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Beyond the grid, the Symbiosis of Virtual Power Plants and Communication Networks: A review

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Abstract: Virtual power plants (VPPs) are smart energy systems that aggregate geographically distributed energy resources (DERs), including renewable and non-renewable energy sources, energy storage devices, and controllable loads, into a single virtual plant. These plants are integrated into distribution networks to enhance grid stability and reliability. VPPs require a two-way communication framework to monitor and control all generation sources and loads, ensuring a balance between supply and demand while providing services to distribution or transmission network operators. In VPPs, various applications are used, each with specific communication quality requirements, such as reliability, latency, and bandwidth. Therefore, selecting communication technologies and protocols that meet these requirements and deliver optimal performance for each application is essential. This research paper presents a comprehensive review of the literature on VPPs, exploring their applications, communication requirements, and structural frameworks. It also examines the protocols and standards necessary to ensure reliability, security, and communication quality. Finally, the paper summarizes the global development and implementation of VPPs over the past two decades.

Index Terms: Communication network, Virtual power plant, Cybersecurity, Renewable energy, Smart grid.

1. Introduction

The increasing demand for energy due to population growth, coupled with concerns about environmental pollution [1], has led to greater reliance on renewable energy sources (RESs) such as photovoltaic (PV) and wind turbine (WT) [2]. However, the increasing integration of RESs into the power system has led to several operational challenges [3]. Since RESs depend heavily on weather conditions, coordinating the operation of the entire power system has become increasingly complex [4]. Moreover, the traditional approach to power generation, which relies on centralized generation, is no longer efficient or practical.

As a result, a new concept in power systems, referred to as Virtual Power Plants (VPPs), has emerged [5]. VPPs aggregate all distributed energy resources (DERs), including RESs with other power generation sources, energy storage systems, and controllable loads, enabling decentralized integration with the distribution network to enhance the stability and reliability of power system operations [6]. By aggregating these DERs, VPPs enable them to function collectively as a single power plant.

Communication systems are an integral part of the VPP concept, with a hierarchical communication infrastructure seamlessly integrated into the power grid. VPPs connect DER units to a centralized control center through a communication network infrastructure. This infrastructure facilitates the transmission of monitoring and control signals between units and the control center, enabling centralized and coordinated control. Simultaneously, this communication network connects the VPP's control center to the energy market, the transmission and distribution system operator, and electricity retailers. Reliable and secure communications are vital to enable two-way information exchange in near-real time through communication networks. This exchange takes place in two directions: downstream to various DERs, and upstream, toward the electricity market, electricity retailers, Transmission System Operator (TSOs), and Distribution

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System Operator (DSOs) [7]. During the normal operation of a VPP, the communication infrastructure facilitates the efficient monitoring, coordination, and control of DERs [3]. The choice of communication systems is also a significant cost factor that can impact the economic feasibility of VPPs. Many processes occur across different parts of the VPP system, generating huge amounts of data from diverse applications. These processes require the exchange of data between different components to ensure optimized performance [8]. To facilitate this, the communication network is responsible for transferring the data efficiently. Consequently, the VPP requires a robust communication network capable of handling the VPP's application requirements. To design a communication network for specific applications, the application requirements must first be defined, which are determined by the application's technical specifications, such as latency, bandwidth, interval time, and availability. Once these requirements are clearly defined, the appropriate network type, communication technology, and protocol are selected to meet them. After that, the network is secured and subjected to performance testing and optimization. This process highlights the importance of choosing the most suitable network type, communication technology, and protocol to ensure the VPP operates reliably and efficiently. Among the various communication protocols available, the most commonly utilized are IEC 61850 and OpenADR, due to their effectiveness and widespread adoption [9].

To further enhance the efficiency and functionality of VPPs, additional technologies can be integrated. These include intelligent control systems, edge computing architectures, smart inverters, and advanced communication protocols. Such integrations enable real-time decision-making, improve system responsiveness, and support the growing complexity of modern power networks.

Alongside operational enhancements, cybersecurity plays a crucial role in VPP implementation. The main goals of cybersecurity in VPPs are to guarantee reliable access to information, ensure availability, maintain data integrity and protect it from unauthorized modifications, and safeguard sensitive information and proprietary data [10]. Given the interconnected nature of VPPs, a robust cybersecurity framework is essential to protect both the communication network and the distributed energy assets.

Over the past two decades, the growing number of real-world VPP projects across the globe highlights their increasing significance in modern and smart power systems. By enabling better coordination, efficiency, and reliability, VPPs have become a cornerstone in the transition toward more resilient and sustainable energy systems.

This review paper adopts a research strategy focused on VPP applications and their communication infrastructure. It compiles research on VPP applications and their technical requirements, as well as research that integrates VPPs with communication networks, communication technologies and protocols, emerging technologies, and network security to enhance VPP performance. In order to collect research related to the review study, several search engines, such as Google Scholar and Semantic Scholar, in addition to academic databases (digital libraries) of both IEEE Xplore and ScienceDirect, were used for the purpose of searching for the required research papers. The following keywords were used in the search engine and databases: VPPs, VPP communication, emerging technologies for VPPs, and VPP security. More than 150 research papers were found, and after filtering, 90 papers remained that were directly relevant to the study topic.

1.2. The Contributions and the Organization

Many review papers address the field of VPPs from various aspects. For instance, in [11], the authors explore VPPs from an energy management perspective, while in [12], the focus is on VPP concepts, applications, and challenges. According to [13], the components and operational systems of VPPs are comprehensively reviewed, whereas [14] provides a detailed examination of demand-side management and revisits the theoretical framework of VPPs. Additionally, the review in [15] highlights the role of VPPs in electricity markets.

Given the importance of communication systems in the operation of VPPs and the limited number of review studies in this specific area, this review paper focuses on the communication aspects of VPPs. It explores recent advancements in VPP communication, highlighting its critical role in VPP operations. The study delves into the communication requirements for VPP applications, network performance metrics, and both wired and wireless communication technologies, such as worldwide interoperability for microwave access (WiMAX) and long-term evolution (LTE), which are considered potential solutions for VPP communication. Furthermore, the paper reviews emerging technologies and security considerations in VPP systems. Finally, it summarizes real-world developments in VPPs over the past two decades. However, this review paper covers the up-to-date works in the context of VPP including the recent review papers to offer a comprehensive and integrated view in terms of communication networks and security. The main contributions of this review paper, compared to related works, are summarized in Table 1.

Table 1. Summarizes the contributions of this review paper compared to related works

Refs.	Contributions						
	VPP concept and components	VPP application requirements	VPP communication networks technologies and applications	VPP protocol and standard	VPP emerging technologies	VPP Security and attacks	Typical case of VPPs
[7]	√	√	√	√			
[11]	√				√		√
[12]	√						√
[13]	√						
[15]	√	√					
[16]	√	√	√	√			
[17]	√			√	√		√
This paper	√	√	√	√	√	√	√

To enhance readability and maximize the usefulness of the information provided, the research content is structured according to the format illustrated in Fig. 1. This research is divided into three main sections, in addition to the introduction and conclusion. In the first section, the basic concept of VPP, their roles in energy management, components, classification, and applications are explored. The second section focuses on communication networks, application requirements for VPP, topology, communication structures, types of communication networks and their technologies, as well as the protocols and standards for VPP. The third section discusses emerging technologies used in VPPs, security, and a summary of VPP implementations worldwide. Finally, the last section concludes with a discussion of the findings from this research.

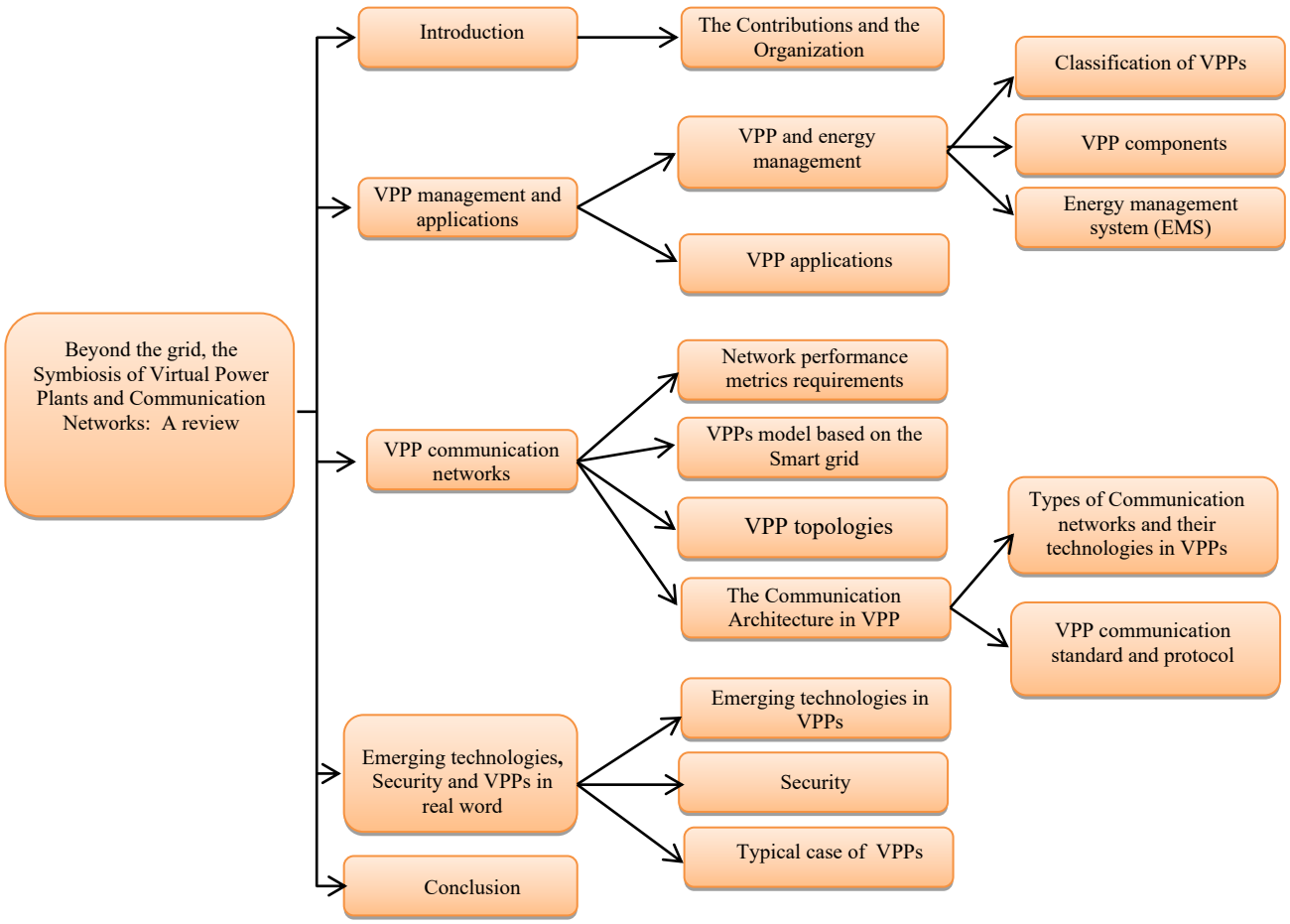


Fig. 1. The organization of this review paper.

2. VPP Management and Applications

2.1. VPP and Energy Management

The VPP concept originates from the definition of the Virtual Utility [18], proposed by Awerbuch and Preston in 1997 [11, 12]. Despite its widespread use, a universally agreed-upon definition of a VPP does not exist, the literature presents various partial definitions based on different perspectives. For instance, from the energy market participation perspective, a VPP is described as a distributed power plant that aggregates the capacity of many small DERs located in different areas, operating as a single entity in power markets [19]. In terms of the VPP's primary roles as key stakeholders in power systems, a VPP facilitates the management of diverse power technologies across systems of varying complexity, connectivity, and scale. The primary objectives of a VPP include ensuring the proper integration of these technologies into power infrastructures, promoting a balance between energy production and consumption, and meeting both commercial and technical specifications. These objectives consider the requirements of various stakeholders, including market participants, consumers, distribution service operators, service providers, energy management systems, and DERs/prosumers/customers [1]. According to [16], a VPP is defined as an aggregator of various DERs, including power generation sources, energy storage systems, and controllable or flexible loads that combines them as a single administrative entity in the power grid. Another perspective provided in [11] describes a VPP as a practical concept that aggregates various renewable energy sources (RESs) to enhance energy management efficiency and facilitate energy trading. While in [13], a VPP is defined as a collection of physical components, including both dispatchable and stochastic generation units, energy storage units, and flexible loads. These components form a virtual entity that engages with supervisory levels for advanced monitoring and control of diverse DERs.

The authors mentioned in the literature have defined the concept of VPPs depending on their research focus or from specific conceptual perspectives. By integrating these definitions from different perspectives with the concept of communications, VPPs can be defined as follows: A VPP is a virtual entity consisting of multiple components such as distributed generation (both renewable and non-renewable), energy storage systems, controllable loads, and electric vehicles. These components are monitored, controlled, and managed by a VPP control center via information and communication technology to ensure the reliability and smooth operation of all components. Simultaneously, the VPP participates in the energy market as a single entity to provide various services. Fig. 2. illustrates the concept of a VPP [20], where the red lines highlight the importance of a two-way communication infrastructure for exchanging data between all entities.

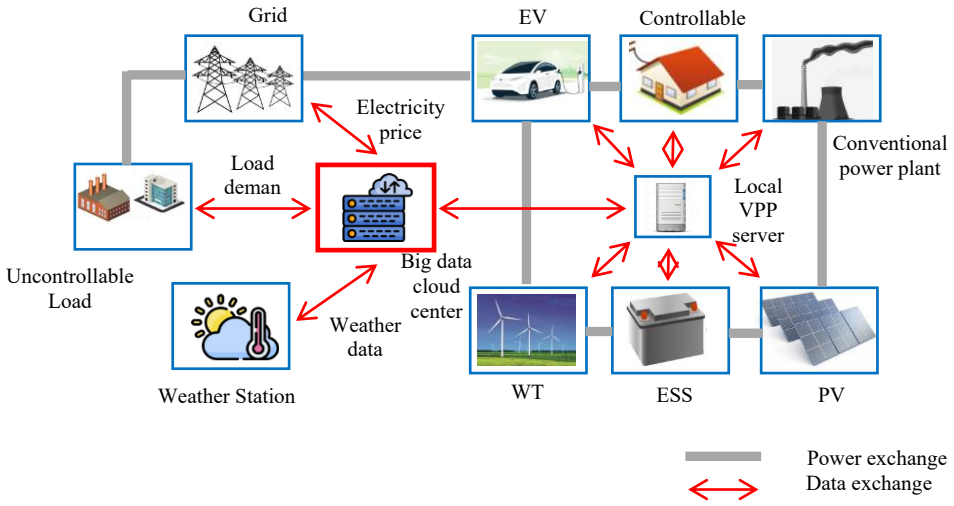


Fig. 2. The basic structure of VPP.

2.1.1. Classification of VPPs

The VPPs consist of two primary types: Technical VPPs (TVPPs) and Commercial VPPs (CVPPs) [21]. DERs from the same geographical region are aggregated by a TVPP for technical objectives, primarily emphasizing resolving local network constraints. A TVPP provides services and functions to both DSO and TSO [22].

The services provided to the DSO include local system management and ancillary services, which are implemented through the active management of the distribution network. This is achieved by utilizing distributed generation and flexible load units at lower voltage levels to balance intermittent RESs and stabilize the network [22]. Meanwhile, the

services provided to the TSO include ancillary services, system balancing, and congestion management [23]. The TVPP is included within the DSO or TSO management structure, but it is not directly associated with the electricity market [7]. Additionally, the TVPP can coordinate multiple CVPPs with their available capacity to deliver specific power system support services. The combined profile and output of a CVPP reflect the DER portfolio's costs and operating characteristics [24, 25]. But the influence of the distribution network is not factored into the combined CVPP profile.

A CVPP provides various services and functions, such as trading in the wholesale energy market, balancing trading portfolios, and submitting bids and offers to the TSO to deliver system services [26]. Fig 3. illustrates the services and functions of both TVPP and CVPP.

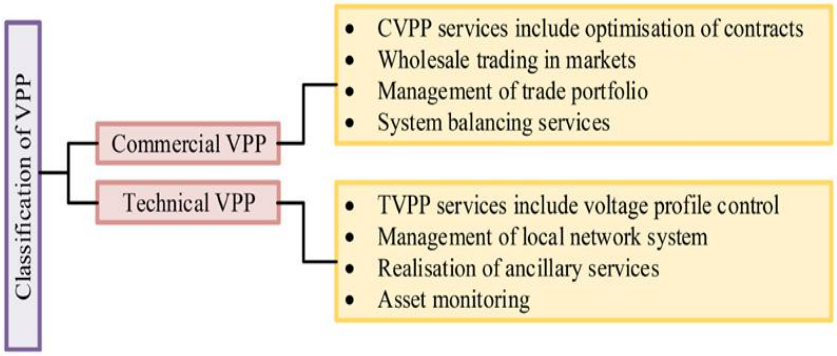


Fig.3. Classification of the VPPs [27].

2.1.2. VPP Components

The ideal VPP system consists of three main elements: distributed generation (DG), energy storage systems (ESS), and information and communication technology (ICT) [13].

In recent years, the number of DGs in the power system has increased. To include various types of small and medium-sized power generators located close to the customer sites to minimize transmission network losses and enhance network reliability and power quality [28]. Based on the type of energy resource utilized, DG technologies can be classified into renewable-based systems, such as PV and WT, and nonrenewable-based systems, such as gas turbines and combined heat and power (CHP) [29].

Energy storage systems serve as a mechanism for storing surplus energy generated by RES during off-peak periods. This stored energy can then be utilized during peak demand, ensuring a balanced alignment between energy generation and consumption [30]. There are many types of energy storage elements, such as battery storage, hydraulic pumped storage, compressed air storage, flywheel storage, and super capacitor storage [31].

ICTs are essential to Energy Management Systems (EMS), overseeing all components within a VPP through bidirectional communication. They collect data from RES, energy storage systems, and consumption units, ensuring smooth coordination and efficient energy distribution among VPP elements [32].

In a VPP, DER is used as a broad term to include all resources generating electricity and/or heat close to the point of use at distribution levels [33]. Depending on the role of the DERs within the system, they can be distinguished as generation, transformation, or storage [34]. If the DER is a generation resource, it may be dispatchable (its output can be controlled and adjusted), such as CHP, or non-dispatchable (its output is not adjustable), such as PV and WT [35].

The Venn diagram highlights the minimum requirements for multi-energy systems at various aggregation levels, focusing on the elements typically included in models [33]. One example of such a system is the VPP, as illustrated in Fig. 4. The relationship between smart grids, VPPs, and Microgrids is complementary and hierarchical. The smart grid represents the overarching framework that encompasses and coordinates the other levels. Microgrids function as independent local power units with DERs and storage, and can operate connected to the grid or in island mode as needed. A VPP, on the other hand, is a higher level that centrally and intelligently aggregates and manages multiple Microgrids and distributed resources, enabling interaction with the electricity market and system operator as if it were a large power plant. The smart grid provides communication, control, and coordination channels between these elements, transmitting control and response signals and ensuring the optimal operation of both local (Microgrid) and VPP systems. This ultimately leads to improved energy efficiency and increased reliability of the electrical system.

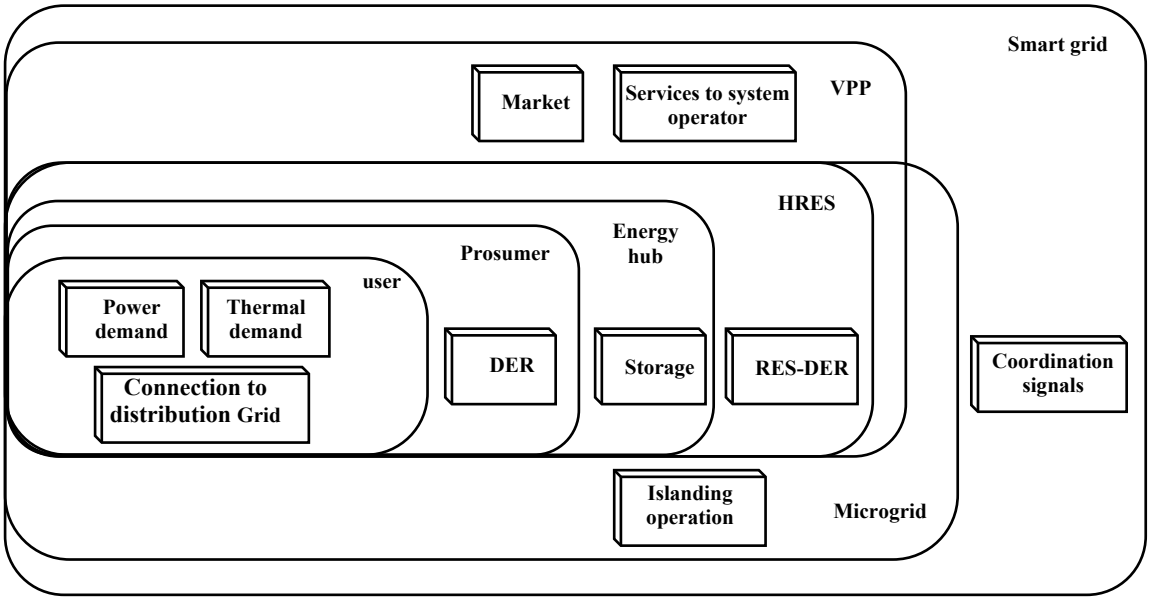


Fig. 4. The Venn diagram, aggregation levels of multi-energy systems.

2.1.3. Energy Management System (EMS)

VPPs operate on the principle of a centralized control system that integrates, regulates, and manages multiple distributed generators [36].

The VPP control center contains an EMS, which is accountable for energy management. The EMS is an essential part of the VPP, efficiently controlling the energy generation based on power load, storage capacity of ESS, weather conditions, load management programs, and the electricity service price [37]. A VPP offers an effective solution for energy management by providing real-time monitoring, energy flow control, and scheduling operations from both the generation and electricity consumption sides [11].

The mechanism of energy management works by analyzing the information collected from all components of the VPP to control and synchronize the demand and supply of energy between all components [11].

2.2. VPP Applications

The main objectives of the VPP are to provide services to its participating partners. In general, these services are categorized as follows [27]:

- **Energy trading :** Providing innovative and cost-effective energy trading opportunities for DER owners in competitive wholesale electricity markets.
- **Grid services :** Offering support services to assist the operators of the transmission and distribution system, this service is known as ancillary services.
- **Balancing services** : Balancing between production and consumption demand, by simultaneously operating across multiple markets in real time, resulting in economic, technical, and environmental benefits for all stakeholders.
- **Optimizing :** Optimization of both production and consumption within the VPP.

These services are closely linked to the structure and operation of electricity markets. Wholesale electricity markets enable the trading of electricity through bulk buying and selling before it is delivered to end consumers, such as individuals, households, or businesses, via the grid. These markets are a subset of electricity markets, while electricity markets cover both wholesale and retail levels. Depending on the specific service provided, participation in different market segments is required. For instance, energy trading occurs primarily in the Futures Market, Bilateral Contracts, and Day-Ahead Market, while Grid Services rely on the Ancillary Services Market and Reserve Market. Balancing Services and Optimization draw on the Intraday Market and Real-Time Balancing Market for continuous adjustment to supply and demand fluctuations [38]. Table 2 summarizes the key characteristics of these markets, while Fig.5. depicts their chronological sequence [15].

Table 2. The key characteristics of electricity markets.

No.	Types of electricity market	Characteristics
1	Futures market	Contracts for the purchase and sale of firm energy are established for a specified period at a fixed price, helping to mitigate the uncertainty of electricity market price fluctuations.
2	Bilateral contracts	Involves a direct electricity sales agreement between a power generator and an energy buyer, providing long-term price stability and minimizing price uncertainty. This stability supports the profitability of both the generator's investment in constructing the generation plant and the consumer's production processes.
3	Day-ahead market	Energy buying and selling offers for every hour of the next day, electrical system flexibility, promotion of high self-consumption, and enhancing operational profitability.
4	Ancillary services market	Ensures the security and reliability of the energy generation and transmission system, maintaining a constant balance between production and demand.
5	Reserve market	Managing surplus generation reserves to guarantee demand fulfillment and ensure the security of the electricity supply, while responding to unforeseen events like generator failures
6	Intraday market	Enables accurate adjustment of energy trades in the day-ahead market, helping to minimize imbalance costs.
7	Real-time balancing market	Managing deviations between energy generation and demand maintains the balance of the electrical system and ensures the security of the electricity supply.

Ancillary services play a key role in supporting grid stability and ensuring power quality. These services are considered grid support services provided by DERs to transmission or distribution system operators, ensuring the reliability, stability, and quality of power within the transmission or distribution network [27]. Key services include balancing load and generation, managing congestion, supporting voltage and frequency, and other emerging services. Ancillary services are vital for the proper functioning of both transmission and distribution systems, as well as for supporting the core activities of power generation and transmission [39].

Demand-side management (DSM) further complements ancillary services by focusing on modifying user demand to meet specific operational and economic goals. It includes all measures implemented at the demand level to reduce energy consumption, costs, and emissions, or to increase income from energy sales, and help balance supply and demand [40]. This also involves strategies to enhance the energy efficiency of buildings and balancing services [41].

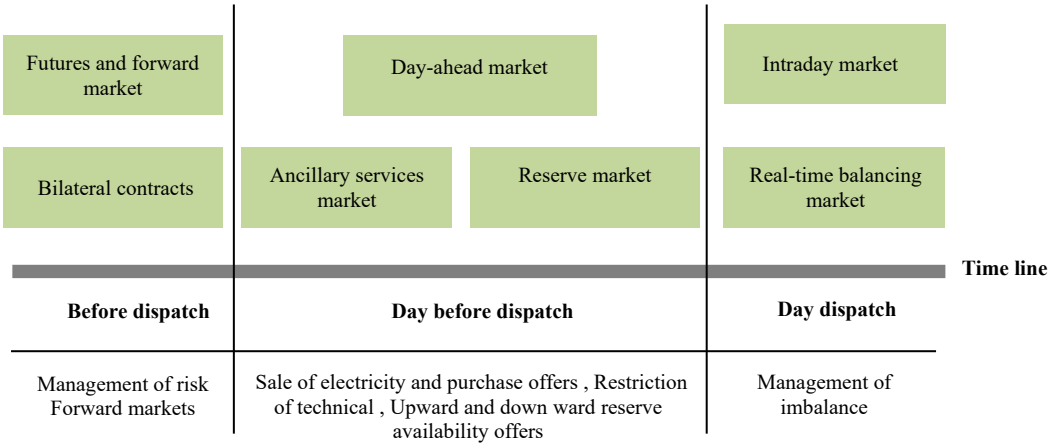


Fig. 5. Timeline of electricity market types sequence

Another commonly used term is Demand side response (DSR) or demand response (DR), which is a subset of DSM. In particular, it represents an evolution of the load management concept [42]. DR specifically refers to non-permanent actions taken to adjust demand [43]. It includes a set of strategies to reduce or shift energy demand through encouraging customers to modify their level or pattern of electricity use. These strategies are based on Pricing or Incentives [14]. For example, lowering prices during off-peak hours encourages customers to shift their energy usage to these hours [26]. The functions of the DR program in the VPP system operation are illustrated in Fig. 6.

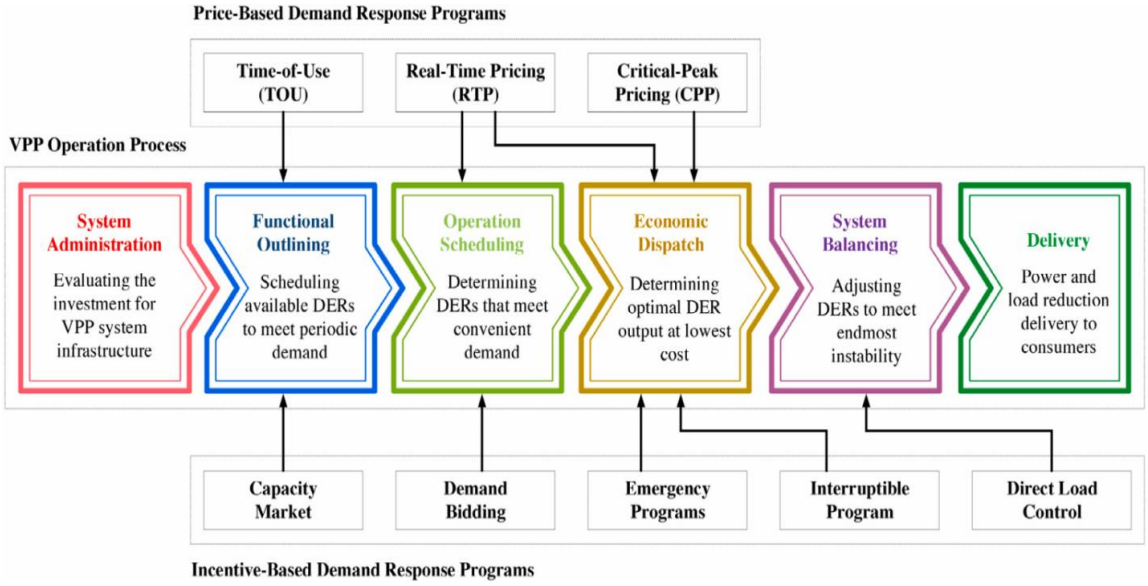


Fig. 6. Functions of the DR program in the VPP system operation [8]

In this context, Home Energy Management System (HEMS) and Building Energy Management System (BEMS) can be considered as a Virtual power plant system. The HEMS manages and optimizes resources within an individual household, operating under the framework of an electricity contract. For example, it can reschedule smart loads to take advantage of cheap electricity prices or maximize the self-consumption of rooftop PV energy using a battery system.

Similarly, the BEMS functions like the HEMS, but on a broader scale, such as a commercial building. If the BEMS incorporates market activities, such as participation in demand response programs, it can be classified as a single-site VPP [44]. This allows buildings to contribute to grid stability, optimize energy use, and participate in market-driven opportunities, further integrating decentralized energy resources into the broader power system.

3. VPP Communication Networks

3.1. Network Performance Metrics Requirements

VPPs are geographically distributed power plants that require advanced information and communication technologies (ICT) for various tasks, including data transmission and management, monitoring, coordination and control, load prediction, validation, and ensuring secure system elements [9]. For a VPP operate to be reliable and secure, the communication system should provide adequate quality of network performance metrics. The aim is to reduce the likelihood of communication failures by evaluating relevant network performance metrics such as latency, bandwidth, round-trip time, reliability, and packet loss during the operation of VPP [39].

Different VPP services and functions require specific levels of network performance metrics to ensure reliable and undisturbed operation [9, 39]. Among these metrics, bandwidth and latency are essential parameters that must be preserved to ensure an acceptable level of service. Required bandwidth is determined by the packet size and the amount of data exchanged among the VPP units [45]. The packet size in VPP communication systems varies depending on the selected protocol and message format. As mentioned in [39], the packet size, depending on the message format, can be 334 bytes for I-format, 126 bytes for U-format, and 126 bytes for S-format. These sizes include the aggregation of transmission control protocol, internet protocol, and Ethernet headers. The inter-arrival time, or the interval time between successive data packets, is affected by the specific requirements of the VPP's control and monitoring systems. In the same study in [39], it was noted that if each message is received within approximately 20ms, and assuming all three types of messages are sent at the same time, the bandwidth required for each DER is approximately 30 kbps.

Optimizing packet size and inter-arrival time is essential to ensure efficient and reliable communication within the VPP. If communication performance becomes low, this could result in loss of operational data or unreliable control. When calculating the overall latency in ancillary services, the technical requirements of DERs, such as ramp-up time, ramp-down time, and activation duration, must be taken into account. The service duration and the ramp duration for each ancillary service are illustrated in Fig. 7.

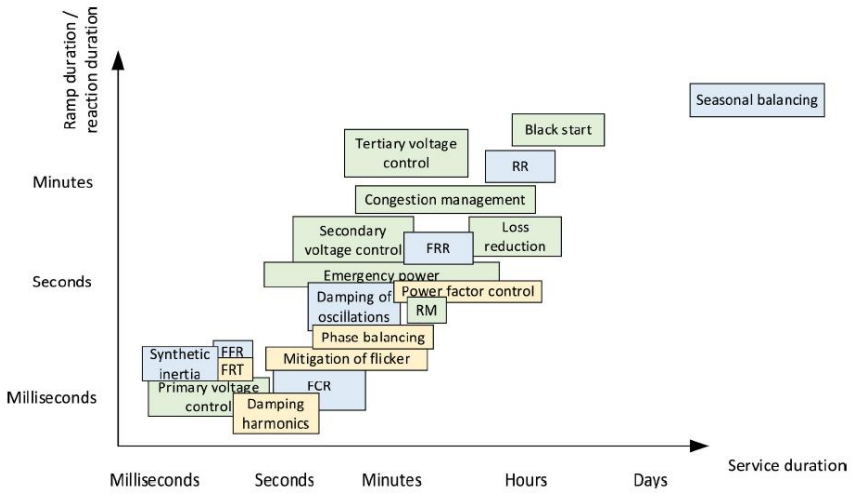


Fig. 7. Services duration and the ramp duration for each ancillary service [46]

The energy management system must process a vast amount of data, including current and voltage values, reactive and active power, and metered values of both energy production and consumption. Consequently, creating a secure communication infrastructure for data flow and exchange is crucial [37].

According to the requirements of the demand response services proposed in [47], the delay required for control services is reduced to 10ms, and the reliability requirement is increased to 99%. Table 3 presents some typical service types and their network performance metrics requirements for VPP systems [16]. These metrics are service requirements and must be met to ensure the application functions correctly. VPP services differ in terms of performance metrics requirements, as frequency regulation and emergency demand response require less delay compared to other services, making the design of a communication network that meets its requirements critical in terms of delay.

Table 3. Some typical service types and their network performance metrics requirements of the VPP system..

VPP services	Bandwidth required	Traffic delay requirements	Minimum communication delay requirements	Target delay	Reliability
Fast frequency regulation	4.8Mbps (100 Terminals/km2)	<280 ms	<120 ms	<50 ms	99.999%
Regular frequency regulation	4.8Mbps (100 Terminals/km2)	<1 min	Seconds	<50 ms	99.99%
Peak regulation	0.82Mbps	<15 min	Minutes	<6 s	99.99%
Emergency demand response	16Mbps (100 Terminals/km2)	-	-	<50 ms	99.999%
Normal demand response	2.74Mbps (150 Terminals/km2)	-	-	500–1100 ms	99.999%
Power trade market	1.33Mbps (1000 trade members)	-	-	<10s	99.99%

Increased bandwidth means the ability to transfer more data faster, and therefore, latency is usually reduced. Conversely, decreased bandwidth leads to data congestion and slower transmission, resulting in higher latency. Therefore, a balance must be struck between bandwidth and latency to ensure the latency value specified by the VPP applications.

3.2. VPPs Model Based on the Smart Grid

In a smart grid system (SG), the power grid interfaces with communication technology through the deployment of numerous interconnected elements for measurement, control, and monitoring [48]. SGs encompass various domains, each responsible for various aspects of the SG infrastructure [49]. There are two primary models that organize the various areas of the SG environment. The first model was proposed in 2009 by the National Institute of Standards and Technology (NIST) in the USA. This model comprises seven SG domains: Generation (including DERs), Transmission, Distribution, Customer, Operations, Markets, and Service Providers. It includes communication and electrical interfaces within its conceptual model for SG information networks. This model was later updated with additional electrical and communication interfaces to better reflect the automation of distribution systems and the growing integration of DERs [50].

The second model, known as the Smart Grid Architecture Model (SGAM), was proposed by the Smart Grid Coordination Group in Europe. This model is three-dimensional, incorporating domains, zones, and a third vertical dimension that consists of five interoperability layers: Components, Communication, Information, Function, and Business [51]. The domains are divided into Generation, Transmission, Distribution, DER, and Customer Premises, while the zones are divided into Process, Field, Station, Operation, Enterprise, and Market [48], as illustrated in Fig. 8.

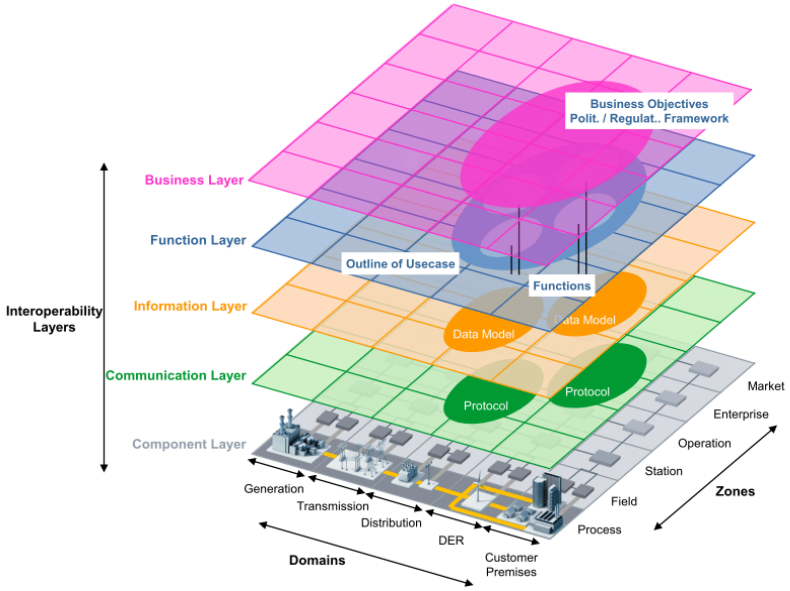


Fig. 8. Three-dimensional SGAM model [49]

The SGAM in Fig. 8. illustrates the complexity of the smart grid domain, highlighting the crucial role of ICT in enabling communication between different components [7].

To map the requirements of a VPP within the SGAM framework, a modified version of the SGAM model is proposed, as shown in Fig. 9.

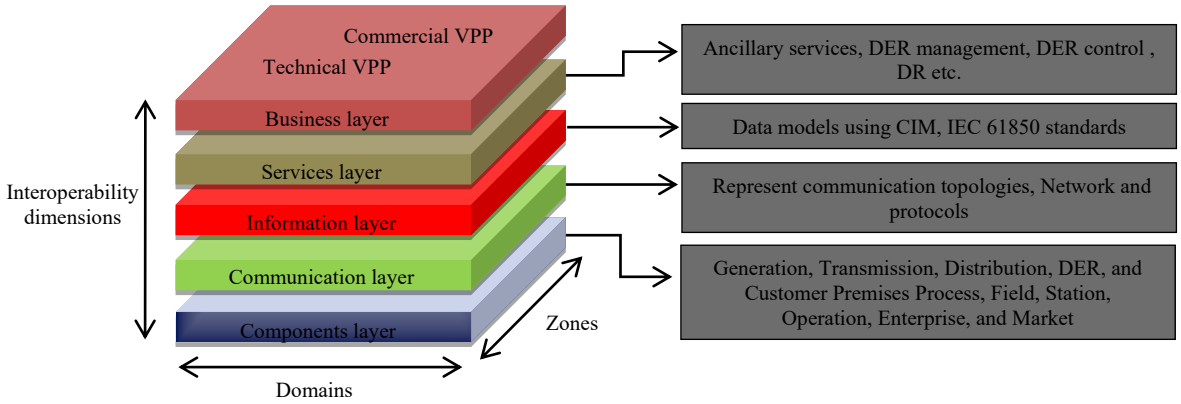


Fig. 9. Modified SGAM model with VPP layers.

This proposed model illustrates the interoperability framework within the context of smart grids and VPPs, showing how technical, informational, and administrative components are integrated to ensure the efficient and unified operation of DERs in modern energy systems. It demonstrates that the VPP relies directly on the smart grid's interoperability architecture. The lower layers are used to ensure data flow, standardization, device integration, service management, and market decision support. Thus, the model highlights that the VPP is not an independent entity but rather depends on the smart grid infrastructure to enable its efficient operation. It represents an advanced functional extension of smart grid capabilities by centrally and intelligently integrating and managing DERs.

3.3. VPP Topologies

There are three types of VPP topologies based on the internal control methods, which are classified into centralized, decentralized, and distributed control [52]. In a centrally controlled VPP, as illustrated in Fig. 10., the control logic is managed entirely by the VPP. The central controller holds all the information about DER production and the energy

market, providing a simple way to utilize DERs to meet grid demand [53]. However, the large number of DERs with diverse ownership within the VPP presents a significant challenge for the central controller in determining an optimal control strategy that aligns with the best interests of prosumers [54].

The VPP requires secure bidirectional communication between the VPP control center and each DER unit to exchange information necessary for monitoring, coordinating, and managing the DERs. This communication demands sufficient bandwidth [24]. Furthermore, centralized control faces the challenge of accommodating a large number of resources because the control center becomes a bottleneck, impacting performance and response time. Also, the system's reliance on a single central point makes it a single point of failure, meaning any malfunction in the control center or its associated network will lead to the complete shutdown of the monitoring and control system.

Fig. 11 illustrates the decentralized-Controlled VPP. In this type of topology, multiple VPPs are arranged at different levels in a hierarchical model. Each VPP at a given level has specific responsibilities

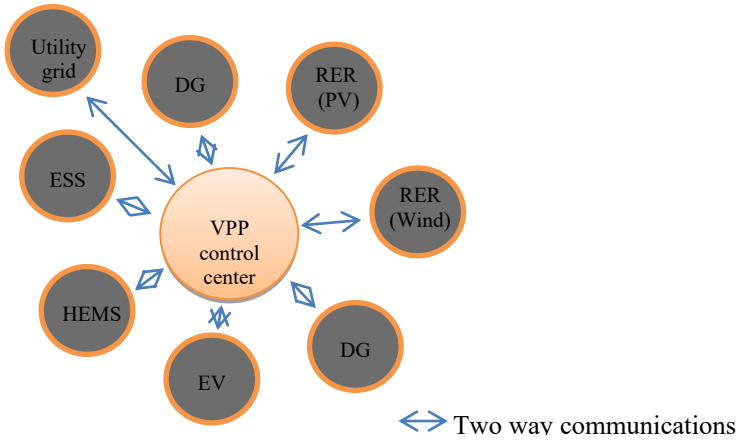
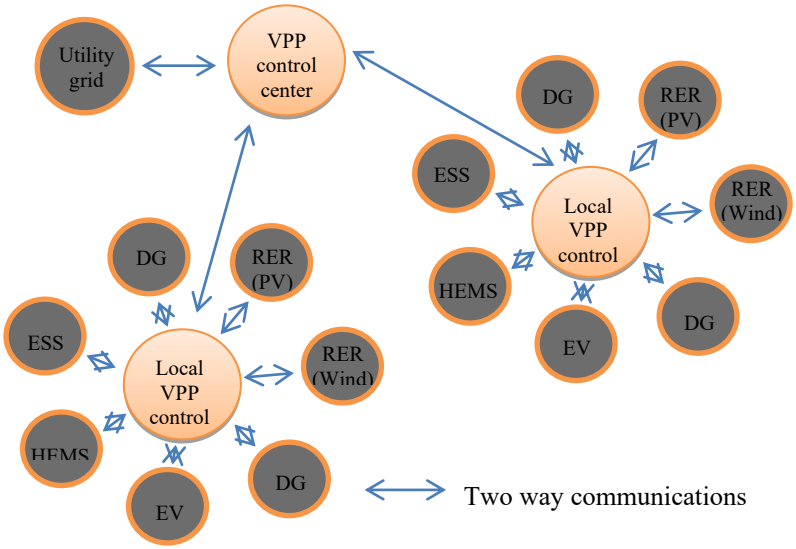


Fig. 10. Centralized controlled VPP.



Fg. 11. Decentralized controlled VPP.

The local VPP is responsible for coordinating and supervising a limited number of DERs [55], while the higher-level VPP is tasked with making decisions. The advantage of this topology is the simplification of responsibility and communication between individual VPPs. Furthermore, this topology provides high flexibility and scalability, and enhances reliability through local control and reduced reliance on a single center, while improving the integration of DERs and rapid load response. Conversely, the disadvantages of this structure are the increased complexity in coordinating and managing communications between units, and it requires a sophisticated and secure communications infrastructure.

Finally, Fig. 12 illustrates the distributed Controlled VPP. Each DER unit in this type of topology operates independently, participating and reacting smartly to different states of the power system and market activity [54]. The disadvantages of this topology include security risks, coordination, and high technical Complexity.

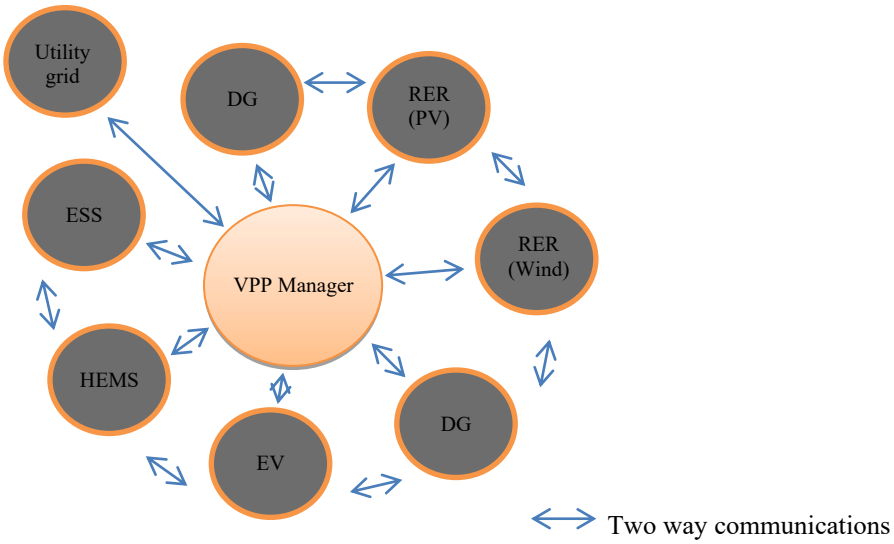


Fig. 12. Distributed controlled VPP

3.4. The Communication Architecture in VPP

The communication architecture of the proposed VPP depends on the specific VPP topology used. In [7], a centralized-controlled virtual power plant topology is proposed, with the communication architecture divided into three network types: Wide Area Network (WAN), Neighborhood Area Network(NAN), and Field Area Network (FAN). Fig. 13 illustrates the architecture of the communication system. The VPP system consists of three DERs, each connected to the WAN network by a different method. The proposed VPP system provides ancillary services for frequency control to TSO and DSO.

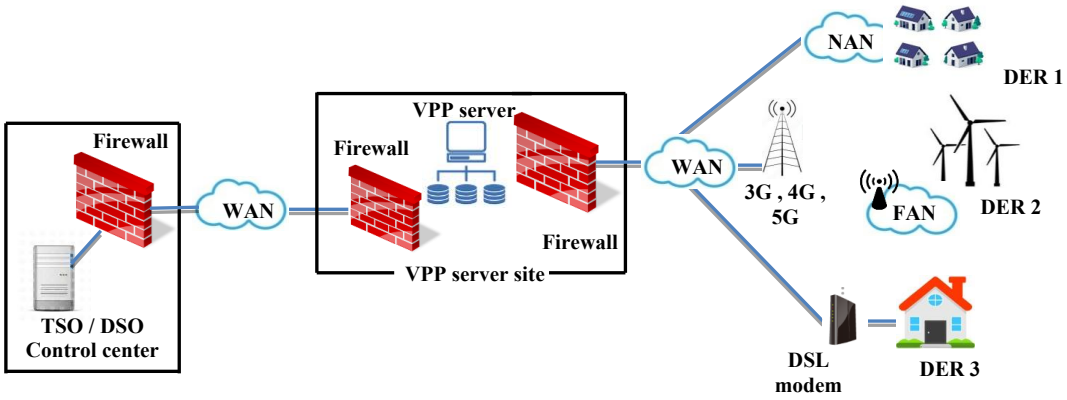


Fig. 13. Communication system architecture of the centralized-control VPP.

In another work [16], a distributed-controlled VPP topology is proposed, with the communication architecture divided into three layers: the local network layer, the remote network layer, and the VPP Platform network layer, as shown in Fig. 14 . The communication functions are divided by the three-layer VPP communication architecture based on their different network performance metrics requirements. To enable diverse access to various end devices, the design incorporates both wired and wireless communication. The VPP platforms consist of three platforms: the VPP control platform, the power dispatching cloud platform, and the power trading market operation platform. Communication within these platforms is enabled by the network layer platform. The remote network layer uses wired and wireless communication technologies that connect these platforms to the local VPP. From the perspective of the different end devices, the three VPP platforms look like a single large VPP control platform. Finally, the local network layer is used to connect the units inside the VPP with an aggregation control gateway (local VPP), such as different DERs (for example, wind power and photovoltaic generation), controllable loads, energy storage systems, and electric vehicles (EVs).

The main elements in the local network layer can be categorized into three types, which include demand-side resources, terminal equipment, and aggregation control devices. Demand-side resources encompass DERs, different types of loads, and energy storage systems. While the terminal equipment consists of smart meters, data collectors, and

inverters. Finally, the aggregation control devices include telecontrol devices, concentrators, distribution, automation terminals, and substation integration terminals.

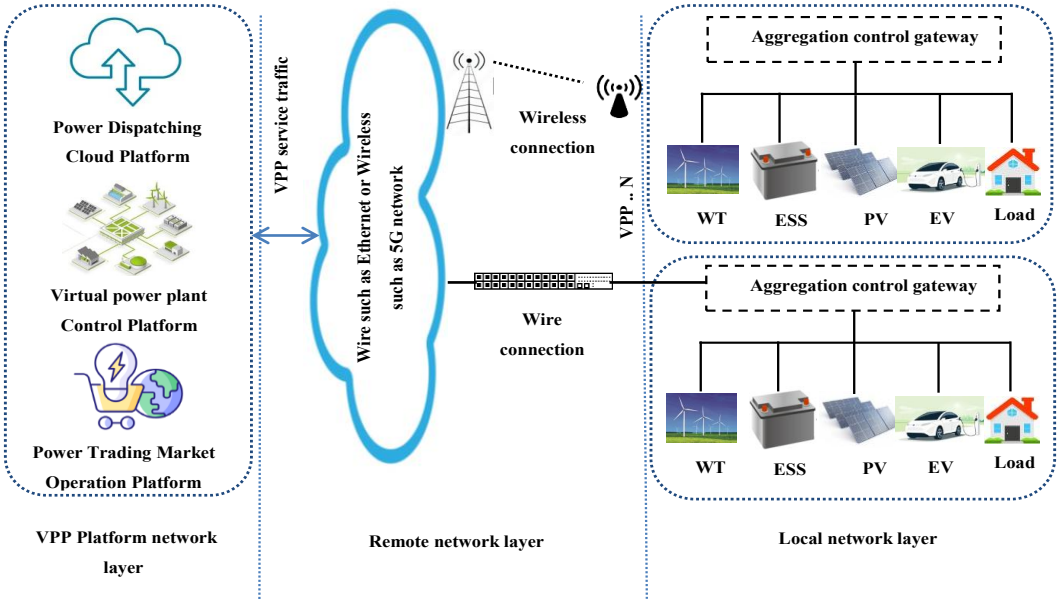


Fig. 14. Communication system architecture of the distributed-controlled VPP topology.

Correspondingly, the proposed communication system architecture, as mentioned earlier, depends on the specific VPP system topology used, where the operational requirements of the VPP are met by the correct choice of communication technologies.

3.4.1. Types of Communication Networks and their Technologies in VPPs

In the VPP, telecommunication systems are characterized by a hierarchical communication architecture [7]. This architecture encompasses diverse network types, including wide area networks (WANs), field area networks (FANs), neighborhood area networks (NANs), and home area networks (HANs). These network types exhibit distinct requirements for data rate and coverage distance. Therefore, the communication technology must be carefully selected to support these specific requirements [48], Table 4 summarizes the communication technologies for each network type [49]. The communication networks use a variety of technologies for communication, both wireless and wired.

Table 4. Summarizes the communication technologies for each network type

Network category	coverage distance	Data rate requirements	Data rate	Technology alternatives
WAN	10–100 km	High data rate. Devices such as routers and switches.	10Mbps - 1Gbps	Wireless: like WiMax[56], 3G,4G,5G. Wired: like Ethernet, Fiber Optic
NAN/FAN	10 m–10 km	Highly dependent on node density and topology	100kbps - 10Mbps	Wireless: like ZigBee[57], Wi-Fi, WiMax, Cellular. Wired: like PLC
HAN/BAN/IAN	1–100 m	Dependent on application. Generally low data rate required.	10–100kbps	Wireless: like ZigBee, Z-wave, Wi-Fi. Wired: like Ethernet, Home Plug, M-Bus

Wired communication technologies offer several advantages, including greater resistance to interference and reduced reliance on batteries compared to wireless technologies. However, they also have certain drawbacks, such as high implementation costs and potential signal quality degradation, particularly in power line communication (PLC) technology [58]. Notably, PLC is the only wired technology with implementation costs comparable to wireless methods, as it utilizes existing power cables for data transfer [59]. Furthermore, PLC technology is known for its wide coverage, ease of implementation, and long range [60]. Some of the wired communication technologies, along with their associated characteristics, in addition to the applications that utilize these wired technologies are summarized in Table 5 [61, 62].

Table 5. A list of wired/ wire-line technologies, their associated characteristics, and related applications

Wired /wire-line technologies	Standard	Eligible to be	Frequency range	Data rate	Coverage area (m)	Applications
PLC	IEEE 1901 family	HAN, IAN, BAN, NAN and WAN	⩽30M Hz	⩽3Mbps	⩽150k	Smart meters (AMI), HEMS communication, LV feeder monitoring, Monitoring small DER (solar, batteries), Residential demand response
Fiber	G.6xx family	FAN, NAN, WAN	1014 - 1015 Hz	Up to 40 Gbps	Up to 100k	Metering data, Monitoring of DER status, Periodic reporting, Backup communication channel
Digital subscriber line (DSL)	ITU G.99x.x	FAN and NAN	Up to 12M Hz	⩽100 Mbps	⩽5k	Smart meters communication, Home Energy Management, Systems (HEMS), LV feeder monitoring, Small-scale VPP components inside buildings

Table 6. A list of wireless technologies, their associated characteristics, and related applications

Wireless Technologies	Standard	Eligible to be	Frequency used	Data Rate	Coverage Area (m)	Security Level	Applications
Radio frequency identification (RFID)	Electronic product code (EPC)	HAN, IAN, and BAN	125 kHz to 5.8 GHz	100 kbps	≤200	Medium	Asset tracking for DER equipment, Inventory and maintenance management
ZigBee	802.15.4	HAN, IAN, BAN, and NAN	ISM	Up to 250 kbps	≤100	High	Home energy management (HEMS), Smart appliances in VPP, Local DER coordination in buildings
Bluetooth	802.15.1	HAN, IAN, and BAN	2.4GHz	Up to 10 Mbps	≤100	Medium	Device-level sensing, Local monitoring (inverters, sensors), Not suitable for grid-level control
Wireless local area network (WLAN)	802.11x family	HAN, IAN, BAN, and NAN	2.4, 3.6, 5.8, 60 GHz	From Mbps up to Gbps	≤1 k	Med to high	Local VPP gateways, DER data uploading, Smart home integration
2nd Generation (2G), such as GSM and GPRS.	European Telecommunications Standards Institute (ETSI)	WAN, NAN, FAN	900 MHz, 1800 MHz	Up to 10 kbps	≤10k	High	Smart meters in remote areas, Basic status reporting from DER, Backup communication channel
3rd Generation (3G), such as UMTS and HSPA	3GPP	WAN, NAN, FAN	2100 MHz	Up to 1 Mbps	≤1 k	High	Distributed asset monitoring, Data exchange from small PV/DER systems
4th Generation (4G) such as LTE	3GPP	WAN, NAN, FAN	700 MHz to 2.7 GHz	Up to 100 Mbps	≤10 k	High	Real-time DER monitoring, VPP aggregator communication, Remote control of distributed generators and batteries
5th Generation (5G)	No uniform standard	NAN, FAN	⩾24GHz	Up to 20 Gbps	⩽500	High	Real-time VPP control, Fast frequency response, Coordinated control of large DER fleets, EV fleet integration and demand response
WiMAX	802.16x family	WAN, NAN, FAN	700 MHz to 66 GHz	Up to 100 Mbps	⩽70 k	High	Rural DER communication, Wide-area monitoring for VPP
Low power wide area network (LPWAN)	Unlicensed like : Lora WAN and Sigfox. Or License like : eMTC and NB-IoT	HAN, IAN, BAN, and NAN, and WAN	⩽2GHz	Up to 250 kbps	⩽35 k	Med to high	Status data from distributed sensors, Smart meters, DER health monitoring, IoT devices in VPP
Satellite	ETSI and ITU	WAN	C, Ku, and Ka bands (up to 40GHz)	Up to 1Gbps (Ave. DL-1Mbps Ave. UL-256Kbps)	Up to 6000k	Med to high	Remote/off-grid DER monitoring, VPP operations in isolated areas, Backup channel for critical sites

Wireless channels offer greater versatility compared to wired ones due to their cost-effectiveness, reliability, and scalability. Expanding a wireless network requires only the addition of new nodes and routers, eliminating the need for additional cabling. While cellular networks (such as 3G, 4G, 5G, and the emerging 6G [63]) are robust and advanced technologies, they operate on licensed radio frequencies, resulting in high operational costs for third-party usage [64]. In contrast, technologies like Wi-Fi and ZigBee offer a more favorable cost-benefit ratio. Nonetheless, because these wireless technologies rely on unlicensed frequencies, they are more prone to interference, line-of-sight limitations, and security vulnerabilities, which can result in significant variations in latency and data loss [65]. For real-time applications in VPP, the WiMax technology based on the IEEE 802.16 standard is a suitable solution for wireless communication [66, 67]. Similar to wired channels, the coverage of wireless systems is determined by the specific technology employed. Table 6 summarizes wireless technologies, along with their associated characteristics, as well as the applications that use these wireless technologies [61, 62].

3.4.2. VPP Communication Standards and Protocols

The integration costs to provide VPP services are a major concern, given the diverse units within the VPP that belong to different owners and are from different manufacturers, each of which may use its own proprietary communication interface. For a VPP to be cost-effective in integrating a wide variety of DERs, standardized communication interfaces are required to support interoperability at multiple levels [68].

Based on a specific communication architecture, the next step is to carefully select and properly configure the relevant communication protocols. These protocols are a collection of technical rules that define how data is formatted, connected, transmitted, and exchanged. The importance of these protocols lies in defining how DERs communicate with each other and with the VPP control center, as well as how to mitigate data conflicts and prevent transmission failures [69].

The process of choosing a protocol begins with analyzing the communication requirements, followed by selecting the protocol that best meets those needs [70]. Several communication protocols are used in VPPs, and Table 7 presents some of these protocols, which serve as a guide for the design of local communication, control/ management systems, automation systems, physical interfaces, cybersecurity, and integration [17].

Table 7. A selection of communication protocols utilized in VPP systems.

Standard	Year	Focus area	Application
IEC 802	1980	Networking protocols for LANs, PANs, MANs	Ethernet, Wi-Fi
IEC 61850	1995	Communication protocols for substation automation	Substations, Microgrid
IEC 61968	2013	Data exchange in electrical distribution networks	System operators, Utility companies, Retailers
IEC 62443	2018	Cybersecurity for automation and control systems	System operators, Utility companies, Retailers
IEC 62264	2020	Integration of enterprise control systems	System operators, Utility companies
IEC 61970	2022	Interfaces for energy management systems	System operators, Utility companies, Microgrid
IEC 62351	2023	Communication security, authentication, and intrusion detection	ICT systems
IEEE 1547	2003	Integration of distributed energy resources (DERs	System operators, Utility companies, Microgrid
IEEE 1646	2005	Communication requirements for substations	Substations
IEEE 2030	2011	Smart grid interoperability guidance	System operators, Utility companies, retailers, End users
OpenADR	2009	Data model, interfaces, and automation for demand response	Demand response

In context, Communication protocols are primarily classified into wired (or wire-line) and wireless protocols [30]. The basic communication technologies for wired protocols include optical fiber, twisted pairs, and Power Line Communication (PLC), while wireless communication technologies mainly rely on Wi-Fi, Bluetooth, Zigbee, and cellular networks (3G/4G/5G) [16, 31].

IEC 61850 is a widely adopted and advanced wired protocol. This protocol serves as an information model and communication architecture standard in the SGAM model, designed to enable interoperability within power utility automation systems [68, 71]. Compared to earlier standards like IEC 60870-5-104 [39], IEC 61850 offers enhanced functionalities, including real-time GOOSE and SMV data exchange, a standardized configuration language, and information modeling approaches [17]. To improve the communication and coordination between a VPP operator and DER units, the author in [68] used IEC 61850 to provide grid services.

In practice, wireless communication technologies are widely utilized, with the IEEE 802 family of protocols being

the most prevalent. Among them, the IEEE 802.11 standard is widely recognized for enabling Wi-Fi and its variants. [72]. In [73], the authors proposed a communication and computing architecture intended to virtualize several RER plants within a VPP, employing IEEE 802.11 and long-term evolution (LTE) technologies.

Finally, the Open Automated Demand Response (OpenADR) is widely used in Virtual Power Plant DR applications [74]. It serves as a communication data model while also defining transport and security mechanisms [75]. OpenADR facilitates the exchange of data, including measurement reports, forecasts, schedules, market price data, and baselines [76]. Notably, OpenADR 2.0b has been adopted by the International Electrotechnical Commission (IEC) as Publicly Available Specification IEC 62746-10-1 [9].

4. Emerging Technologies, Security and VPPs in Real word

4.1. Emerging Technologies in VPPs

In the implementation of VPPs, additional technologies can be integrated to enhance operational efficiency, such as intelligent control systems, edge computing architectures, smart inverters, and advanced communication protocols [8]. The use of emerging technologies in VPPs enhances their performance in several aspects, including security, advanced control, data analysis, and decision-making. In the security domain, artificial intelligence and machine learning algorithms can detect anomalous activity within the network and identify security vulnerabilities.

Artificial intelligence (AI) employs intelligent methods and algorithms that can be applied in various aspects. It enables efficient management of numerous entities, such as plants, consumers, prosumers, and energy storage systems, by analyzing data to facilitate autonomous operations, grid maintenance, and decentralized control. In VPPs, AI accelerates and optimizes data analysis for energy generation, supply, and consumption. Moreover, it enhances energy trading through machine learning, deep learning, and reinforcement learning, utilizing weather forecasts, electricity market conditions, demand trends, participant data, and historical data, which is known as algorithmic trading [77, 78].

Blockchain technology offers a solution for enabling decentralized energy trading and enhances transparency and trust among participants in virtual power plants through the use of smart contracts and tamper-proof transaction records. Despite its benefits and advantages in terms of security and reliability, its maturity level in virtual power plant applications remains limited. Most current studies are limited to simulation models or small pilot projects. Furthermore, challenges related to latency, scalability, and computing power requirements prevent their practical adoption in real-time response applications.

The distributed control solutions for VPPs are not limited to peer-to-peer (P2P) sharing [79] and blockchain technology [80]. Emerging approaches like federated learning and edge computing also enable distributed decision-making. Federated Learning (FL), also referred to as collaborative learning, is a decentralized approach that eliminates the need for exchanging local datasets. Instead, the FL model can be fed with heterogeneous datasets to expand the model pool on the cloud side, thus improving overall system performance [81]. In contrast, edge computing aims to create a distributed model that processes data locally, near its sources, making it an ideal solution for energy management in VPP. The smart inverter is considered one aspect of technological development. It receives commands from the control center, processes data, and makes decisions, thus reducing response time and sending the status to the control center.

4.2. Security

Cybersecurity plays a vital role in providing comprehensive protection across the enterprise for modern VPPs. It involves securing communication infrastructure, control systems, and computer networks, along with monitoring, managing, and safeguarding the power supply [82]. Although protection is important, achieving it in real time is a critical and sensitive point based on latency issues caused by poor wireless connectivity [83]. As shown in Fig. 15, the cybersecurity objectives in VPPs include ensuring the availability and reliable access to information, maintaining information integrity and protection against unauthorized modifications, and safeguarding privacy and proprietary data [84].

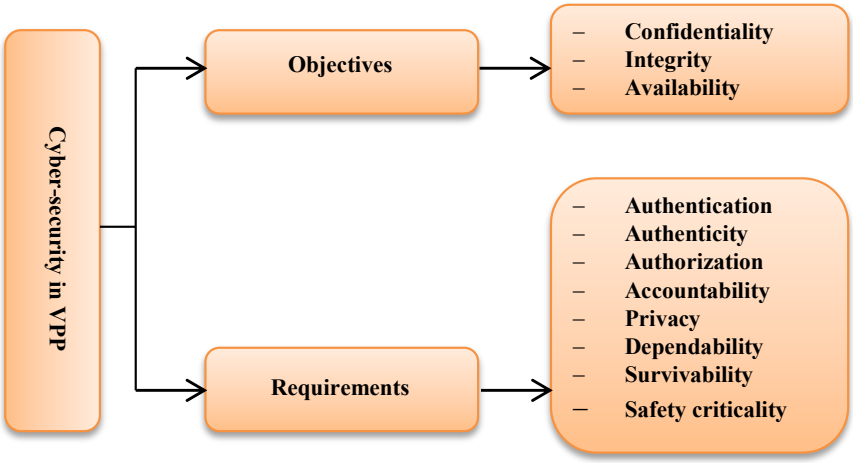


Fig. 15. VPP security objectives and requirements.

In addition to these objectives, cybersecurity entails various requirements, including user and device authentication, information encryption, accountability, consumer confidentiality, prevention of internal faults, system survivability, and the implementation of efficient and secure communication protocols [10]. These objectives and requirements are vulnerable to various cyber threats, including replay attacks, data modification or injection, denial of .service, and masquerade attacks [85]

Table 8 illustrates the most prominent attacks faced by the VPP at different security levels and their relationship to the cybersecurity requirements and objectives that must beachieved [86].

Table 8. VPP attack at different security levels

Security level	Objectives	Requirements	Attack methods
Communication infrastructure	Availability	User authentication	Jamming, Eavesdropping
Control systems	Availability	Device authentication	Denial of service, Sniffing
Computer networks	Information integrity	Information encryption	Data tampering
Monitoring	Availability	Communication protocols security	Traffic flooding, ARP spoofing, wormhole
Management	Confidentiality	Accountability	MITM attack, Social engineering
Power supply protection	Confidentiality	Internal faults and physical protection	Control tampering, Time synchronization

4.3. Typical Case of VPPs

The first real virtual power plant project in Europe, the Virtual Fuel Cell Power Plant (VFCPP), was developed between 2001 and 2005. The project focused on installing fuel cells as a RES in households. To maximize profits for both consumers and utilities at the same time, the project enabled utilities to manage CHP generators during peak hours [87]. However, as a project developed based on mixed-integer linear programming optimization focused solely on fuel cells, integrating other resource types significantly increases the algorithm's complexity and slows down its performance, making it less efficient [11].

Between 2005 and 2024, numerous VPP projects have been launched globally, featuring various scales, structures, and technologies [87]. These projects are systematically documented in Table 9, which highlights the pivotal strategic and operational significance of VPP technologies in contemporary distributed energy resource management [69].

Several studies provide summary reports on VPP projects. Among these reports, such as [87, 88], the Fenix and Edison projects are highlighted as two of the most internationally renowned. The Fenix project is a European collaborative initiative, partially funded by the European Commission under the 6th Framework Program for Research. It involves 20 partner organizations and operates with a total budget of €14.7 million [89]. This project aims to integrate DER into the operation and development of electricity networks in a cost-effective manner [12]. While the Edison project utilized the aggregation of electric vehicles, including plug-in hybrid electric vehicles, to provide the energy balance required to increase the use of wind energy in the Danish electricity grid [90]. VPPs around the world are built

on needs and realities, therefore there is no general framework for them, although their architecture is similar. This review study was presented to clarify this point by providing a comprehensive overview of the communication network infrastructure, its requirements, and its integration with VPP applications.

Table 9. A selection of real virtual power plants from around the world

No.	Project name	Country	Time duration	Type of DER	Function
1	Fenix	Spain, U.K, France	2005-2009	PV, WT, μ-CHP	Ancillary services, Reactive power control, Balancing and congestion management
2	Edison	Denmark	2009-2012	PV, WT, μ-CHP, DSL	Energy balance, Vehicle-to-grid
3	Twenties	Denmark	2010-2013	PV, WT, μ-CHP, hydropower, heat pump, EV, industrial load, building	Fast frequency demand response, Reserves and voltage control
4	Web2Energy	Germany, Poland	2010-2015	PV, WT, CHP, hydropower, biogas	Smart energy supply and management
5	Smart Power hamburg	Germany	2011-2015	Heat storage, CHP	Thermal storage, Energy balance
6	City-zen	Netherlands	2014-2019	PV, residential load, home BES	Local energy balancing
7	Insulae	Denmark	2019-2023	PV, WT, EV, biogas, thermal storage	Flexibility support
8	Statkraft VPP	Germany, U.K.	2019-2023	PV,WT, EV, hydropower, industrial load, hydrogen storage	Balancing services
9	VPP4Islands	France, Germany, U.K, etc.	2020-2024	PV,WT, EV, BES	frequency and voltage control, Reactive power, Renewable energy integration
10	POSITYF	France, Spain, etc.	2020-2023	Renewable energy resources	Ancillary services
11	Sunrun VPP	U.S. - California	2019-2022	PV, BES	Capacity reserve services
12	OhmConnect VPP	U.S. - California	2020-2023	PV, WT, residential load	Peak load reduction, Smart thermostat control
13	Shelter Valley VPP	U.S. - East San Diego.	2022-2023	PV, BES, DG, thermostat	Demand shift and reduction, Reduce outages, Improve reliability
14	SPEEDIER	Canada	2018-2022	PV, BES,EV, controllable water tanks	Reduce peak load, Energy balance
15	AGL VPP in Southern Australia	Australia	2017-2022	PV, BES	Charging fleet management, Demand-side management, Voltage control
16	Tesla VPP in Southern Australia	Australia	2020–2023	PV, BES	Fast frequency response, Inertia/Emergence response, Voltage support
17	Northern Hebei VPP	China	2019	DG, EV, heat pump, storage system, industrial/commercial users	Ancillary services, Demand response, Energy trading
18	Shenzhen VPP	China	2020	PV, EV, storage system	Voltage control, Energy balance
19	Miyakojima VPP	Japan	2021–2024	PV, BES	Self-sufficient energy supply, Solar energy integration

5. Conclusion

This paper provides a comprehensive review of communication networks for VPPs. While many studies address VPPs from the perspective of energy management, energy optimization strategies, and algorithms, few studies focus on their communication networks. It was observed that existing research on VPP communication lacks a network design

that integrates communication technologies, communication protocols, and the data size in bytes, and classification of signals exchanged in communication networks. This lack of design prevents a complete and practical understanding of network performance in terms of latency, reliability, and bandwidth. Furthermore, the use and integration of emerging technologies in communication networks has often been limited to conceptualization without providing a simulation model to demonstrate their impact and how they improve network performance. On the other hand, regarding cybersecurity and cyberattacks, many studies describe attacks and the security requirements for mitigating them, but without offering a simulation model for these attacks in VPP communication networks and proposing practical solutions to mitigate their effect within the simulation model itself.

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