZEG's objective is to achieve self-sufficiency in a part of the grid, through the bottom-up operating mode. Figure 6 shows the scheme of a smart grid with VPPs, and the proposed novel concept of NZEG. The distribution network shows a section of three feeders (F1, F2 and F3), which operate with bidirectional power flows due to the presence of DER elements.

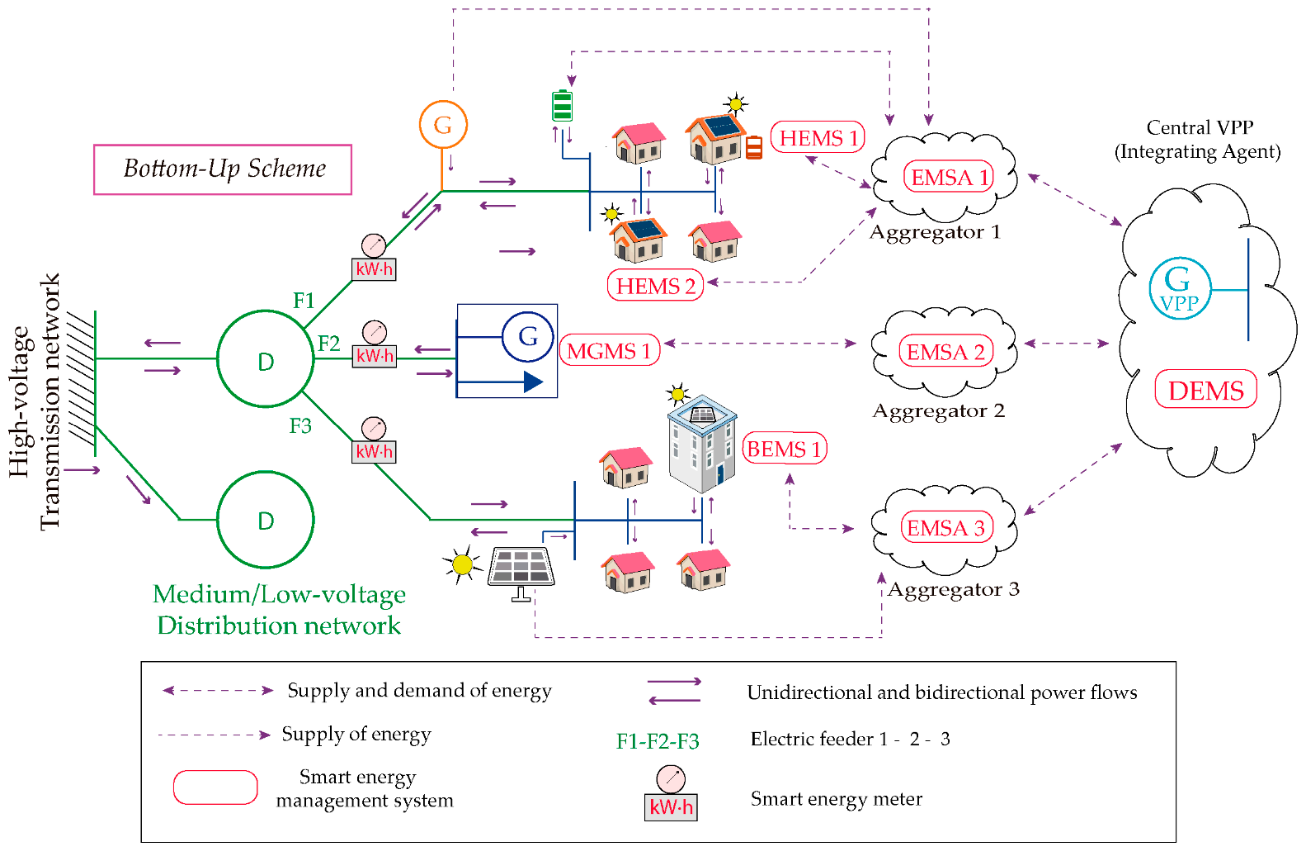


**Figure 6.** Operational architecture of a smart grid with NZEG objectives.

Each feeder provides services to a set of loads (neighborhoods, buildings, microgrids, etc.) and has a smart metering system. Likewise, each house, building or microgrids has its own DEMS system that is monitored and controlled by an aggregator, and this agent is responsible for meeting the demand and technical requirements of the entire feeder. The cooperative operation between two or more aggregators is the responsibility of the central VPP, which coordinates its operation with the DSO. In this way, feeders can offer services to other parts of the distribution network and receive services in times of energy deficit. It is important to highlight the flexibility that the distribution network can acquire through the NZEG concept and due to the energy complementarity between different DERs. The distribution network can manage multiple subsystems and attain better benefits than it would from managing each DER individually.

## 4. Coordination Strategies between Power System Participants for the Integration of DERs

In addition to the participation of DERs in the VPP analyzed in the previous section, the management of DERs through VPPs requires analyzing the coordination of the VPP with the system operators.

This section analyzes the participation of VPPs in the power system. To achieve technical and commercial integration of DERs, the VPPs must coordinate their operation with the system operators (TSO and DSO). Therefore, Section 4.1 analyzes the proposed architectures for coordination between aggregators and system operators, while Section 4.2

reviews the coordination strategies for the operation of the VPP. Finally, in Section 4.3, these strategies are analyzed and compared.

### 4.1. Coordination Architectures between Aggregators and System Operators

Conventional power plants supply energy, capacity and ancillary services in different markets, namely, the Day-Ahead Market, the Real-Time Balancing Market, the Futures Market and the Ancillary Services Market [58–60]. The DERs can participate in these markets, but proper management of their services is required for their integration into the EPS [80]. VPPs can manage the distributed elements through DERMS, but the efficient use of available resources depends on optimal coordination with the system operator (for example, the TSO), or with the local operator (for example, the DSO) [33].

It is expected that in the coming years, the number of DERs will increase significantly in the distribution network, so it will be necessary to consider efficient coordination solutions [120]. In addition, appropriate coordination mechanisms are important to meet technical and commercial requirements in the electricity markets. The coordination between DSO and TSO for system balance is a challenging aspect, especially due to the restrictions of the distribution network. Furthermore, aggregators are new agents in the system that require coordination with the TSO or DSO. In this new operating approach, the specific responsibilities of each agent have not yet been defined [32].

The aggregators, the local operators and the system operator must work collaboratively to improve the visibility of DERs in distribution networks. Likewise, they will promote the active participation of these resources in the system, and will improve the quality and transparency of the operation data [11,121,122]. There are two types of architecture for the coordination of these aggregators. In Figures 7 and 8, they are identified as "Centralized Operational Architecture" and "Decentralized Operational Architecture", respectively.

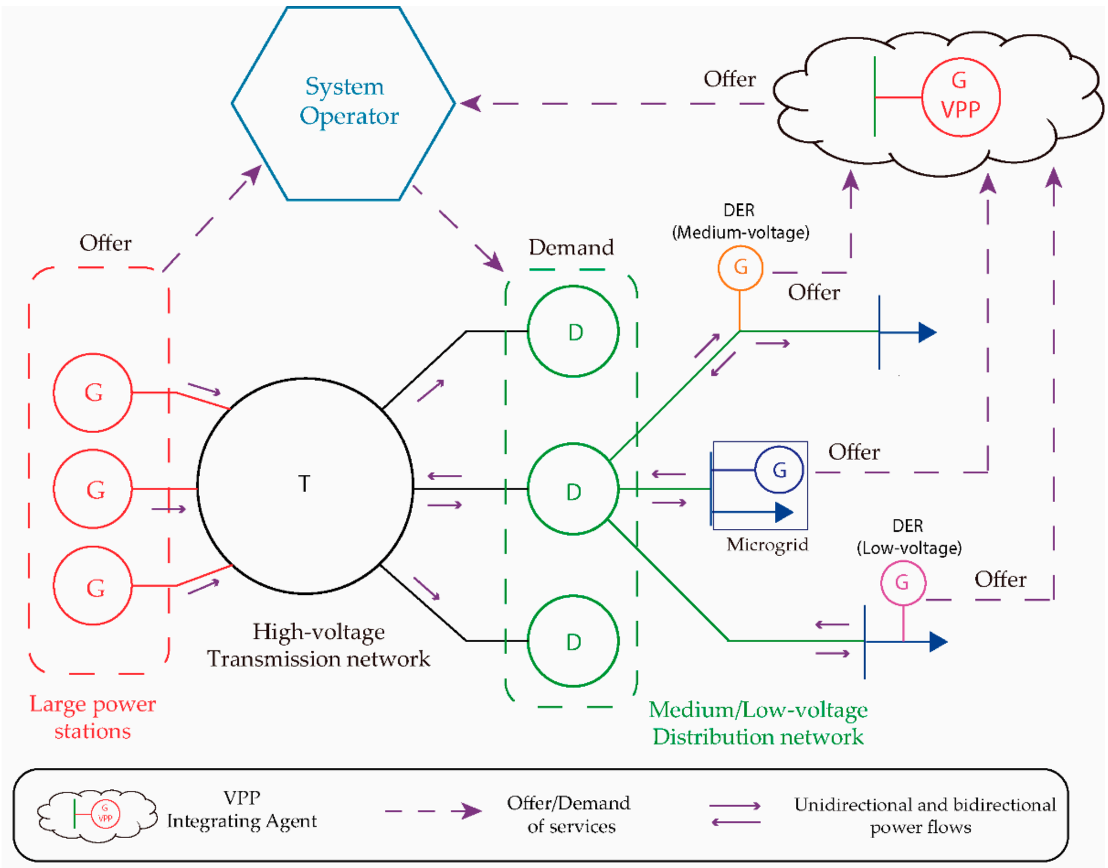


**Figure 7.** Centralized Operational Architecture.

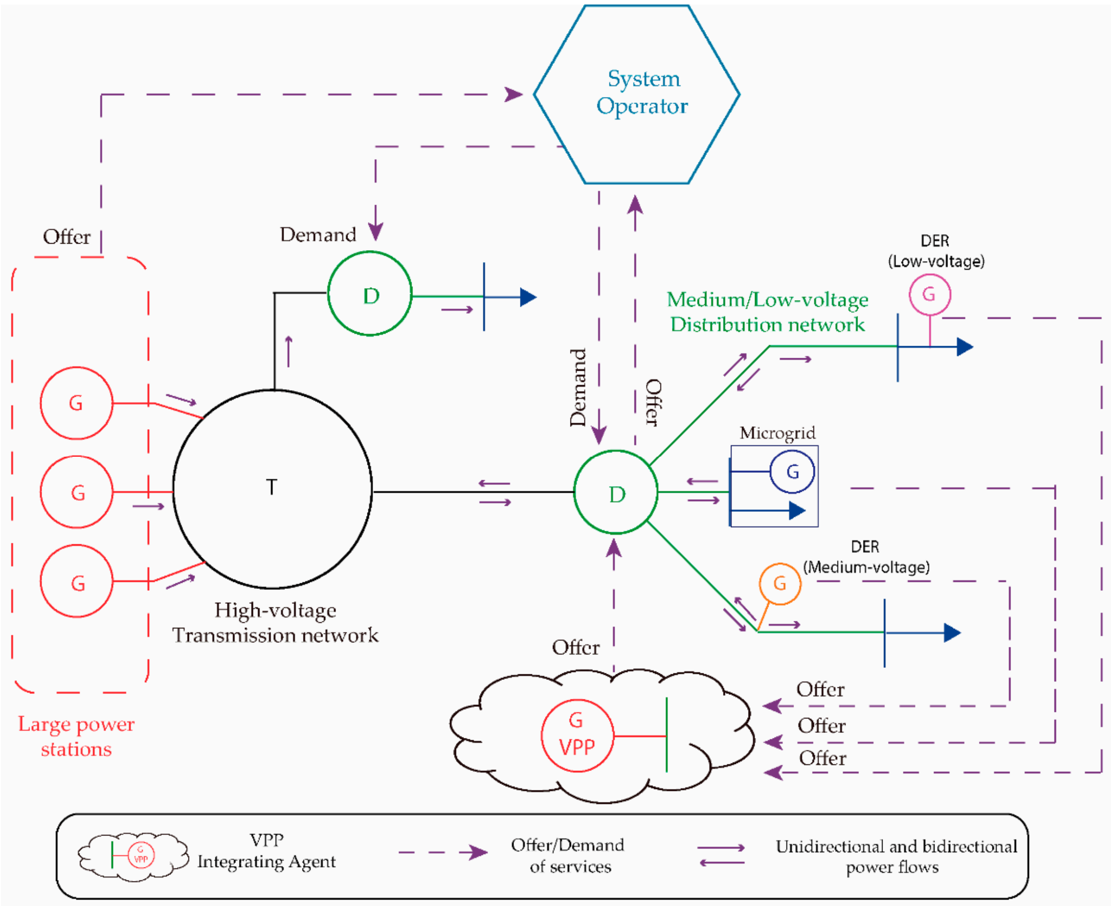


**Figure 8.** Decentralized Operational Architecture.

In Centralized Operational Architecture, the aggregator coordinates its operation directly with the system operator and offers the available resources from a set of DERs. In this architecture, the VPP actively participates in the markets in a similar way to a conventional power plant. In Decentralized Operational Architecture, the aggregator coordinates its operation and offers its services to the DSO. In this architecture, the DSO could actively participate in markets with supply/demand for services with the system operator.

The choice between the different types of coordination schemes and the roles assigned to each agent will depend on the needs of each system. In each case, the objectives to be achieved, the technical restrictions of the networks, communication systems, DER capacity and the established regulatory frameworks must be considered.

### *4.2. Coordination Strategies between Aggregators and System Operators*

The purpose of the different coordination strategies is to identify the most efficient interaction and the most appropriate organization in the electrical system between aggregators, local operators and the system operator. Individually, the main service that a DER provides is energy. However, the set of DERs managed with VPPs could operate in a similar way to a conventional power plant, with flexibility to supply capacity, reserve, balance and voltage regulation, among others. Five coordination schemes have been identified between TSO and DSO to take advantage of the flexibility of the DERs and the ability to supply ancillary services to the system [11,34,123].

In the five identified coordination strategies, aggregators can not only participate in ancillary service markets, but they can also coordinate their operation with the TSO and DSO to participate in the traditional energy and reserve markets. The coordination strategies correspond to the architectures indicated in Figures 7 and 8. However, the difference between each proposal lies in the roles and responsibilities assigned to each participant.

(a) Centralized model [11,32,33]

The system operator controls the requirements of the transmission and distribution networks. The DSO does not have any operation decision, so the system operator is the only actor responsible for the balance of the system. In this model, the VPP coordinates its operation directly with the system operator (like a conventional power plant) and can offer energy, power reserve and ancillary services. The large power stations and the DERs (through VPPs) offer services to the system operator. TSO defines the energy dispatch based on the best technical and economic scenario for the entire system. DSOs receive the services available in the market and the balance of the system is fulfilled through the collaborative contribution of all participants.

The architecture of this coordination model corresponds to Figure 7.

(b) Local model [11,32,33,121]

The VPP organizes and manages the available DERs. The DSO coordinates with the aggregator the services of these DERs located in its own local network, and the transactions are carried out through its own market (aggregator/DSO). After meeting local requirements and restrictions, the DSO can offer services to the rest of the system. However, in this model, the system operator maintains responsibility for balancing the system. This coordination mechanism uses a bottom-up operational approach.

The architecture of this coordination model corresponds to Figure 8.

(c) Shared balancing responsibility model [11,124]

Balancing responsibilities are divided between the system operator and the DSO, clearly defining the roles of each operator. The DSO organizes a local market according to the restrictions agreed with the system operator. The flexibility of the distribution network is reserved for the DSO to meet its operational requirements and the balance of its local network.

The architecture of this coordination model corresponds to Figure 8.

(d) Common TSO-DSO market model [11,123]

The system operator and the DSO have a common goal of optimizing overall operating costs and meeting the requirements of transmission and distribution networks. The DSO will make technical and economic decisions to meet its grid requirements. In the common market, collaborative work is important between the flexibility of DERs through VPPs (distribution network) and the flexibility and robustness of large power plants (transmission network).

The architecture of this coordination model corresponds to Figure 7.

(e) Integrated flexibility model [11,34,124]

In this model, both the system operator and the DSO will be unregulated participants. This market is organized by an independent operator and no priorities are set for any participant.

The architecture of this coordination model corresponds to Figure 7.

### 4.3. Comparison of Coordination Strategies

In [124], a methodology for the validation of these schemes is presented. This allows the results obtained from them to be useful as a proof of concept and they can serve as a guide for the development of new regulations. In addition, implementation difficulties, operating costs, participation in the electricity market and the soundness of the system are analyzed.

In the centralized model, the DERs offer services only to the system operator through the VPP. The central VPP gathers the resources available in the distribution network and offers them as if they were a single generation unit. This model facilitates the balance of the system and directly benefits the TSO. However, the TSO must manage the transmission network and the distribution network, and therefore, it becomes complex.

In the local model, the DERs services are managed only in a DSO marketplace. DSO has priority to acquire these resources and the ability to offer services to other participants in the system. The VPP has the function of integrating the DERs with the DSO. System balance is the responsibility of the system operator. In this scheme, the DSO actively participates in the supply and demand of services. In addition, the DSO knows the restrictions of the distribution network, which improves coordination with the aggregators. However, the optimization of a single market decreases.

In the shared balancing responsibility model, a responsibility agreement exists between the DSO and the TSO at certain grid points. There is a local market in the DSO where DERs participate with energy supply, power reserve and frequency control to maintain balance in the distribution network. This model could operate adequately in emergency conditions. However, the DSO assumes responsibilities that have traditionally been of the TSO.

The common TSO-DSO market model does not have priority for any participant, and service supplies are taken according to the best offer. The power reserve and ancillary services are acquired by the system operator to solve problems of voltage, frequency and grid congestion, while the DSO acquires them for local voltage services.

The integrated flexibility model is based on a common market managed by an independent operator. DSO supplies and acquires energy, capacity and ancillary services to satisfy its voltage requirements and grid congestion. The TSO supplies and purchases ancillary services to solve voltage, frequency and grid congestion problems. Finally, other participants will be able to supply and acquire energy, capacity and ancillary services to balance their generation and/or consumption units.

The main characteristics of these five coordination models are summarized in Table 4.

**Table 4.** Characteristics of coordination models between VPPs and TSO-DSO.

| | Centralized Model | Local Model | Shared Balancing Responsibility Model | Common TSO-DSO Market Model | Integrated Flexibility Model |
|---|---|---|---|---|---|
| Centralized Operational Architecture | ✔ | | | ✔ | ✔ |
| Decentralized Operational Architecture | | ✔ | ✔ | | |
| TSO with responsibility for the balance of the system | ✔ | ✔ | ✔ | ✔ | ✔ |
| DSO with responsibility for the balance of the system | | | ✔ | ✔ | ✔ |
| Requirement of an independent market operator | | | | | ✔ |
| Participation in the top-down market | ✔ | | | ✔ | ✔ |
| Participation in the bottom-up market | | ✔ | ✔ | ✔ | ✔ |

## 5. Discussion

Generally, the implementation of DERs in low-voltage distribution networks has been motivated by consumers themselves, without long-term centralized planning. For this reason, in several cases, actions have been required to mitigate unwanted operations as erroneous responses from the protection systems, reverse power flows or operations outside voltage limits [125]. Therefore, planning is important to achieve the proposed objectives quickly, with lower economic costs and with fewer unforeseen events. In this sense, the VPP plays an important role as a strategy to facilitate planned management and the technical and commercial integration of DERs.

Based on the review of the literature, there are many alternatives to exploit the potential of VPPs, However, much of the available literature focuses on the economic advantages that VPPs achieve, but the technical benefits that they provide to the system are increasingly being studied. VPPs have shown significant potential to successfully contribute to the integration of DERs in the EPS. In addition, their flexible characteristics and their participation in the electricity market are achieving notable importance in the energy transition to promote the use of smart and decentralized systems. Although several research works have been carried out around the world and the evidence collected from those projects have shown the potential of this new system, there is still a need to overcome challenges to continue with the development of this alternative for the management and operation of DERs.

The literature review has made possible the identification and classification of various aspects that require further research to reach the common goal of consolidating VPPs as an alternative for large-scale implementation in EPS. Figure 9 presents these criteria.

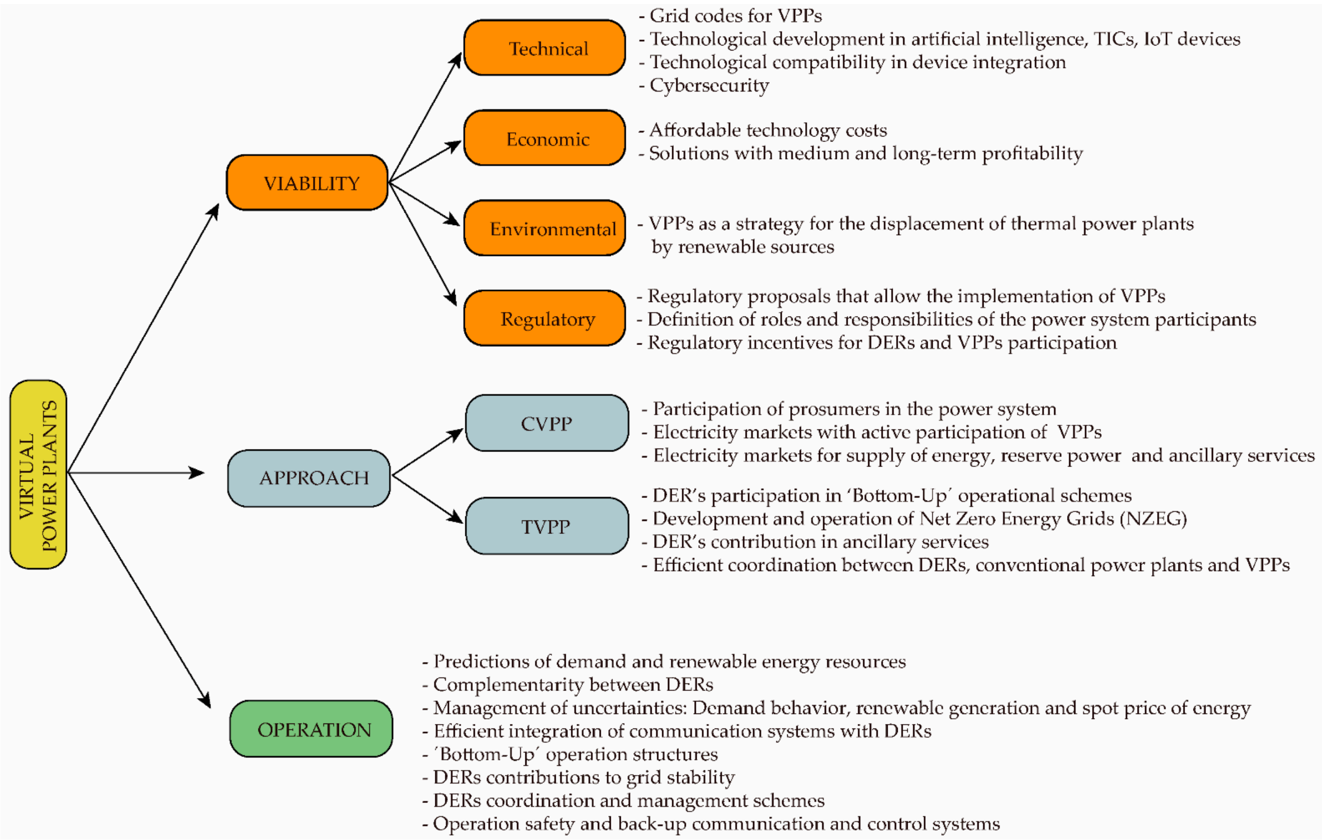


**Figure 9.** Research challenges and development for the large-scale implementation of VPPs.

The integral viability of a project depends on the individual sustainability of four pillars: technical, economic, environmental and regulatory. It is imperative that all four pillars are developed in parallel so that VPPs become applicable in any EPS. Technological development is the most important pillar in smart grids, where there are countless manufacturers, devices of all kinds and various alternatives in operating systems. In increasing the integration of DERs, compatibility between all the units that will integrate the VPP is crucial. The SCADA devices and systems that are currently in operation must work cooperatively with elements that are still under development. The need for a robust TICs system is emphasized to coordinate requirements and decision making, guaranteeing data security and information privacy through solid cybersecurity platforms. Although security researchers have tried to reduce risk, vulnerabilities remain a challenge. A relevant aspect in the technical operation of VPPs is the communication system, where coordination is carried out in real time and the information transfer is carried out in a bidirectional way between the aggregator, a set of highly distributed DERs and the TSO-DSO. DEMS management and control systems are the basis of smart grids; therefore, they are essential units for the operation of VPPs and their algorithms must be optimized and designed with artificial intelligence criteria. Regarding the technological development of DERs, storage systems are of great interest for research. The need for an energy storage system in VPPs is unavoidable, as it plays an important role in managing the energy balance and ancillary services. Therefore, this is a major challenge that must be overcome to strengthen the technology of VPPs. Finally, technological solutions must have competitive prices and allow aggregators to find economic profitability.

Regulatory aspects and political support play a relevant role in the energy transition process towards smart grids and the large-scale integration of DERs. This will be accomplished through the definition and assignment of roles and responsibilities of each participant of the system and the policies established in the electricity market's operation, which were analyzed in Section 4. One analysis and evaluation aspect will be the impact of the implementation of adequate policies that encourage the application of VPPs. Thus, these decisions could boost the interest of the industrial sector, causing an acceleration in technological development and creating a competition that will reduce prices in the market. VPP technology has been developed over many years. There are numerous theoretical studies and several demonstration projects that have validated the technical and economic potential of VPPs. However, an important challenge is to achieve a regulatory change that promotes the large-scale application of this alternative. There are exceptions; for example, in Germany, the VPP "Next-Kraftwerke" works efficiently and is competitive in the electricity market. In Australia, this technology is also promoted by the Australian Energy Market Operator (AEMO), the Australian Renewable Energy Agency (ARENA), the Australian Energy Market Commission (AEMC) and the Australian Energy Regulator (AER). Currently, a VPP is managed in real time with photovoltaic plants and storage (700 MW). Therefore, if regulatory change is effective, VPPs can be implemented and become dynamic elements in the power systems.

VPPs facilitate the technical (TVPP) and commercial (CVPP) integration of DERs. The commercial approach has been significantly developed in the literature for traditional energy markets; however, VPPs and prosumers could also participate in reserve markets and ancillary services. These aspects are still under development and are of great interest. The technical approach is at the peak of its development. There are several proposals to optimize the technical benefits to the system through DERs; however, several of these works require more demonstration projects in real networks. From an operational point of view, a major problem is that the management of the TVPP must be operated and coordinated by the DSO. Currently, TVPP services cannot be implemented by any entity other than the DSO. Therefore, the DSO must adapt and modernize its tools to assume new responsibilities in the electricity sector.

The management of DERs is the essence of VPPs' operation; however, decision making under uncertainty is an aspect that cannot be neglected. There are uncertainties in the energy resource of RES, the behavior of demand and the spot price of energy. All of these aspects require analysis and development for optimal VPP performance. Additionally, the coordination strategies between the VPPs and the system operators represent the final phase for the integration of DER; therefore, greater efforts are required for the development and large-scale implementation of VPPs.

## 6. Conclusions

The VPP is a feasible alternative for the integration of DERs in the EPS. It controls the operational management and allows the commercial participation of each generation unit, regardless of its capacity, geographic location or grid voltage level. The main objective of VPPs is to increase the visibility of DERs to the system operator, and to allow small plants to commercialize their energy and even to offer power and ancillary services for the stability of the grid. In this paper, we contrasted the theoretical VPP concepts with the results obtained in several projects developed around the world, demonstrating VPPs' efficiency in guaranteeing flexibility to the EPS.

We analyzed the VPP as a novel proposal the division of the distribution system into a set of several subsystems supplied by microgrids and small- and medium-capacity DERs. These subsystems are coordinated and managed by distributed VPPs that seek to satisfy the requirements of the grid, under a bottom-up operation scheme. The VPP acquires the responsibility of managing the offers from each DER, making them available to the system operator through the specific role of "integrating agent". In this way, supply and demand services will be coordinated in the electricity market.

According to the concepts related to smart energy management systems, an architecture of smart grids is described, where VPPs are the fundamental basis for the technical and commercial operation of DERs. Regarding energy management, the concept of a bottom-up operation is used and a general architecture is proposed for the management of net zero or nearly zero energy grids, where the VPP plays an important role. Five alternatives for coordination between operators and participants of the EPS are evaluated for their effectiveness in market participation. The VPP concept proposed in this work adjusts to these coordination schemes, allowing the understanding and assignment of responsibilities of each participant for the operational and commercial integration of DERs. Finally, the challenges to be overcome for the application of VPPs in the EPS are described, and some lines of future research are identified.

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**Abbreviations**

(AS) Ancillary Services; (ASM) Ancillary Services Market; (BEMS) Building Energy Management System; (DAM) Day-ahead Market; (DER) Distributed Energy Resources; (DEMS) Distribution Energy Management System; (DEMS) Dynamic Energy Management System; (DSO) Distribution System Operator; (EMSA) Energy Management System Aggregator; (EPS) Electric Power System; (HEMS) Home Energy Management System; (IoT) Internet of Things; (MGMS) Microgrid Energy Management System; (NZE) Net Zero Energy; (NZEG) Net Zero Energy Grid; (PCC) Point of Common Coupling; (RBM) Real-time Balancing Market; (SG) Smart Grid; (TIC) Technology Information Communication; (TSO) System Operator; (VPP) Virtual Power Plant.

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