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A Review of the Evolution and Main Roles of Virtual Power Plants as Key Stakeholders in Power Systems

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ABSTRACT Virtual Power Plants (VPPs) allow the aggregated management of diverse power technologies in systems of different size, complexity and connectivity. The main objectives of a VPP are to ensure the correct integration of these technologies into power systems, to optimize the power production and load demand, and to meet the technical and commercial requirements, considering the stakeholders' needs. This paper provides a literature review of the most influential factors as regards the management of VPPs. This literature review includes aspects like the evolutionary frequency of the concepts/definitions most used, the VPP operation, planning and interaction with the systems, programming methods, math techniques and software tools used to solve the issues proposed and the international VPP projects as reference for the systems development. Therefore, this work aims to provide the reader the information and concepts that can support for a better understanding of the role of VPPs in power systems, the approach to sustainability and the interaction with the power market as the good way to bring new economic opportunities to small producers, consumers and prosumers of renewable energy.

INDEX TERMS Power market, power system, renewable energy, virtual power plant.

NOMENCLATURE

BESS	Battery Energy Storage System.
CHP	Combined Heat and Power.
CO_2	Carbon dioxide.
CVPP	Commercial VPP.
DER	Distributed Energy Resource.
DG	Distributed Generation.
DGC	Digital Grid Controller.
DGR	Digital Grid Router.
DNO	Distribution Network Operator.
DoE	Department of Energy.
DR	Demand Response.
DSO	Distribution System Operator.
EC	European Commission.
ECN	Netherlands Energy Research Center.
EEA	European Environment Agency.
EMS	Energy Management System.
EU	European Union.
EV	Electric Vehicle.
G2V	Grid-to-Vehicle.
ICT	Information and Communication Technology.
IoT	Internet of Things.
KKT	Karush-Kuhn-Tucker.
LP	Linear Programming.
LSVPP	Large Scale Virtual Power Plants.
M2M	Machine-to-Machine.
MILP	Mixed-Integer Linear Programming.
MINLP	Mixed-Integer Non-Linear Programming.
MPC	Model Predictive Control.
NLP	Non-Linear Programming.
P2P	Peer-to-Peer.
PHEV	Plug-in Hybrid Electric Vehicle.
PHSP	Pumped Hydro Storage Plant.

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PV	Photovoltaic.
REC	Renewable Energy Certificate.
RES	Renewable Energy Sources.
SDG	Sustainable Development Goal.
SFR	System Frequency Response.
TSO	Transmission System Operator.
TVPP	Technical VPP.
V2G	Vehicle-to-Grid.
VPP	Virtual Power Plant.

I. INTRODUCTION

The population growth, globalization and technological developments imply a continuous increase in power consumption and production. The environmental pollution on the planet has consequently undergone a notable increase in the last few decades. The European Environment Agency (EEA) notes that 60% of the sulfur oxides emitted in the last five years have originated from energy production and distribution, in addition to which, more than 40% of nitrogen oxide emissions have originated from road transport [1]. The European Union (EU) has, therefore, defined objectives in order to reduce the environmental pollution caused by the so-called greenhouse gas emissions.

The EEA hopes to achieve climate neutrality in Europe by 2050, proposing to reduce greenhouse gas emissions by 55% by 2030 [2]. The commitments acquired by the EU as regards the reduction in greenhouse gas emissions are established through its energy policies [3] and energy strategies [4], which are in line with the United Nations' objectives for sustainable development [5].

The evolution of power production is developed according to the balance between power consumers' requirements and power producers' objectives. Various authors state that the appropriate combination of technologies will allow Virtual Power Plants (VPPs) to guarantee a reliable power supply in power distribution networks [6]–[10].

VPPs must, therefore, be properly managed in order to optimize the corresponding stakeholders' power production and consumption. Moreover, researchers indicate that, by considering different Distributed Energy Resources (DERs) and even combining them with other distribution networks, VPPs can be considered as independent units that interact with power markets. Knowing the technical and economic constraints of the units within VPPs, the operation can be optimized in order to maximize the profit from the sale of power surplus, in addition to minimizing operating costs.

A. OVERVIEW OF RELATED SURVEYS/REVIEWS

Scientific literature currently presents a huge compendium of definitions, models and projects, among other topics related to VPPs and power systems. This paper, therefore, takes as a reference 21 surveys/reviews related to concepts inherent to VPPs and power systems in order to present an overview of the scientific content that the reader can find in this study field.

In [11], it is proposed a descriptive approach in which the future development areas of smart grids and their interaction with VPPs are indicated. The smart grid architecture model, Demand Response (DR) programs and Battery Energy Storage System (BESS) are mentioned in order to establish the interaction of stakeholders and VPPs within power systems. In [12], the authors analyzed the convergence areas between the collaborative networks discipline and the VPP concept, considering development trends in power systems. Moreover, concepts such as virtual power players, virtual organization, collaborative networked organizations, among others, are described in order to propose a scientific base that will support future research in power ecosystems.

In [13], a description of the concepts related to controllable load management according to the integration of smart grids by VPPs is indicated. The load characteristics, the control strategies and the control effectiveness are mentioned, highlighting the concepts of Vehicle-to-Grid (V2G), BESS, combined cooling, heating and power of hybrid systems with renewable energy. Moreover, in [14], the strategic planning for the interaction of smart grids through VPPs using Information and Communication Technologies (ICTs), advanced distributed automation, energy storage technologies, power electronics and other concepts are mentioned. Power system models such as smart grids and smart homes present key information for the development of smart cities.

In [15], the authors mention concepts such as DR, Grid-to-Vehicle (G2V), V2G, Machine-to-Machine (M2M) and Internet of Things (IoT), indicating an overview of different technologies applied in smart grids with VPPs. Connections between smart grids, conventional power grids, Electric Vehicles (EVs) and smart devices, through software and technologies, are described.

In [16], the planning, operation and mathematical formulation of VPPs in order to operate in power systems and power markets are described. The uncertainties related to the production from renewable energies, smart energy hub and the classification of VPPs as commercial and technical entities are mentioned. Furthermore, in [17], the relationships between micro grids and VPPs are indicated. The activities and operations managed within micro grids are indicated, together with the concepts of Energy Management System (EMS), scheduling and solving multi-objective problems. In addition, in [18], the uncertainties related to renewable energies, market prices, load demands and the integration of VPPs are considered. The objective functions and mathematical constraints with which to measure the influences of uncertainties, in addition to the tools used to solve optimization problems, are described.

In [19], the authors describe the evolution from smart grids toward smart cities, indicating concepts such as micro/nano grids, smart cities and smart water grids. The descriptive evolution makes it possible to attain a more detailed differentiation between the operations and structural processes of each power system mentioned. Moreover, in [20], the evolution of digital technologies for data communication in power distribution networks is indicated. Concepts such as internet of energy, EMS and power line communication are described, presenting comparative schemes between present and future power grids, together with the bidirectional power transfer of prosumers.

In [21], the authors describe the concepts that define the blockchain technology, along with Peer-to-Peer (P2P) protocols (e.g.,Bitcoin and Etherium), network architectures (e.g., centralized and decentralized), consensus algorithms (e.g.,PoW, PoS, PoC) and the potential impacts on the power companies and power market. The integration of power systems with blockchain technology through VPPs using IoT, smart devices and artificial intelligence are mentioned.

Furthermore, in [22], the blockchain applications in power trading, EVs, micro grid operations and cyber-physical security are indicated. Base concepts for the interpretation of blockchain technology are mentioned, as are projects and case studies that have been successful with the implementation of this technology. In [23], the analysis of the interaction of smart grids power trading operations in the power market using blockchain technology is mentioned. The definition of concepts such as transactive power, supervisory control and distributed ledger technology is provided in order to indicate the differences between several blockchain architectures that are applicable to power systems.

The evolution of micro grids with converter-interfaced generations is provided in [24]. The micro grids characteristics, their classifications, together with the advantages, disadvantages and benefits of integrating with ICTs, renewables energies, smart meters and cyber-security protocols are described in detail.

In [25], the interactions between power distribution networks, power electronics devices, ICTs, technologies for small-scale generation, hybrid technologies and storage power systems are described. The technical and economic impacts of active management power systems are highlighted, as are the regulatory policies. In [26], the authors indicate technical barriers to up-scaling smart local power systems according to integration, uncertainty and diversity in power systems. Some digital technologies, the EVs integration, the demand and supply of power and some non-technical barriers are analyzed.

A descriptive information on smart grids is presented in [27]. The definitions, characteristics, components, functions, infrastructural, technical and technological evolutions are mentioned in detail, showing graphic diagrams. The different applications of smart grids technologies for home and building automation, substation automation and feeder automation are indicated. In [28], the opportunities and challenges of smart grids are analyzed in a Japanese smart grid in which blockchain technology is applied. Technologies for the production, distribution and storage of power within the smart grid, along with those of its interaction with other systems and the interaction with VPPs, are mentioned. Moreover, smart grid relationships with other ICTs, together with the economic, social, environmental and institutional impacts are described.

In [29], the authors mention concepts related to power generation and bidding optimization through the integration of power distribution networks by a VPP. The VPP concepts are described, in addition to their forms of operation in the systems and the technical structures for the definition of mathematical models are presented. In [30], the active management of micro grids and VPPs is analyzed. The activities description and control operations carried out in micro grids in order to share and properly distribute the power produced and stored are mentioned. The power trading carried out by the micro grids through the interaction of VPP in the power markets is schematically indicated. In [31], the analysis performed to expose non-technical losses during transmission and distribution of power in a smart grid with the operation of a VPP is described in an Indian context. The actions required for the measurement, control and contingencies applied to the power network in power losses situations are indicated.

Table 1 compares this work with the surveys/reviews mentioned above.

B. MAIN CONTRIBUTIONS OF THIS REVIEW

Considering the above, this paper provides a review of the main references for the systems integration by VPPs, addressing the interaction with the power market, the mathematical optimization and the digital technologies applied to power systems.

Within this context, the main contributions of this paper are fourfold:

- A chronological scheme of the last 15 years that shows the first appearance and evolutionary frequency of the concepts/definitions related to VPPs that are mostly used by researchers within the articles cited in this review.
- An overview of the way in which the VPPs operate, plan and interact with the internal elements of their power systems and with the external elements: other power systems, power markets and stakeholders.
- An organized identification of programming methods, math techniques and software tools used to solve the issues proposed by researchers, towards power production, distribution and profit in different power systems.
- A compilation of more than 20 international projects that are taken as reference for the development of new power systems integrated by VPPs.

In summary, this paper provides a composite review in the field of smart power systems and VPPs. In order to achieve this goal, the concepts required in order to enable the reader to interpret the key strategies for VPPs and the strong factors as regards decision-making are indicated.

C. ARTICLE STRUCTURE

The remainder of this paper is organized as follows. Section 2 mentions a general context to initially understand the key focus used by VPP in power systems. Section 3 describes the interaction of VPPs with traditional

TABLE 1. Proposed approach vs. Related surveys/reviews.

Reference	Traditional and Renewable Power Technologies	Industry 4.0 Integration	Power Market	Mathematical Optimization	International VPP Projects	Sustainability	VPP Concepts Evolution Timeline
[11]	·	✓	·	·	·	·	·
[12]	·	✓	✓	·	·	·	·
[13]	·	✓	·	·	·	·	·
[14]	·	✓	·	✓	·	·	·
[15]	·	✓	·	·	·	·	·
[16]	✓	·	✓	·	✓	✓	·
[17]	✓	·	·	✓	·	·	·
[18]	✓	·	✓	✓	✓	✓	·
[19]	·	·	·	·	✓	✓	·
[20]	✓	✓	·	✓	·	·	✓
[21]	·	✓	✓	·	·	✓	·
[22]	·	✓	·	·	·	·	·
[23]	·	✓	✓	·	·	·	·
[24]	✓	·	·	·	·	·	·
[25]	·	✓	·	·	·	·	·
[26]	✓	·	·	·	·	·	·
[27]	·	✓	✓	·	·	·	·
[28]	·	✓	✓	·	·	·	·
[29]	·	·	✓	·	·	·	·
[30]	·	·	✓	·	·	·	·
[31]	·	·	·	·	·	✓	·
Proposed Approach	✓	✓	✓	✓	✓	✓	✓

and modern power systems. In Section 4, the concepts of pricing according to power demand and supply in the power market are shown. Section 5 classifies several models proposed by researchers according to the strategies to solve uncertainty problems through mathematical optimization methods. Section 6 provides a description of trends and innovations in power systems integrated by VPPs so as to encourage present-day and future researchers in renewable energy research through VPP interaction. Section 7 provides the conclusions.

II. VPP GENERAL CONTEXT

As a preamble to guide the reader, below is a general mention of basic concepts and fundamentals that connect with the roles of VPPs in power systems. This information allows the reader to initially understand the key focus used by VPP in power systems.

A. VPP CONCEPTS EVOLUTION TIMELINE

The in-depth reading of more than 180 scientific papers has allowed the generation of a concept scheme to help the reader to interpret the timeline of the concepts and definitions mentioned by different researchers. Most of the papers analyzed are publications that have appeared in the last 15 years.

Among the analyzed papers, terms such as "Distributed Generation (DG) Units" have been mentioned less frequently than terms such as "Micro Grids" and "Smart Grids" [32], while individual terms such as producers and consumers have been unified in the form of Prosumers [33]. Therefore, Figure 1 is a timeline that shows the first appearance and frequency relatives of the key concepts mentioned within the papers analyzed in this review. The concepts and definitions that are shown in blue (High Mention) are those that have been mentioned with a high frequency since their appearance within the papers analyzed in this review. The concepts and definitions that are shown in black (Middle Mention) are those that have been mentioned with a middle frequency compared to the previous ones. And finally, the concepts and definitions that are shown in gray (Low Mention) correspond to those whose frequency of mention has decreased since their first appearance. Their mention is infrequently within the papers analyzed in this review.

As research has progressed, several of the concepts have been complemented with others, forming new strategies and techniques with which to address the different challenges that arise with the requirements of sustainability and efficiency for power consumption and production. The operation and planning of VPPs allow the continuous integration of new technological elements and the development of new operational techniques with which to adequately satisfy stakeholders' requirements on a day-to-day basis.

B. VPP OPERATION

As the systems and technologies related to VPPs have been developed, so have their operating strategies. Each power distribution network has its own characteristics that allow VPPs to operate them using various techniques to obtain the best performance from each system.

VPPs can integrate their components in a distributed or centralized manner, controlling DERs by means of various agents that interact with the power market in the case of a

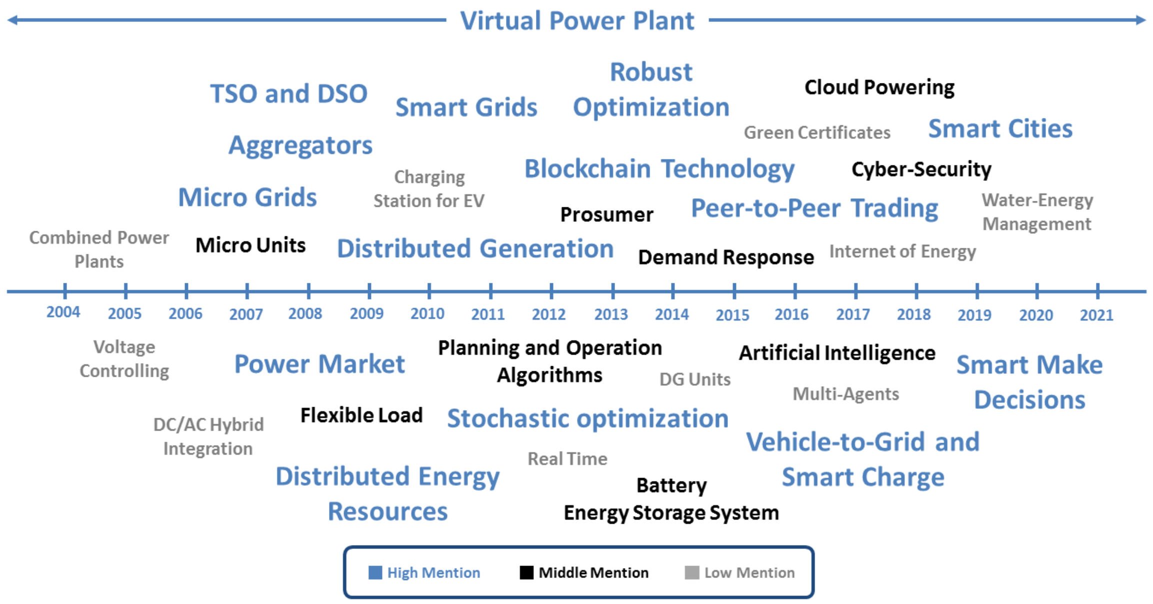

FIGURE 1. Evolution timeline of VPP-related concepts.

decentralized strategy, or by considering that the VPP is the only entity to interact with the power market in the case of a centralized strategy [34]–[36].

As an extension, in [37], the authors mention a distributed strategy in which DERs tend to have greater participation and autonomy. Moreover, these authors comment that there are approaches such as the direct approach, which allows VPPs to exercise control over the power system and make decisions centrally. There is also the distributed approach, which allows VPPs to exercise control over and make decisions regarding the system in a decentralized manner. Finally, in [38], the authors mention that there is a hierarchical approach in which the VPPs exercise control and make decisions according to the level of importance and authority that the stakeholders give them within the system.

During the operation of a VPP, it is important to control energy loads. In [39], a model that relies on the analogy between the direct control of differential loads and the flow admission control in telecommunication networks is presented. The model indicates the balance between resource usage, control overheads and privacy leaks. In the case of a control system, in [32], the authors maintain that it is important for VPPs to participate in the power market by carrying out operations as a management unit. In terms of control type, VPPs can be classified according to the way in which DERs are integrated, in which a decentralized control system allows each DER to be controlled locally by its own agent, while in a centralized control system there is a single coordination center for all the DERs in the system. With regard to the operation of VPPs, it is important to understand the impact of the different architectures of the integrated systems and which elements or characteristics allow them to interact in an appropriate manner. In [40], the interaction of renewable energies and VPP in interconnected networks can reduce inertia and spinning reserve in power systems. To maintain frequency stability within the system, a new System Frequency Response (SFR) model is proposed. This model allows, in the VPP operation, the best frequency response in frequency recovery for the system disturbances.

There are different levels of participation as regards the interaction of VPPs with DERs, operating agents, the power market and even with EVs. In this respect, VPPs are classified into two categories, considering the technological architecture of their systems, which are denominated as local VPPs and regional VPPs [41].

With the implementation of the hybrid system between DC/AC, VPPs are able to reduce the maintenance costs of their systems, promote the use of domestic generators, and have a better interaction in the power market [42] and [43]. The management of power systems to optimize the power flow, in order to determine the optimal sell price, minimize costs and maximize profits can be generated through the power transaction between the VPPs and the Distribution Network Operator (DNO) [44]. Moreover, in order to maintain a stable system, the application of game theory allows distribution systems to improve the reliability of transactions and reduce power losses in the power distribution network [45].

According to [46], the DR is related to the voluntary changes made by end-consumers to their consumption patterns in response to market signals, and the authors define two types of DR programs: explicit and implicit. Consumers can, therefore, receive lower billing prices (implicit) and payments for their participation in incentive programs (explicit). It is consequently important to establish incentives with which to stimulate DR in the systems integrated by VPPs.

The model presented in [47] shows the division of three modules, including data handling, data mining and decision-making, whose objective is to provide a solid strategy with which to allow VPPs to operate through the continuous processing of the data provided by the system managed. VPPs can compensate for variations in internal power production within their systems owing to the ability of energy storage systems. VPPs can also, through access to the different units or power charging systems, disconnect and reconnect the power flows according to the stakeholders' needs [48].

C. VPP PLANNING

Identifying and measuring the technical limitations of VPPs is essential for their good performance. The VPPs plan and schedule their operations before engaging with internal and external elements. However, the performance of the operations of VPPs may be restricted by infrastructural, technological and technical limitations, as they are not properly planned.

Analyzing the uncertainties derived from factors such as the weather and achieving forecasts with high levels of assertiveness, therefore, allows VPPs to maintain reliable data in order to interact with the power market, obtaining good benefits [49]. The model proposed in [50] indicates that measuring and controlling the controllable load of heating, ventilation and air-conditioning systems, together with the interaction of Photovoltaic (PV) panels and BESS, are key aspects as regards calculating the feasibility and flexibility that a VPP requires for its systems. Preparing a program for the measurement and control of the power available at specific time intervals, therefore, allows VPPs to improve their interactions with all the elements in their system and with Distribution System Operators (DSOs). The integration of power distribution networks led by VPPs can be divided into two main stages: one stage in which the planned program is executed by the various power production resources and energy storage devices that are available, and another in which, the scheduled program is executed by VPPs, DERs and other loads in the system at the DSO level [51]. Moreover, it is important to consider that good planning stipulates corrective actions in contingency cases. A corrective strategic programming model that focuses on the strategy of load serving entities is presented in [52]. The grid-level energy system and VPP models are formulated, which establish the power storage times with and without the interaction of the VPP.

Creating good planning strategies implies analyzing multiple time scales, since they are key aspects as regards determining the viability of the plans require by VPPs in order to satisfy their stakeholders' needs. This is indicated in [53], in which an analysis of multiple time scales makes it possible to guarantee the economic viability of the integration of VPPs into their systems. The planning of VPPs in relation to economic viability focuses on understanding long-term investment and short-term operation.

Moreover, it is important to bear in mind that good operational planning is directly related to good economic planning. The economic planning of VPPs is established by not only calculating the purchase and sale prices in the power market, but also considering Renewable Energy Certificates (RECs). The planning of the VPPs, therefore, defines schedules for each DER according to the production, consumption and distribution of power, along with the relationship of their power storage vs. REC values [54].

It is important to define all variables in order to establish the appropriate metrics that will guarantee the good performance of VPPs as regards maximizing benefits and minimizing desired costs [55]. The planning of VPPs at the level of integration and synchronization between different power distribution networks could make it possible to share power reserves, thus minimizing the possibility of system collapses that would not be feasible with other models [56]. The interconnection of the power systems integrated by VPPs would, therefore, make it possible to balance the excess power of one system versus the power shortage of another adjacent system, thus benefiting both systems economically. In addition, the power storage and auxiliary functions that establish the reliability of each system could also be shared, thus possibly allowing VPPs to take advantage when interacting with the power market owing to multi-grid planning.

D. VPP SUSTAINABILITY FOCUS

The United Nations have done excellent work as regards establishing and defining Sustainable Development Goals (SDGs) [5], giving humanity a path on which to evolve while protecting its habitat. At the European level, and considering the SDGs, the European Commission (EC) has established energy policies [3] and energy strategies [4] with which to confront sustainability challenges and achieve competitive growth in their countries.

The impact of Renewable Energy Sources (RES) must be considered in order to allow VPPs to define the objectives and sustainable compliance goals according to the requirements of their stakeholders. It is important to consider that forecasting renewable power production is not an easy task since it depends on many factors, such as weather, infrastructure and technology, which make this production unpredictable. However, the search for sustainable models and systems, such as P2P or V2G applicable to power systems, allow VPPs to align their operations with the environmental commitments required by stakeholders [57]. Moreover, by applying methodologies for the calculation of Carbon dioxide (CO_2) emission trading, it is possible to optimize the benefits in the markets, correctly taking advantage of the trader attributes that the VPPs have [58]. It is important to know the characteristics of the "Green Certificates" (see also REC in [54]), their relationships with the commercialization of CO_2, the power production from RES and their limitations in relation to certain technical and regulatory situations inherent to our times, with the aim of maximizing economic benefits [21] and [59].

The new energy business models and their cooperation strategies allow the interacting agents of the systems integrated by the VPPs to improve their organization. The organization of the agents encourages the use of renewable energies for power production and allows them to develop new sustainable business models as entrepreneurs in order to interact directly or indirectly with the power market while maintaining an environmental vision [60]. The increased penetration of renewable energy in power systems has created enormous challenges for grid operators to balance supply and demand in real-time. The interaction increase of the producers, consumers and prosumers of renewable energy managed by the VPPs could cause an imbalance between generation and demand. Considering the above, the authors in [61] describe a VPP business model with which concepts can be interpreted for the sustainable development of power systems led by VPP.

Achieving a competitive economy among the countries in the EU requires an increase in its renewable energy portfolio and a reduction in CO_2 emissions, focusing on the guidelines established by the EC for the year 2050. Achieving the guidelines proposed by the EC signifies that it is necessary to seek ingenious and efficient alternatives in the medium and long term, increasing the interaction of different power-producing technologies (e.g., nuclear plus wind), generating systems whose elements are more proactive to DR and even optimizing risk rate measurement strategies to make the most of the power produced. However, the regulatory frameworks in some countries and the high initial investment costs make it difficult to implement innovative systems integrated by VPPs [62].

Moreover, it is important to define a reliable measurement system that will make it possible to correct or adjust network designs, agent roles, and production and consumption policies. Considering infrastructural, technical and management deficiencies (network cabling, urban and rural areas, agents, stakeholders, etc.) will consequently make it possible to ensure that a power system will guarantee the reduction in power losses and optimize the production operations [63]. The difficulties encountered when implementing power systems integrated by VPPs must, therefore, be continuously analyzed. Difficulties can be mitigated by applying incentive strategies for the acquisition and implementation of BESS [64], or policies in which power producers, consumers and prosumers can access subsidized rates in trading operations [65].

III. POWER SYSTEM INTERACTION AND TECHNOLOGIES LINKED TO VPP

Several definitions of what a VPP is can be found in technical literature, some of which are more complex than others, but each of which provides key information that can improve the infrastructural and technological development of electric energy systems. Key concepts for VPPs are, therefore, presented below for the purpose of general knowledge interpretation with the objective of stimulating the analysis, discussion and interpretation of VPPs, and their link with different power systems.

A. VPP AND GENERAL DEFINITIONS

This paper features the concepts related to micro grids and smart grids, in which the aggregators are a type of agents. By knowing the definitions and main characteristics of micro grids, smart grids, aggregators and VPPs, the reader will have sufficient support with which to interpret the key concepts related to the integration of VPPs into power systems. The definitions and concepts obtained from the papers reviewed that are valuable and serve as an initial support in order to enable the reader to begin elucidating the concepts are shown below.

1) MICRO GRID

An interesting definition of micro grids is provided in [66]: "*A Micro Grid is an integrated energy system consisting of distributed energy resources and multiple electrical loads operating as a single, autonomous grid either in parallel to or "islanded" from the existing utility power grid*".

Micro grids generally trade the power from their system using a retail distribution model. When micro grids are carrying out their operations on the island, they normally confront legal and political obstacles as regards trading power with other power grids. Moreover, depending on the approach that stakeholders wish to provide to the performance of the system, they will focus on reliability or economic benefits [17].

The use of ICTs in micro grids makes it possible to improve the monitoring and control of power by applying concepts such as internet of energy and management of energy. Support for Industry 4.0, such as artificial intelligence, IoT, cloud computing, big data, mobile devices and cyber-security, are important as regards optimizing power trading [67]. Micro grids can include the participation of multiple consumers, producers and prosumers, and are able to connect power from different power sources with DERs owned by different stakeholders. Micro grids can be systems implanted in residential/commercial buildings, shops, schools, tourist complexes, hospitals, etc. A micro grid is, therefore, a small local network that manages DR programs and critical and non-critical loads in a specific community, which is interconnected with flexible DERs (e.g., BESSs, EVs, DRs, etc.) with a high renewable energies penetration [68].

2) SMART GRID

Two concepts of Smart Grids are highlighted in [69]: One is mentioned by the European Union (EU): "*a smart grid is an electricity network that can intelligently integrate the behavior and actions of all users to ensure sustainable, economic and secure electricity supply*" and the other is mentioned by the US Department of Energy (DoE): "*a smart grid uses digital technology to improve reliability, security and efficiency of the electricity system*".

Smart grids can include monitoring and automation components that improve control operations and increase access to system data. The infrastructural architecture of smart grids allows the production, distribution, consumption and storage of power according to DR programs. Components that synchronize the interaction between the DERs and power source production are defined in smart grids [70]. A smart grid provides a bidirectional network in real-time and allows the interacting agents in the system to participate in DR programs with the objective of integrating DERs by using ICTs to optimize power use [35]. By being implemented and deployed in the smart grids' advanced meter infrastructures, the bidirectional interaction between different entities and/or systems such as the power market, power storage systems and the public power grid, among others, improves the interaction and the connection in real-time [47] and [71].

3) AGGREGATOR

When mentioning the Aggregator concept, the authors of [13] state: *"An aggregator serves as a central control node which collects information from both the power grid and connects controllable loads. A load aggregator can also act as an interface between the controllable loads and the grid operator to provide the regulated management with joint consideration for benefits of both users and the grid"*.

Aggregators are used in power charging models for EVs and help optimize the charging of their batteries and improve the modeling of driving patterns and price forecasts when interacting with the power market [72]. In the power market, DERs can be represented by an aggregator in order to maximize profits according to the power levels dispatch based on remuneration prices [73]. Moreover, in [74], the aggregators can choose between different power plants according to pre-power-cost-based bids in a power market with bilateral contracts.

4) VIRTUAL POWER PLANT

A VPP is a system that groups and integrates different power production and consumption sources in order to generate benefits as regards consumption, production, storage and distribution according to its stakeholders' requirements.

Different classes of power production sources can be integrated on a small scale, allowing the interaction of wind turbines, PV panels, small hydroelectric plants, reciprocating natural gas engines and micro Combined Heat and Power (CHP) systems. A VPP that integrates its system centrally can operate dispatchable and non-dispatchable power sources in order to participate in the power market and maintain a reliable power supply for stakeholders [52]. Methodologically speaking, VPPs connect multiple power production facilities that are distributed territorially through a virtual smart network, controlling a single main service provider (power/capacity) and auxiliary services (regulations, reserves, etc.), in order to integrate the power grids [75].

As a communication system infrastructure, a VPP is an autonomous entity that provides flexibility and balancing services to the DSO and Transmission System Operator (TSO). It, therefore, needs to communicate (in a two-way, near-real-time manner) in the upstream direction toward the DSO or TSO control center equipment (e.g., SCADA) [76] and [77].

One of the main characteristics of the VPP is that it has the ability to market its services with the aim of being profitable. It is mentioned that there is a more detailed differentiation for a VPP in which a Commercial VPP (CVPP) and a Technical VPP (TVPP) are described. The purpose of the CVPP is to participate in the power markets, while the objective of a TVPP is to provide services to the system. In both cases, the idea is to give greater support to DERs and counteract their individual limitations in relation to commercialization and power distribution [32], [34] and [78].

B. VPP INTERACTION ON POWER ENVIRONMENTS

VPPs have the ability to coordinate different power production units in order to provide reliable power as a conventional power plant. Each power system has different elements, characteristics and behavior according to its infrastructural and technological architecture, its geographical distribution and its ability to link with other power systems.

1) VPPs AND EMSs

The organization of the power systems integrated by VPPs into EMSs makes it possible to measure, control, optimize and satisfy the stakeholders' requirements. Hybrid EMSs (central and local) allow a VPP to manage cooperative power exchange for networked microgrids interconnected with the main grid [79], while an EMS based on levels in order to guarantee the safe and stable operation and enhance the reliability of the networks allow VPPs to apply an optimal reliability-oriented day-ahead self-healing scheduling [80].

Furthermore, owing to the attributes of VPPs as traders, the indirect participation of DERs in the power market is achieved through their interaction [81]. Achieving behavior similar to that of a conventional power plant allows VPPs to participate in the power market as an independent trader and even interact with ancillary services. Moreover, a VPP may interfere in flexible loads entering the pool, thus promoting the integration of power production units from RES in its stakeholders [48].

2) VPP AS MANAGER AND TRADER

The digitization and virtualization of power allow VPPs to integrate the physical devices of their power systems in a measurable and controllable manner. However, the efficiency of the monitoring and control that VPPs have over their systems depends on the centralized or decentralized architecture that stakeholders require and on the technical and technological capabilities that are available to their operating agents [82].

Some authors, therefore, mention that VPPs are units that manage systems composed of generating resources, storage systems and flexible loads capable of interacting independently in the power market. VPPs have the characteristic of internally handling the forecast errors related to renewable energy units that interact in their systems. The forecasts related to the renewable energy units allow VPPs to self-balance the production and have the possibility of providing power to the TSOs [83]. Other authors mention that the interaction of VPPs in power systems should stimulate the dynamic integration of prosumers in the participation of advanced DR programs. In addition, VPPs control the aggregation of several DERs owned by different stakeholders (e.g., end-users, utilities and independent power producers), thus allowing individual users within the system greater participation to act as agents or operators for production, distribution or power storage [84]. Flexible loads in different kinds of systems, e.g., heating and cooling systems, lighting systems and controllable appliances, plug-in EV charging stations and medium voltage to low voltage transformer units, can, therefore, be measured by the proper virtualization of DERs [82]. Other references similarly indicate that a VPP is an intelligent and autonomous unit capable of controlling power flows according to the needs of the operators, agents and/or elements of its network. VPPs have an architecture that is composed of power production units, power storage systems, controllers and power converters, in which all of them are connected and synchronized to the network of the system. VPP integration must, therefore, guarantee power system security by maintaining constant power flows and preventing malicious attacks against its algorithms [85].

3) TECHNICAL AND COMMERCIAL VPP DUTIES

In [86], the authors mention that a TVPP establishes a dynamic relationship for the integration of power distribution with the DSOs and a relationship based on auxiliary services with the TSOs, while a CVPP focuses on establishing its operations based on power trading, either internally within its own system, or as an independent participation with the power market. In addition, in [87], the authors indicate that a VPP integrates the capacities of several DERs in order to form a flexible portfolio capable of carrying out contracts in the power market and offering services to the operators of its system.

The stakeholders of the power distribution networks focus on requesting the VPP to adequately integrate the operations of production, consumption, distribution, storage and the trading of power. A centralized EMS led by a VPP must, therefore, seek to satisfy the demands of consumers by acquiring power through its internal power production system or by buying power from the power market. A VPP consequently has the ability to integrate the operators or interacting agents into its system in order to participate in data mining-driven incentive-based DR programs [47]. VPPs can participate in the power market (day-ahead and real-time) by establishing power marketing strategies according to their stakeholders' requirements. The interaction strategies employed in the power trading of VPPs are related to the definition of incentives according to their DR, to the adjustment of scenarios and conditions of the different types of existing power markets and to the ability to interact with multiple power markets [88] and [89].

VPPs can, therefore, integrate their power systems by establishing billing systems based on a retail distribution. The billing systems can be addressed by VPPs with the objective of minimizing the power production costs and maximizing the profit in the power market [90].

4) VPP SYSTEMATIC STRATEGIES

Determining optimal strategies implies that it is necessary for VPPs to be able to solve uncertainty problems. VPPs can solve these problems by integrating new power sources into their systems, thus reducing losses from power production and peak load [91]. Protocols for the definition of cost reduction must, therefore, be established, in which it is important to define the penalty parameters necessary to benefit each consumer according to the commitments that have been established with the VPP and to ensure uninterrupted power service [34].

Integrating ICTs into power systems with the interaction of VPPs provides notable advantages, such as: i) the minimization of time as regards decision making owing to the proximity to producers, consumers and prosumers; ii) the association with local systems (e.g., micro grids), thus allowing management problems to be addressed locally; iii) and the reduction in latency by centralizing data collection and analysis more efficiently [92]. In addition, dynamic synergies are established between RES and EVs, either to be shared or for autonomous driving. ICT support enables VPPs to optimize EV battery charge and discharge so as to minimize the operating costs of their systems [93].

VPPs can apply ICTs directly in order to control DERs individually and indirectly send incentive signals with which to influence consumers' and prosumers' decisions. Moreover, VPP operations carried out by relying on ICTs such as blockchain technology improve information reliability within the system, and its management may resemble that carried out by TSOs and DSOs [33]. VPPs can take advantage of blockchain technology in order to establish agreements between the agents that interact within the system and maintain the cyber-security that is transmitted through the network [94].

Figure 2 shows conceptually the physical and cyber layers managed by VPPs when interacting with power systems.

C. TECHNOLOGIES APPLIED IN VPPs

In general, authors mention that the combination of different power production sources allows the systems integrated by VPPs to optimize the performance of their DERs. Technical literature mentions that unidirectional power flows are generated in the top-down direction (large generators towards consumers), while bidirectional power flows are generated in the top-down and button-up direction (large generators towards consumers and small generators towards consumers). The following highlights the information related to the different power production technologies used in VPPs.

DER integration by a VPP should ensure the stakeholders' required continuous consumption, keeping the proper

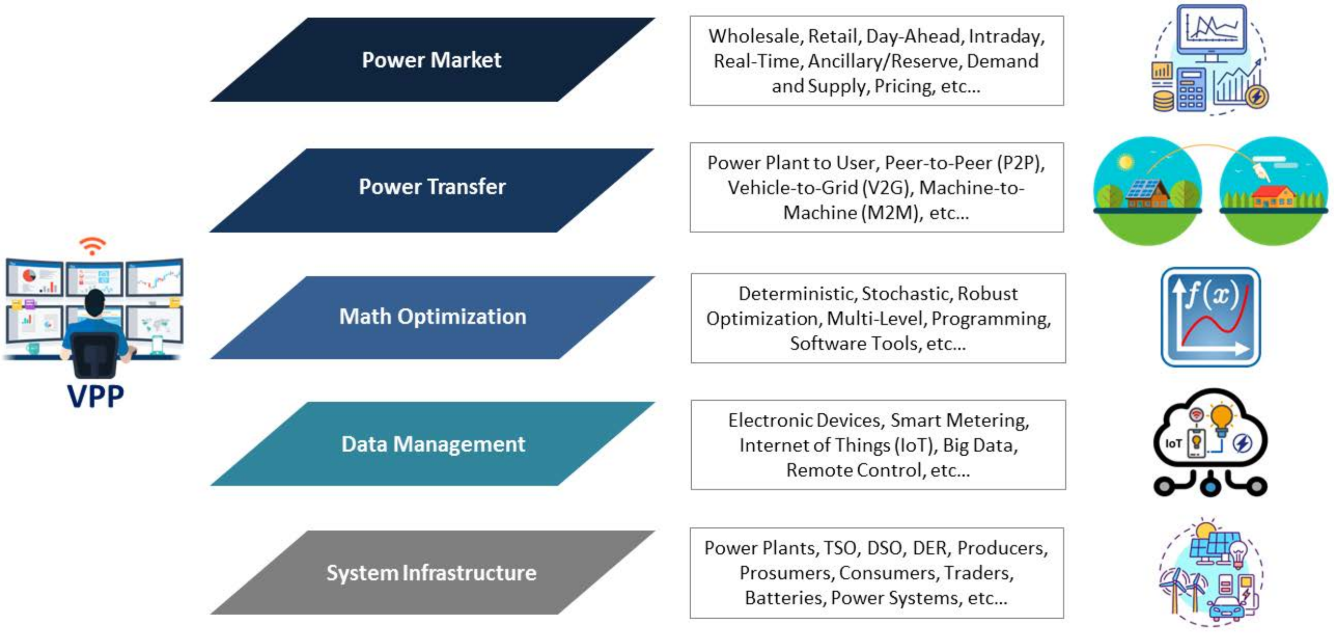

FIGURE 2. **Physical and cyber layers managed by VPPs.**

operations in the system [95]. Considering the technologies highlighted by authors, the interactions of VPPs with them are mentioned below, classifying them into three groups according to the strategies of the systems.

1) INTEGRATION WITH CONVENTIONAL PLANTS

In [48], a system composed of a thermal plant, a pumped storage plant, a wind farm and PV plant, is integrated by a VPP. The authors propose that, in order to promote the integration of renewables in the grid and enhance their participation in grid services, it is necessary to group several RES of different types, such as wind, solar, biomass, or hydro. In [58], the authors propose a system in which EV owners are the protagonists, supplying information on connection times, disconnection times and initial charge states. It is mentioned that the system managed by VPPs is formed of gas turbines, wind power units, PV units, EVs and other flexible loads. It is indicated that price subsidies are provided in order to encourage the scheduling of EV charging. In [62], the authors propose a model that includes two sources of off-shore power: small and medium-sized reactors and wind farms. The benefits and costs of including small nuclear reactors within the system and combining them with the system managed by VPP are mentioned. The model proposed in [88] consists of a gas turbine power plant, a PV power plant, a power storage system, and a central air-conditioning system. It is mentioned that the VPP participation in the day-ahead power market, real-time power market and CO_2 trading market could be simultaneous with an interruptible load. The study system mentioned in [96] is composed of thermal, hydroelectric and PV energy systems. The VPP integrates the system that interacts with the following models: modeling of the hydropower system, modeling of distributed PV system and modeling of thermal power system. Another model is proposed in [97], in which the VPP comprises a conventional gas turbine power, wind power, PV power and Pumped Hydro Storage Plant (PHSP). The objective function of the VPP is to maximize profit by considering the power sold/purchased in the power market, the cost of conventional gas turbine production and the cost of conventional gas turbine start-up. The model analyzes the mid-term VPP operation planning in order to maximize the profit in a weekly time frame.

2) INTEGRATION WITH COMBINED UNITS

The model in [98] integrates CHP units, gas turbines and fuel cells, along with PV panels and wind turbines. The cogeneration units are connected to the heating networks and to the main power network. Moreover, it is considered that the power distribution networks are interconnected and that the heating networks are isolated from each other, which makes it possible to capture the differentiated data between the power supply and demand. Controlling the power production for power distribution networks that use renewable energies such as PV and wind power is not easy owing to climatic variations. However, the use of sources such as biomass power and biogas power allows VPPs to adjust their power units at certain times. In [99] a system integrated by a VPP with CHP micro-units is presented. It is highlighted that the system managed by the VPP should be adjustable, while only the CHP and biomass units have this attribute. Moreover, a model composed of different wind farms and a biomass plant is proposed in [100] in order to optimize a multiple-scale renewable energy-based VPP. The authors indicate a dispatchable generator operating with biomass of low emissions, which is integrated with DERs in the same VPP system. The objective is to trade across geographic scales by aggregating multiple DERs so as to maximize their profits. In [101], the researchers mention a model that consists of CHPs, hydro units, wind turbines, photovoltaic panels, storage devices, electric appliances and cooling/heat facilities. The multi-energy interconnection addressed by a VPP is considered, with the focus on formulating an optimization problem that saves economic costs and enhances power quality. In [102], the authors describe the innovative concept of CHP-VPP that enables the coordinated dispatching of heat and power. CHP-VPP operation models with uncertainties show the inherent behaviors of DERs operating in two coupled energy networks.

In [103], the authors present a system integrated by a VPP in which they seek to maximize expected profit, which comprises the power sold/purchased in the day-ahead power market, analyzing the behavior of combined cycle gas turbine, wind power and PHSP. The expected hourly profits and cumulative expected profit of the VPP in the day-ahead power market are provided. The authors of the model described in [104] state that a gas system and a heating supply system improves their operational efficiency on the basis of the price forecast value. The VPP system integrates CHP, wind, PV, and BESS in order to efficiently convert gas, heat and cold energy into power and obtain the minimum power operation costs. In [105], the authors evaluate the power consumption and the reduction in operating costs of the customers of a system composed of CHP, wind and BESS. Loss and load factors, along with emissions, are considered by the interconnection within the system, and the functions are analyzed according to the DR programs proposed.

3) INTEGRATION WITH STORAGE UNITS

In [83], the authors consider a system composed of a wind or PV power unit, a conventional thermal unit and a power storage unit. They propose that the total amount of power production (or consumption) addressed by the VPP must coincide with the amount of power exchanged with the power market. An interesting case study is that of Western Australian in [106], in which a detailed financial analysis of implementing a VPP is carried out. The system integrated by VPP is formed of 67 residential homes, with a rooftop PV farm, smart appliances and heat pump hot water. Moreover, a centralized vanadium redox flow battery with which to store power during high PV generation and low power market prices is mentioned. In [107], the authors define a VPP that includes BESS, wind, PV and conventional power plants. The model establishes a prediction-correction with which to distribute power within the system using multi-agents or multi-operators and to optimize the BESS. An interesting case study that analyzes the commercial viability and technical feasibility of BESS in Malaysia is mentioned in [64]. The case study addresses peak demand reduction, demand response and frequency regulations, as well as financial model analysis applied in the region. Moreover, there are described some of BESS technologies and their interaction with VPP system.

The interaction of VPPs, EVs and DERs within the same system requires the management of various strategies for the power storage integration. Power consumption and production plans, EV charging and discharging plans and power exchange plans between DERs, therefore, require the advance definition of parameters such as the DERs geographic distribution, incentives to stimulate the use of EVs and the load differences.

An interesting model is mentioned in [108], which describes an active distribution network with multiple VPPs composed of power storage units, together with a group of PV, wind and EVs. A decentralized and collaborative integration is considered according to the stakeholders' needs. Another interesting model related to EVs is provided in [109], in which the authors indicate that the optimized energy procurements in VPP operations are developed in a system that integrates industrial load units, powered for wind, PV and CHP. The clearing sequence of joint operations in day-ahead and intra-day markets in the model are classified according to trading periods. In [110], the authors define a system composed of BESS, wind and PV in which the power system is divided by areas.

The power resources of each area are combined to generate time series of power consumption and power production, averaging the data according to daily measurements. The power system integrated by the VPP is not, therefore, restricted by the geographical area, thus establishing a centralized or decentralized control mode. In [111], the authors indicate that the VPP comprises a group of distributed PV panels and thermostatically controlled loads. The VPP determines the planning of power consumption in advance in order to carry out a continuous optimization based on intra-day power market information according to the performance of the PV.

As an integral operation, the power storage in power distribution networks is generally mentioned by authors in relation to the procedures carried out for domestic, industrial and EV environments.

Scientific literature mentions, for example, the VPPs have the ability to organize and synchronize the collective operation of domestic batteries in order to generate different benefits within the integrated system and even economic income by taking advantage of the excess of power. The interaction of the VPP with the power market allows the owners of domestic batteries to operate them according to cost minimization or profit maximization, considering the needs of the time periods established [65].

Moreover, the integration of the VPP into an EV storage system can achieve the stable generation of an intelligent load in which a control mechanism allows the distribution of the load to the system points in a regulated manner. The VPPS adequately relate the measurement of the charge and discharge times of each battery to other parameters, such as

TABLE 2. Technologies applied in VPPs systems.

Reference	B/BP	BESS	CHP	CL	CPP	EV	FCP	GTP	HP	HPP	HVACS	NP	PHSP	PLU	PVP	TP	WP
[38]	·	·	·	✓	·	✓	·	·	·	·	·	·	·	·	·	·	·
[48]	✓	·	·	·	·	·	·	·	·	·	·	·	✓	·	✓	✓	✓
[57]	·	·	·	✓	·	✓	·	·	·	·	·	·	·	·	·	·	·
[58]	·	·	·	·	·	✓	·	✓	·	·	·	·	·	·	✓	·	✓
[62]	·	·	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	✓
[65]	·	·	·	✓	·	✓	·	·	·	·	·	·	·	·	·	·	·
[83]	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	✓	✓	✓
[88]	·	✓	·	·	·	·	·	✓	·	·	✓	·	·	·	✓	·	·
[96]	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	✓	✓	·
[97]	·	·	·	·	·	·	·	✓	·	·	·	·	✓	·	✓	·	✓
[98]	·	·	✓	·	·	·	✓	✓	✓	·	·	·	·	·	✓	·	✓
[99]	✓	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	·
[100]	✓	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
[101]	·	·	✓	·	·	·	·	·	✓	·	✓	·	·	·	✓	·	✓
[102]	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	✓	·	✓
[103]	·	·	✓	·	✓	·	·	·	·	·	·	·	✓	·	·	·	✓
[104]	·	✓	✓	·	·	·	·	·	·	·	·	·	·	·	✓	·	✓
[105]	·	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
[106]	·	✓	·	·	·	·	·	·	·	✓	·	·	·	·	✓	·	·
[107]	·	✓	·	·	✓	·	·	·	·	·	·	·	·	·	✓	·	✓
[108]	·	✓	·	·	✓	✓	·	·	·	·	·	·	·	·	✓	·	✓
[109]	·	·	✓	·	·	✓	·	·	·	·	·	·	·	✓	✓	·	✓
[110]	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	✓	·	✓
[111]	·	·	·	✓	·	·	·	·	·	·	·	·	·	·	✓	·	·
[112]	·	·	·	✓	·	✓	·	·	·	·	·	·	·	·	·	·	·

B/BP: Biomass/Biogas Power; **BESS:** Battery Energy Storage System; **CHP:** Combined Heat and Power; **CL:** Controlled Loads; **CPP:** Conventional Power Plant; **EV:** Electric Vehicle; **FCP:** Fuel Cells Power; **GTP:** Gas Turbines Power; **HP:** Hydro Power; **HPP:** Heat Pump Power; **HVACS:** Heating, Ventilation and/or Air-Conditioning System; **NP:** Nuclear Power; **PHSP:** Pumped Hydro Storage Plant; **PLU:** Power Load Units; **PVP:** Photovoltaic Power; **TP:** Thermal Power; **WP:** Wind Power.

the distances traveled by the EVs, or the useful life of their batteries [57].

A simple local plug-in system for EV charging coordinated by a VPP can, therefore, reduce billing costs when compared to other cases. While the system works and collects information, the VPP can adjust the initially analyzed deviations and improve the efficiency of the system over time. Depending on the system structure integrated by the VPP, the EV displacement trajectories, power consumption rates, load measurements and consumption at the charging stations can be predicted with greater precision [112].

The integration of power storage systems can involve public and private systems. VPPs can improve the interaction between their power distribution networks and the power systems by properly classifying the power storage points and EV charging points [38]. In the case of an EV system, therefore, the classification of the charging points is defined according to the EV real-time locations, identifying themselves as public, private and mixed charging points (private with restricted access to public requirements).

As a summary, Table 2 shows the technologies applied in VPP integration systems.

IV. POWER MARKET INTERACTION OF VPPs

In power distribution networks, power is produced, consumed, stored and traded by the DERs and stakeholders according to their respective roles. However, neither DERs nor the stakeholders that interact within the power systems have the attributes required to carry out power trading operations with the power market. A decentralized market agent can, therefore, develop targets for a cost efficient operation and expansion planning of all system elements, including generation, storage systems and demand side management, while maintaining grid stability [113]. VPPs address and control the distribution and trading of power with the power market. They set up power deals and settlements in a centralized manner on the basis of historical generation and demand forecasts. VPPs can additionally make power purchase and sale actions in real-time using smart metering data according to the power digitization capacity [38].

The requirements of the stakeholders associated with the economic values expected by the system must be properly identified by VPPs before planning the trading operations. Moreover, VPPs must consider the different sources of potential income and simultaneously carry out a vulnerability study according to the behavior of similar systems [50]. It is important for VPPs to clearly identify the strengths and weaknesses of their units in order to properly calculate the deviation between real consumption and the power supply curves in the power market settled according to hourly prices [114].

VPPs must validate that the main DER sources have a sufficient capacity to balance production at maximum demand and must regulate production by distributing power to places in the system at specific times. VPPs can, therefore, provide various services as traders in the power markets. They can participate in portfolio management activities and can even optimize contracts with other power providers by acting as a consumer, producer, or prosumer at the time of negotiation [32]. Moreover, the economic valuation of system investments in power markets makes it possible to analyze how the investment costs of the different technologies applied to power systems can be recovered in the short-term when a locational marginal pricing scheme is employed [115].

The precision of price forecasting is determined according to the characteristics of each power market and the different decomposition alternatives in order to interpret each behavior of the supply and demand curves analyzed by VPPs. A price analysis in the power market can be managed by VPPs according to the uncertainty related to the hourly variability of the prices [96]. It is also important for VPPs to identify the characteristics of the power market in which they operate. The power market can be composed of two settlements (day-ahead and balancing), in which different types of prices and settlements are generated in the same period of time [83]. This is even the case of the markets in which CO_2 emission credits can be bought and sold to obtain economic benefits [54].

VPPs can also participate simultaneously in transactions with power markets and even in transmission rights and auxiliary service operations jointly with TSOs. The emergence of prosumers signifies that the viability and diversity of demand in systems with P2P schemes have made it possible to generate models that reduce power transmission costs. Moreover, by generating systems with P2P schemes, small power providers can compete with large power providers through VPPs [33] and [116]. Since most RES are far from load centers, in [117], therefore, the power system architecture mainly considers the end-user location, giving the VPP a greater role in operations related to the power transmission and its interaction with the power market. Likewise, a model with a P2P trading structure can be found in [118]. In this model, commercial prices are negotiated between several buyers or sellers of the same level in a parallel scheme and a continuous and interruptible load is used to promote DR, with which VPPs can control internal demand.

A. DEMAND AND SUPPLY

In general, depending on purchasing and selling power quantities, power markets are classified as being wholesale and retail markets [119] and [120]. At a more specific level, according to the type and characteristics of the trading operations to be carried out in the power markets, they are classified as day-ahead power markets, real-time power markets (also known as balancing markets), intra-day power markets, ancillary/reserve power markets and trade CO_2 emission markets [54], [58], [59] and [121]–[124]. The agreements that are established for the generation and execution of the power trading operations between VPPs and power markets must contain minimum conditions, which can be established in four items: i) the quantity and price of the electric power in different time segments; ii) certain special requirements for power reliability and power quality; iii) the fluctuating range of the set value, and iv) penalty methods [6].

In large conventional power systems/networks, the TSOs are currently responsible for adjusting the power supplies to the demand in real-time in order to balance the system and avoid power outages. In these systems, the producers are the owners of power plants and are in charge of selling the power produced to retail power providers through future bilateral contracts or in the wholesale power market [100]. In addition, the growing bidirectional interaction between wholesale and retail markets is growing as VPPs integrate their power systems with greater operability based on DR, renewable resources and the distributed generation and storage of power.

An impact, therefore, occurs at the distribution-retail level in the operations of the transmission system and the wholesale power markets [125]. In [126], it is mentioned that, unlike conventional producers, VPPs can add DERs to subsystems that exchange power with the main grid. Adding DERs at certain times allows VPPs to generate projected production curves over certain periods of time (weeks, months, quarters, etc.) and thus balance the power supply vs. power demand.

Furthermore, two power trading strategies can be developed when the VPP manages the integration of several DER owners in order to form a coalition. One strategy focuses on generating an internal system that is controlled by the VPP, defining predetermined rates according to the system characteristics, and another is that in which the VPP sells the power production in the power market [121]. DR models can also be generated in order for the VPP to have greater control and to reduce the power imbalance caused by errors or deviations in forecasts of power production and consumption. It is important to keep in mind that the forecasts have errors or deviations since, when derived from RES, power production makes it difficult to obtain production curves prior to interaction with the power market [111].

B. PRICING

The adoption of variable power rates refers to the application of different power rates in different periods. The power variability rates allow a strategy to be generated for prices in real time according to the power market conditions. However, one of the problems for end users when interacting with the variation of rates is price fluctuations. The static tariff scheme, which is related to the times of power use, minimizes the risk for end users in relation to guaranteeing a flat price in power consumption, but does not maximize their benefit when taking advantage of power in off-peak hours [127].

Establishing confidence limits with which to define uncertainties in the power production obtained from RES makes it possible to generate price predictions in the power market with greater precision. The objective of using scenarios to model prices in the power market is to build predictive supply and demand curves. It is, therefore, important to analyze climatic behavior such as wind speed and solar radiation, identifying difficulties and probabilities at the time of modeling production prices [128].

Different types and methodologies for pricing can be found in the spot transactions of the power market. An interesting proposal is presented in [129], which describes a model in which day-ahead trading and real-time trading are indicated.

The market clearing price or system marginal pricing and the pay as bid are taken as pricing methods with which to generate a power purchase scheme with a minimum cost and a power sale scheme with the maximum benefits. Another interesting proposal is that described in [130], in which the VPP integrates the DERs of its system in a centralized manner, taking responsibility for the bidirectional communication, monitoring and control of each component. According to the system architecture, the VPP can obtain the data required to manage its portfolio (e.g., prices and load data) with which to generate their scheduling for each hour of the coming day in joint day-ahead and real-time power markets.

In [131], it is stated that the price forecast must be analyzed through the use of multiple scenarios, because VPPs do not have control over the power production derived from renewable energies. Moreover, owing to the limitations of the conditions of the system themselves, it is not possible to forecast 100% the load consumption, energy reserve services or DER energy outputs. Defining the characteristics of multiple scenarios and considering stakeholders' requirements, therefore, allow VPPs to analyze, process and forecast price models according to the behavior of the power markets. Furthermore, in [132] and with regard to power derivatives, it is important to note that power derivative exchange markets emerge as a risk management tool to protect against financial risk.

It is, therefore, possible for VPPs to trade with underlying power for the future (ranging from one week to several years) at today's prices and thus obtain different alternatives by which to maximize profits in their power systems. In addition, in [133], the providers of system peaking resources (thermal units and DR resources) and wind farms can make better decisions as regards maximizing their profits when knowing the information exchanged between the providers and consumers of peaking resources. Considering the profit goals, therefore, allows a VPP to define a compensation mechanism.

When VPPs operate in the power market bedding large volumes of power, they have the capacity to impact the power price by acting as Price-Maker [134] and [135]. The TVPPs behavior can be modeled in the wholesale energy market as a Price-Maker agent with the aim of maximizing profits or minimizing costs [136]–[138].

Furthermore, when VPPs interact with the power market, strategies are defined according to the role or operational position. When VPPs aim to interact with the power market, selling the power generated by their power system or buying the power to feed it, each strategy (e.g. strategy of price bidding) is managed based on operational capabilities and limitations [58] and [118]. Therefore, the VPPs analyze, in addition to the incentive models and the power market interactions, the marginal prices with which they can generate more accurate and favorable forecasts. However, when the VPPs have a participant or competitor role in the power market, they analyze the historical behavior of the power market and price market to generate their forecasts [100].

As a summary, Table 3 shows the interactions of VPPs with power markets.

V. MATHEMATICAL OPTIMIZATION

Generally, the issues to be resolved by researchers focus on optimizing power production and distribution, as well as maximizing benefits and minimizing costs by developing good forecasts to carry out correct trading operations in the power market. According to the analysis of the papers cited for this chapter, to model the issues in the different proposed power systems researchers most frequently use the methods of Linear Programming (LP), Non-Linear Programming (NLP), Mixed-Integer Linear Programming (MILP) and Mixed-Integer Non-Linear Programming (MINLP). Therefore, the works that use mathematical optimization are listed below, grouped according to the programming methods used by researchers.

A. LINEAR PROGRAMMING (LP)

The model defined in [139] is focused on providing maximum cost savings while trading operations in the day-ahead market. The cost/worth is formulated in order to maximize the power export capability of the VPP by minimizing the total energy curtailments. The Monte-Carlo method is used to obtain results. In [140], the VPP economic dispatch model has the objective of minimizing the total DERs' generation cost, maximizing profits of the system, and maximizing energy-saving and emission-reduction. In [141], an algorithm is proposed that can be used to control the operation of an integrated electricity-hydrogen VPP in a real-time market, with uncertain prices and renewable generation. Through the receding-horizon stochastic optimization, a stochastic Model Predictive Control (MPC) scheme that does not resort to scenario forecasts is proposed.

B. NON-LINEAR PROGRAMMING (NLP)

The model defined in [44] has a formulation that is related to the product of dual and primal variables. In the bi-level math formulation, the upper level of the problem represents the profit maximization of the VPPs and the lower level of the model presents the total cost of DNO to be minimized subject to constraints. In [142], the authors propose a model in which a VPP integrates multiple operators according to a bidding method adapted for that purpose. A quadratic programming method is used to allocate the operator's power generation. A bi-level structure is, therefore, considered with the objective of maximizing the operator's own profit under conditions of price uncertainty.

C. MIXED-INTEGER LINEAR PROGRAMMING (MILP)

In [53], the authors indicate that the robust optimization application allows the analysis of the solution in the worst-case scenario, according to problem uncertainty. The proposed model uses uncertainty intervals while minimizing the

TABLE 3. VPP interactions with power markets.

Reference	INCENTIVE MODELS				POWER MARKET INTERACTIONS				PM
	D&S	P	DR	P2P	DA	ID	RT	A/R	
[6]	✓	·	·	·	·	·	·	·	·
[32]	·	·	·	·	✓	✓	·	·	·
[33]	·	·	·	✓	✓	·	·	·	·
[38]	·	·	·	·	✓	✓	·	·	·
[50]	·	·	·	·	✓	·	✓	·	·
[54]	✓	·	·	·	✓	·	✓	·	·
[58]	✓	·	FD	·	✓	✓	·	·	·
[59]	✓	·	·	·	·	·	·	·	·
[83]	·	·	·	·	✓	·	✓	·	·
[96]	·	·	·	·	✓	·	·	·	·
[100]	✓	·	·	·	✓	·	✓	·	·
[111]	✓	·	TP	·	✓	✓	✓	·	·
[113]	·	·	·	✓	✓	·	✓	✓	·
[114]	·	·	DER	·	✓	·	✓	·	·
[115]	·	✓	DER	·	·	·	✓	·	·
[116]	·	·	DER	✓	✓	·	·	✓	·
[118]	·	·	·	✓	✓	·	·	·	·
[119]	✓	·	CPP/DER	·	✓	·	✓	·	·
[120]	✓	·	·	✓	✓	·	✓	·	·
[121]	✓	·	·	·	✓	·	✓	✓	·
[122]	✓	·	·	·	·	·	·	✓	·
[123]	✓	·	CBP/DER	·	✓	·	✓	·	·
[124]	✓	·	·	✓	✓	✓	✓	·	·
[125]	✓	·	FD/DER	·	✓	·	✓	·	·
[126]	✓	·	·	·	✓	·	✓	·	✓
[127]	·	✓	·	·	·	·	✓	·	·
[128]	·	✓	·	·	✓	·	✓	·	·
[129]	·	✓	·	·	·	·	·	·	·
[130]	·	✓	·	·	✓	·	✓	·	·
[131]	·	✓	·	·	✓	·	✓	·	·
[132]	·	✓	·	·	✓	·	·	·	·
[133]	·	✓	CPP	·	·	·	·	·	·
[134]	✓	·	·	·	·	·	·	✓	✓
[135]	✓	·	·	·	·	·	·	·	✓
[136]	✓	·	·	·	✓	·	✓	·	✓
[137]	✓	·	·	·	✓	·	✓	·	✓
[138]	·	·	·	·	✓	·	·	✓	✓

D&S: Demand and Supply; **P:** Pricing; **DR:** Demand Response; **CBP:** Capacity Bidding Program; **CPP:** Critical Peak Pricing; **DER:** Distributed Energy Resources; **FD:** Fast Dispatch; **TP:** Thermostat Program; **P2P:** Peer-to-Peer; **DA:** Day-Ahead; **ID:** Intraday; **RT:** Real-Time; **A/R:** Ancillary/Reserve; **PM:** Price-Maker

investment cost, determining the optimal DER generation mix for system installation. A study is presented in [88], in which the objective function is defined in order to determine the profit obtained in the power market for the worst case. The Karush-Kuhn-Tucker (KKT) method is used to transform the bi-level of the sub-problem into a single-level. The model maximizes the cumulative profit, including the income obtained from participating in the day-ahead and real-time markets. A model that seeks to optimize operations in the power market in order to supply system consumers when power production conditions are deficient is presented in [143]. The model establishes a robust optimization approach, whose objective function is to maximize the expected income from the power sale in the power market, subtracting the operating costs incurred for a set period. The model mentioned in [58] formulates an optimal dispatch problem in order to maximize profit. The objective function includes income from the power market and operating costs from power production, CO_2 trades and EV charging/discharging. The model considers the CO_2 emission costs to optimal dispatch of the VPP.

In [83], the goal is to maximize the total expected profit by applying stochastic programming. The optimal daily offers take into account the uncertainty and endogenous models in order to make future decisions in the balancing power market. In addition, the objective of the model proposed in [144] is to minimize the length and costs of power transport by taking advantage of the power stored throughout the system in order to meet local consumption needs. A trading power supported by blockchain technology is established owing to the nature of the Boolean variables. Another case study is proposed in [50]. The model is based on a problem that includes data from power markets, auxiliary services markets for frequency control, DR for capacity support and coverage controls. The objective function is minimized to the overall net cost, which is defined as the operational costs subtracted from the revenues.

In [145], the authors propose a robust bi-level model with which to address the uncertainty in the VPP system connected to a wind-photovoltaic-power storage system. The objective function considers the DR according to day-ahead power market scheduling in several scenarios. The lower layer model represents the day-ahead power market scheduling plan, while the upper layer model represents the maximum revenue of the VPP operation. In [146], a function is proposed that employs Volt-Watt Control and Volt-Var Control distribution system constraints when the VPP participates in a wholesale power market. The problem considers a model with which to maximize profits according to the hourly power supply.

A three-level model is proposed in [128], in which the power market price and the power production generated by a renewable source such as wind are analyzed. The three-level optimization problem is solved using a column-and-constraint generation algorithm. The problem models uncertainty in order to derive the bid decisions using robust optimization approaches and seeks to maximize profit through power market operations. In [138], a bi-level model for the offering strategy problem of a price-maker VPP participating in power and reserve power markets is presented. The VPP aims to maximize its expected profit, considering power market behavior. The model applies stochastic programming and KKT in order to discover the optimized values in the upper and lower levels defined. In [52], the function is defined through a structure of a corrective strategic reprogramming approach based on the bi-level bidding model. The function maximizes the profit in the day-ahead market, considering energy storage use as a priority condition.

In relation to EVs, the authors of [72] indicate that the stochastic model considers the EV characteristics, battery degradation and seasonal power price cycles to determine uncertainties. The system consists of a wind power producer and a DR aggregator with EV clients, allowing their interaction with the power market. The model consists of maximizing the revenues that it earns from power offering to the day-ahead market less the market trade operation costs. In [147], the authors mention a regulation market in presence of EVs, analyzing the problem of optimal bidding strategy according to the associated uncertainties regarding EVs and DERs, where a stochastic optimization model is used.

The model proposed in [81] seeks to maximize profits in the power market by taking advantage of natural gas networks under the DR paradigm. The model is established by defining a simulated level that compensates snapshots of steady-state natural gas network operations with the day-ahead power market. The bi-level model is linearized with the support of the Monte-Carlo method. In [148], the stochastic function is applied in order to solve the problem with the support of the Monte-Carlo method. The objective function aims to minimize the total system cost by considering the probability of each scenario obtained within a system composed of a wind farm, a BESS and a diesel plant. In [149], the authors present a model that integrates a power to gas system and a gas storage tank into a VPP. The power to gas based VPP system is formed of a wind power plant, PV station, conventional gas turbine, EV group and controllable load, in which the objectives are the maximum operation profit and the minimum operation risk, which are solved using a schematic of robust optimization.

In [98], the power price and power operation cost are the principal factors employed to define the stochastic model. The consideration of power prices, power demand and power production derived from renewable energy resources lead to greater uncertainty at the time of data collection as the system strengthens. The model proposed, therefore, attempts to discover an operating schedule for the system with minimal costs. In [150], the model considers available wind power production, requests for reserve deployment and market prices. The function is defined for the day-ahead self-scheduling problem of a VPP trading in both energy and reserve power markets. The strategy considered in the case study is the application of robust optimization.

In [151], it is presented a model in which the Benders decomposition method is used, introducing a stochastic programming model based on the owner market under uncertainty. The function is focused on investment status in order to maximize profits, along with maintaining the reliability and operational cost of the power system at acceptable levels.

In [152], the objective function focuses on cost minimization and involves the constraint set of investment and operational considerations. The chance constrained models for the investment and operating decisions of alternative DERs are defined using a stochastic model. With regard to the risks, the authors of [153] establish a stochastic model with a conditional value-at-risk linear formulation, which is defined through the use of a bi-level structure. The objective is to maximize the day-ahead profit in conjunction with minimizing the anticipated real-time production and the consumption of imbalance charges.

D. MIXED-INTEGER NON-LINEAR PROGRAMMING (MINLP)

A model that establishes the power purchase in the power market by considering the internal deficits that can compromise the power demands required by consumers is provided in [47]. The proposed deterministic problem is formulated as an optimization model with which to minimize VPP operation costs and to guarantee consumers' interests. In [54], the proposed problem involves non-convex optimization programming. A deterministic scheme of power supply with marginal price and CO_2 trading is defined. The model is developed in order to minimize the impact of forecasting errors and maximize the incentives according to the schedule of DERs and the interaction with the day-ahead and intraday markets.

In [111], the bi-level scheduling model considers the unbalance cost minimization, including the unbalance power cost (accumulated value) and the unbalance capacity cost (maximum value). The uncertainty generated when carrying out operations with the power market is considered owing to the gap between the actual net power exchanged and that expected in order to discover cumulative values. In [154], a stochastic conic model is divided into two stages in order to consider the uncertainties from multiple sources, dual-mode operations and representations of non-linear power flows. The problem is formulated in order to minimize the annualized investment cost in the architecture of networked microgrids and minimize the operation cost of DERs.

In [155], the authors propose an optimization model in which, according to the concept of Industrial VPP, a stochastic mathematical formulation maximizes the profit of a VPP and minimizes the load shedding. The study considers the income of power production, the cost of interruptible loads and the penalty cost for customers, among others. In [156], the authors mention a model in which PV is connected to the distribution network by an adjustable inverter. The model is established using the results of the AC power flow to define the parameters in the simulation. The function minimizes the long-term social utility loss by considering the voltage security, operational requirements of DERs and VPP service requests. In [157], the deterministic problem constraints take into account an AC power flow model with which to determine the active and reactive power that flows in each line of the distribution network. The objective function is set in order to minimize the cost of the degradation of EV batteries used.

A proposal related to water-energy management is shown in [158], whose authors state that the uncertainty regarding the availability of water resources is modeled through the use of a function, focusing on minimizing the operating cost in each hourly period. In [159], the proposed problem is focused on uniform distributed power during the distribution time period, maintaining an allocation of optimal flows in consumption. The model is established in order to minimize the operational cost and maximize the load curve equilibrium. In [92], the objective is to identify the unused generation capacity that can be activated in order to provide frequency balancing by correcting power imbalances. The impact of decentralization using a genetic algorithm to determine an approximate solution is analyzed.

The model, therefore, proposes maximizing the prosumers' profit. In [96], the non-linear quadratic function model with the production ratio of hydropower, PV and thermal power in each period, whose objective is to optimize the operating system costs, is shown. The operating cost model considers the time as the coefficients change. The problem modeled has the objective of seeking maximum annual profits and expected complementary indexes.

Considering the above, Table 4 summarizes the models, methods, techniques and software tools that authors have used to define and solve the proposed mathematical optimization problems.

VI. FEATURED VPP PROJECTS AND INDUSTRY 4.0

The power industry has, over the last few years, developed strategies with which to plan the growth and evolution of its power systems/networks. Infrastructure designs, the integration of digital technologies and public-private economic investments have been the key aspects as regards enabling VPPs to perform as lucrative agents in power markets. VPPs additionally focus on optimizing the characteristics of DR in order improve the operation of the system according to the analysis of the results obtained thanks to the operations performed [143] and [160]. Some of the projects have focused on business models and platforms for the development of power markets, similarly to that which has occurred with big power supplier roles in the power sector, while others have been targeted toward the local control of technological systems in the power distribution network through the use of ICTs [161] and [162]. It is important to consider that, over time, the DERs managed by VPPs may belong to structures that vary in design (from centralized to decentralized, and vice versa). The information networks and the high-level software architecture that are used within the systems that manage the VPPs in order to connect and control the DERs must, therefore, be adjusted according to technological possibilities. However, it is not necessary to change the structure connected to the network and the distributed topology of DERs, but rather to adapt operations to new technologies [163].

A. INTERNATIONAL VPP PROJECTS

Several authors take as a reference the infrastructural and technological models of projects that involve connections to the network of DERs integrated by VPPs, which have been disruptive for the optimal dispatch modes. The projects considered include power storage devices, DR programs and multi-level optimal scheduling, among other interesting aspects [29], [58], [86] and [164]. Some of the most relevant projects are described below.

1) THE VIRTUAL FUEL CELL POWER PLANT (VFCPP)

This project, which was developed with the cooperation of Germany, the Netherlands and Spain, integrated 31 decentralized stand-alone residential fuel cell systems distributed in each of these countries and operated through the use of a VPP. The objectives achieved showed fuel efficiencies of up to 90% and electrical efficiencies greater than 30%, successfully demonstrating the operation of decentralized micro-CHP fuel cells [29], [58], [160] and [165].

TABLE 4. Summary mathematical optimization strategies.

Reference	PROGRAMMING METHOD				MODEL				MATH TECHNIQUE			SOFTWARE TOOL					
												Computing Platform			Optimization Engine		
	LP	NLP	MILP	MINLP	DT	ST	RO	ML	KKT	BEN	MCM	MATLAB	GAMS	PYTHON	CPLEX	LINGO	GUROBI
[44]	·	✓	·	·	·	·	·	✓	✓	·	·	·	✓	·	·	·	·
[47]	·	·	·	✓	✓	·	·	✓	·	·	·	·	·	·	·	✓	·
[50]	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	·
[52]	·	·	✓	·	·	·	·	✓	✓	·	·	·	·	·	✓	·	·
[53]	·	·	✓	·	·	·	WR	·	·	✓	·	·	·	·	·	·	·
[54]	·	·	·	✓	✓	·	·	·	·	·	·	·	·	·	✓	·	·
[58]	·	·	✓	·	·	·	·	·	·	·	·	✓	·	·	✓	·	·
[72]	·	·	✓	·	·	P/W	·	·	·	·	·	✓	·	·	·	·	·
[81]	·	·	✓	·	·	·	·	✓	✓	·	✓	·	·	·	·	·	·
[83]	·	·	✓	·	·	P/W/PV	·	·	·	·	·	·	·	✓	·	·	✓
[88]	·	·	✓	·	·	PV	WR	✓	·	✓	·	✓	✓	·	·	·	·
[92]	·	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
[96]	·	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	✓	·
[98]	·	·	✓	·	·	P/D/RP	·	·	·	·	·	·	·	·	✓	·	·
[111]	·	·	·	✓	·	·	·	✓	·	·	·	·	·	·	✓	·	·
[128]	·	·	✓	·	·	P	WR	✓	✓	·	·	·	✓	·	✓	·	·
[138]	·	·	✓	·	·	RP/RR	·	✓	✓	·	·	·	✓	·	✓	·	·
[139]	✓	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	·
[140]	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
[141]	✓	·	·	·	·	P/RP	·	·	·	·	·	✓	·	·	·	·	✓
[142]	·	✓	·	·	·	·	·	✓	·	·	·	✓	·	·	·	·	·
[143]	·	·	✓	·	·	·	WOR	·	·	·	·	·	✓	·	✓	·	·
[144]	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	·
[145]	·	·	✓	·	·	PV/W	WOR	✓	·	·	·	·	✓	·	✓	·	·
[146]	·	·	✓	·	·	·	·	·	·	·	·	✓	·	·	✓	·	·
[147]	·	·	✓	·	·	P/DER	·	·	·	·	·	·	✓	·	✓	·	·
[148]	·	·	✓	·	·	W/D/UA	·	·	·	·	✓	·	✓	·	·	·	·
[149]	·	·	✓	·	·	·	WOR	·	·	·	·	·	✓	·	✓	·	·
[154]	·	·	·	✓	·	D/RP	·	·	·	✓	✓	✓	·	·	✓	·	·
[150]	·	·	✓	·	·	P	WR	✓	✓	·	·	·	✓	·	✓	·	·
[151]	·	·	✓	·	·	D/CO	·	·	·	✓	·	·	✓	·	✓	·	·
[152]	·	·	✓	·	·	D	·	·	·	✓	✓	✓	·	·	✓	·	·
[153]	·	·	✓	·	·	P/D/DER	·	✓	✓	·	·	·	✓	·	✓	·	·
[155]	·	·	·	✓	·	W/P	·	·	·	·	✓	·	✓	·	✓	·	·
[156]	·	·	·	✓	·	·	·	·	·	·	·	✓	·	·	·	·	✓
[157]	·	·	·	✓	✓	·	·	·	·	·	·	·	✓	·	✓	·	·
[158]	·	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	✓	·
[159]	·	·	·	✓	·	·	·	·	·	·	·	✓	·	·	·	·	·

LP: Linear Programming; **NLP:** Non-Linear Programming; **MILP:** Mixed-Integer Linear Programming; **MINLP:** Mixed-Integer Non-Linear Programming; **DT:** Deterministic; **ST:** Stochastic; **P:** Prices; **W:** Wind; **PV:** Photovoltaic; **D:** Demand; **RP:** Renewable Production; **RR:** Reserve Requirements; **DER:** Distributed Energy Resources; **UA:** Unit Availability; **CO:** Component Outages; **RO:** Robust Optimization; **WR:** With Recourse; **WOR:** Without Recourse; **ML:** Multi-Level; **KKT:** Karush-Kuhn-Tucker; **BEN:** Benders Decomposition; **MCM:** Monte-Carlo Method

2) FLEXIBLE ELECTRICITY NETWORKS TO INTEGRATE THE EXPECTED ‘ENERGY EVOLUTION’ (FENIX)

This project was developed with the participation of France, Spain and the United Kingdom, and was focused on boosting DERs by maximizing their contribution to the electric power system, through aggregation into Large Scale Virtual Power Plants (LSVPP) and decentralized management. The project was organized in three phases and incorporated Research Centers and Universities from the EU [16], [18], [29], [85], [132], [143], [153], [157], [162] and [166]–[168].

3) SMART WATTS

This German project was a Smart Grid that integrated different kinds of ICTs, proposing new approaches with which to optimize power supply. It developed a concept that included the intelligent kilowatt hour: an open system that would enable new services, added value and increased efficiency for utility companies, digital device manufacturers, service providers and consumers or final users [161] and [169].

4) ELECTRIC VEHICLES IN A DISTRIBUTED AND INTEGRATED MARKET USING A SUSTAINABLE ENERGY AND OPEN NETWORKS (EDISON)

This project was managed thanks to collaboration between Denmark and Germany, and its aim was to create a power network using a digital platform to support the optimal integration of EVs. A VPP was employed to provide solutions for EV development systems and achieve grid connection with large-scale Renewable Energy principally with systems PV and wind. The project analyzed the reduction in CO_2

emissions in a V2G system including EVs and Plug-in Hybrid EVs (PHEVs) [18], [36], [85], [160], [163] and [170].

5) THE POWER-MATCHING CITY VPP

This project was developed by the Netherlands Energy Research Center (ECN) in Hoogkerk, a suburb of the city of Groningen in the Netherlands. The power network established a power-matching device consisting of 10 micro-CHP units equipping 25 homes. Power was not only used but also generated in each of these dwellings. The power-matcher enabled supply and demand matching in a Smart Grid [36], [160], [171] and [172].

6) Web2Energy

This project, which was developed in Germany, had the objective of implementing and approving all three pillars of "Smart Distribution": i) Smart Metering, in which the consumer participates in the energy market; ii) Smart Energy Management, in which there is a clustering of small power producers; and iii) Smart Distribution Automation, in which the supply is more reliable [160] and [173].

7) FLEXIBLE APPROACHES TO LOW CARBON OPTIMISED NETWORKS (FALCON)

This project was developed in the United Kingdom and investigated how new 11kV network techniques work in practice so as to determine the best ways in which to manage power system problems resulting from the implementation of low carbon power production technologies [57], [164] and [174].

8) ZhangBei

This Chinese project consisted of developing an energy comprehensive utilization platform integrating wind power, PV power generation, energy storage and intelligent power transmission. The total capacity of the project was 49.5 MW and the estimated annual power supplied to the grid was about 96.53 MWh at full capacity [16], [160] and [175].

9) PEER ENERGY CLOUD

This German project developed cloud-based technologies for a local electronic trading platform. The objective of the platform was to deal with local excessive power production, and it was used to develop or integrate the trading operations of power renewable energies and minimize power waste. Moreover, the local power market was able to use the P2P strategy for power trading [161] and [176].

10) IPOWER - FLEXIBILITY CLEAR HOUSE (FLECH)

This Danish Smart Grid Project was designed to facilitate the interactions between DSOs and VPPs across multiple stages, from the auctioning of flexible contracts to final settlement. The Smart Grid platform was able to trade ancillary services between DSOs and VPPs that managed aggregated DERs. The system employed a transaction-based method that incorporated the support of point-to-point tariffs [157] and [177].

11) PICLO

This project was developed thanks to the collaboration between an innovative technology company called "Open Utility" and a renewable energy supplier called "Good Energy" in the United Kingdom. The local use of renewable energy allowed consumers to buy power directly from producers or prosumers. Producers and prosumers had control and visibility over who bought power from them, while consumers could select and prioritize from which generators to buy power [33], [161] and [178].

12) UNIVERSAL SMART ENERGY FRAMEWORK (USEF)

This Dutch project had as objective of employing demand-side flexibility to address problems at different levels, such as the localized peak load issue in the distribution network and the system-wide balancing problem. The DSO-Aggregator interface could be used for flexibility trading between aggregator and DSO for congestion management and/or grid capacity management [157] and [179].

13) VANDEBRON

This project was developed in the Netherlands by a P2P network connecting consumers with renewable energy. The platform enabled direct power transactions between energy suppliers and consumers. The consumers choose their own source of wind, biological or solar energy and the means to plan consumption and save according to their needs [33], [120], [161] and [180].

14) COMMUNITY FIRST! VILLAGE

This American project set up a small power network with a 27-acre master-planned community that provided power to the housing of the disabled and chronically homeless in Austin, Texas. The small power network employed RES, such as PV, to take advantage of regional weather, achieving the consumption and storage of power by houses and some community business [161] and [181].

15) ELECTRON

This British project developed a platform for gas and power metering and billing systems. System architecture worked in digitally optimized marketplaces in which the sum of small operations was managed as common transaction packages. Renewable energies were set out as requirements in order to show the profit stakeholders in existing and emerging markets [161] and [182].

16) MOSAIC

This American project was a P2P-PV system whose objective was to encourage interested consumers, such as apartment owners and others who did not own solar systems, to pay for a portion of the solar power generated by the host solar system. Decentralization in the system was adapted to consumers and prosumers rather than dealing with a central corporate entity [161] and [183].

17) SonnenCommunity

This German project allowed owners to share self-produced power with others. As a result, there was no longer any need for a conventional power supplier. The batteries, which were fed by a PV system, totally covered the owners' power needs on sunny days (often even generating a surplus) [33], [161] and [184].

18) THE BROOKLYN MICROGRID

This American project was a community-driven initiative in which two residents of Brooklyn President Street participated in the first-ever P2P power transactions by applying blockchain. The power used was derived from renewable energies such as PV. Prosumers sold their excess solar energy to the marketplace, from which consumers purchased the available solar energy using Brooklyn Microgrid app [33], [120] and [185]–[187].

19) THE COMMERCIAL BUILDING VPP

The objective if this Chinese project was to develop a VPP for commercial buildings in the Shanghai urban area in order to respond to the intelligent, automated, large-scale and diversified demand of commercial buildings. Power network that was put into operation was assembled from numerous distributed renewable energy storage sources in Huangpu District of Shanghai [18] and [160].

20) THE FEASIBILITY VPP CHONGMING SYSTEM

The project proposes a model with PV, wind and biomass renewable energy to assess the feasibility of VPPs located in Chongming country, China. The main objective is to analyze the application feasibility and performance of VPPs based on the aggregation of renewable energy power units and the advanced power-saving equipment implemented in some city buildings [188].

21) AGL VPP BATTERY STORAGE ARENA

The objective of this project was to simplify local network constraints, stabilize power prices and support RES in Australia. The VPP integrated a large number of small-scale Batteries and PVs into the smart grid. The total capacity of indicated units was 5 MW. The system took advantage of weather, and more than 40% of the generated power originated from wind farms or rooftop PV systems [85], [106] and [189].

22) DIGITAL GRID URAWA MISONO

This Japanese project connected prosumers to sub-power lines for P2P trading with one shopping mall. Each prosumer was equipped with a PV system, battery, smart meter, Digital Grid Controller (DGC) and Digital Grid Router (DGR). The DGR recorded information, such as power supplies and prices, and enabled AC-DC-AC conversion for grid interconnectivity [28].

23) SOURCE-GRID-LOAD SMART GRID

This project was developed for the large-scale consumption of clean energy using digital technologies in China. The smart grid used artificial intelligence to efficiently coordinate power production in power plants, along with balancing household consumers' power consumption. The first point was Jiangsu, which achieved a dynamic equilibrium between supply producers' and consumers' demands [160].

24) XIONG'AN

This project used the geothermal renewable energy located in Baoding, Hebei, China to build a self-sufficient and sustainable city. The strategy developed for sustainability was a multi-energy source complementary scheme, which integrated medium-deep geothermal power, shallow geothermal power and the waste heat from regenerated water and waste generation [160].

Table 5 shows the starting year of each project, along with the countries that developed the implementation of the respective power systems. In addition, Figure 3 shows a world map indicating the participation percentage for each country according to the total number of international VPP projects.

B. VPPs AND INDUSTRY 4.0

Each project has taken a step forward toward the improvement of infrastructural designs and technological applications increasing their power performance into their systems. The integration of digital technologies, such as computing (effective control of physical systems); cloud computing (software platform for optimization); data networking; big data analytics; adaptable and computable control algorithms, allows VPPs to integrate power systems by means of a software service that predicts, analyzes, monitors and optimizes the production, consumption and storage of power [166]. Furthermore, the authors of [190] state the importance of effectively scheduling the use of several household electronic and electrical devices, owing to the importance that consumers place on these devices. Such devices can acquire continuous power during each time slot without interruption, generating a large amount of data that can be processed by the VPP in real time applying Smart Metering in order to analyze power costs and essential constraints within their power systems.

The VPPs also use collaborative environment strategies to improve the planning, monitoring and controlling of their systems according to their limitations and their stakeholders' requirements. The strategies mentioned basically highlight three types of network structures or, from an interaction point of view, three types of collaborative environments: i) P2P refers to direct power trade between producers and consumers without the intermediation of conventional power providers [120]; ii) V2G refers to the use of EVs as mobile generation devices, in addition to being mobile storage devices, passing their stored power to the grid in a manner that is convenient for both the grid operator and the vehicle owner [191]; and iii) M2M refers to achieving connectivity between virtual machines through a data processor that is generally used to connect to multiple devices and transmit the data to the cloud [192] and [193]. This therefore, gives VPPs the possibility of dynamically integrating their systems

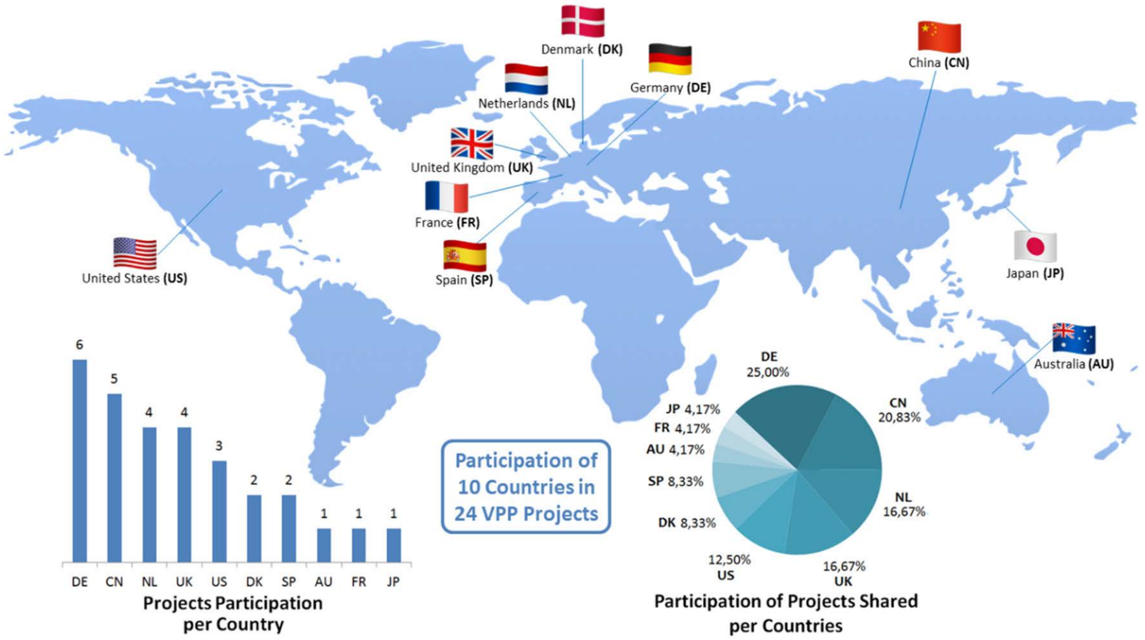

FIGURE 3. World map of VPP projects.

TABLE 5. International VPP projects.

YEARS	PROJECTS	AU	CN	DK	FR	DE	JP	NL	SP	UK	US	References
2001	The Virtual Fuel Cell Power Plant (VFCPP)	·	·	·	·	✓	·	✓	✓	·	·	[29], [58], [160], [165]
2005	Flexible Electricity Networks to Integrate the eXpected 'energy evolution' (FENIX)	·	·	·	✓	·	·	·	✓	✓	·	[16], [18], [29], [85], [132], [143], [153], [157], [162], [166], [167], [168]
2008	Smart Watts	·	·	·	·	✓	·	·	·	·	·	[161],[169]
2009	Electric Vehicles in a Distributed and Integrated Market Using a Sustainable Energy and Open Networks (EDISON)	·	·	✓	·	✓	·	·	·	·	·	[18], [36], [85], [160], [163], [170]
2010	The Power-Matching City VPP	·	·	·	·	·	·	✓	·	·	·	[36], [160], [171], [172]
2010	Web2Energy	·	·	·	·	✓	·	·	·	·	·	[160], [173]
2011	Flexible Approaches to Low Carbon Optimised Networks (FALCON)	·	·	·	·	·	·	·	·	✓	·	[57], [164], [174]
2011	ZhangBei	·	✓	·	·	·	·	·	·	·	·	[16], [160], [175]
2012	PeerEnergyCloud	·	·	·	·	✓	·	·	·	·	·	[161], [176]
2014	iPower - Flexibility Clear House (FLECH)	·	·	✓	·	·	·	·	·	·	·	[157], [177]
2014	Piclo	·	·	·	·	·	·	·	·	✓	·	[33], [161], [178]
2014	Universal Smart Energy Framework (USEF)	·	·	·	·	·	·	✓	·	·	·	[157], [179]
2014	Vandenbron	·	·	·	·	·	·	✓	·	·	·	[33], [120], [161], [180]
2015	CommunityFirst! Village	·	·	·	·	·	·	·	·	·	✓	[161], [181]
2015	Electron	·	·	·	·	·	·	·	·	✓	·	[161], [182]
2015	Mosaic	·	·	·	·	·	·	·	·	·	✓	[161], [183]
2015	SonnenCommunity	·	·	·	·	✓	·	·	·	·	·	[33], [161], [184]
2016	The Brooklyn Microgrid	·	·	·	·	·	·	·	·	·	✓	[33], [120], [185], [186], [187]
2016	TheCommercialBuilding VPP	·	✓	·	·	·	·	·	·	·	·	[18], [160]
2016	The Feasibility VPP Chongming System	·	✓	·	·	·	·	·	·	·	·	[188]
2017	AGL VPP Battery Storage ARENA	✓	·	·	·	·	·	·	·	·	·	[85], [106], [189]
2017	Digital Grid UrawaMisono	·	·	·	·	·	✓	·	·	·	·	[28]
2017	Source-Grid-Load Smart Grid	·	✓	·	·	·	·	·	·	·	·	[160]
2017	Xiong'an	·	✓	·	·	·	·	·	·	·	·	[160]

The AU–US columns are printed under the spanning header COUNTRIES.

AU: Australia; **CN:** China; **DK:** Denmark; **FR:** France; **DE:** Germany; **JP:** Japan; **NL:** Netherlands; **SP:** Spain; **UK:** United Kingdom; **US:** United States

by organizing them operationally in a centralized, decentralized, or hybrid manner [194], as mentioned in previous sections.

The increased participation of small producers and prosumers in local power markets integrated by VPPs, and the variety of collaborative environments in which they interact, has led to the emergence of autonomous agents who operate dynamically with other consumers, producers, or prosumers in different environments. According to the characteristics of the agents defined by their production or prosumption objectives, small companies are established that make up the called multi-agent systems [195]. Establishing reliable, timely and secure information channels between VPPs and all the stakeholders of their system, therefore, requires the application of increasingly robust infrastructural and technological tools. In [196], the authors mention that the application of blockchain technology allows various agreements called smart contracts to be organized between VPPs and their stakeholders for data analysis, real-time information processing and timely decision making. Moreover, [197] indicates that, in order to guarantee transparency in power transactions by producers, prosumers and consumers, VPPs using blockchain technology can generate commercial exchange elements within the system, which are called tokens or cryptocurrencies. Furthermore, according to [198], when integrating blockchain technology within the systems integrated by VPPs for interaction with the power market, the following benefits can be found: encryption of power savings, exchange of power savings, proper value power savings, increased transparency, lower transaction costs, increased reliability, increased security and customer trust and increased market sources. Moreover, in [199], the authors mention that by defining a hierarchical agent structure, data management complexity is reduced at each agent level of inter-operation in order to improve the value information blocks within the power system. In addition, in [200], it is indicated that in a P2P environment, the trading operations in the power market can be developed by end-users. The end-users could decrease the negative impact on expected profit by defining a system with the perspective based on a behavioral risk attitude, according to the implementation of an adequate communication technology.

Furthermore, the authors of [201] present a functional model, island, that is decentralized and defined by layers and which focuses on radial distribution networks with a single feeder connected to the renewable energy network and the public network that provides support to the user, as it is applied generally. The model proposes an interaction between the power integrated by the VPP within the system and its interaction with the power market. It is also important to note that cybersecurity plays a very important role in the systems that operate with VPPs in situ or through remote control. The VPP can be supported for the automation of its operations in blockchain technology accompanied by the IoT, structuring cybersecurity mechanisms that evaluate the proper functioning of scheduled tasks. One good scheme is that shown in [202], which would make it possible to diagnose smart contracts in terms of functionality and cybersecurity. From a comprehensive perspective, in [203], the authors propose a model in which the power management offered by smart homes is generated using blockchain technology, where the DERs available are evaluated for each discrete trading period during one day. The power prices are those of a typical time-of-use distribution system, which allows smart homes to have any combination of DERs, defined by the mathematical modeling of PV, BESS and EV units. The authors of [204] consequently state that it is important to consider the power limitations that balance the state of charge in order to maintain the profits of the system in comparison with the baseline price and time-of-use pricing schemes. At the level of analysis and information processing, in [205], a model is proposed in which a trading strategy that involves an artificial intelligence algorithm is developed in order to evaluate the economic impact according to the forecast of the power market services. The algorithm uses machine learning techniques to forecast trends according to supervised and reinforced learning tests, achieving results when working with data from multi-market trade scenarios. In [206], it is proposed the application of deep learning techniques in order to improve competition between VPPs and achieve the best cost vs. benefit ratio in each of the systems integrated by them. A comparison between supply function approximations allows the reader to understand the importance of using deep learning as a complementary technique to machine learning and to improve the evolution of artificial intelligence each time the VPP feeds the algorithm with the day-to-day data obtained from power systems. In addition, according to [207], it is important to consider that, in order to achieve the optimal bidding strategy of a VPP, the correct collection of data in every element of the system and a robust deep learning-based approach is required.

It is suggested that interested reader analyze the case study of ‘‘The Brooklyn Microgrid’’, because it integrates many of the concepts mentioned above and provides a detailed description of the design and implementation of the micro grid using various elements of Industry 4.0. Its authors mention how it is possible to take advantage of a structure of a power system powered by renewable energy to commercialize P2P power in a local independent power market by using blockchain technology. The way in which the system maintains power supply continuity by taking advantage of PV use and the connection with the power network is explained in [185]. In addition, the ‘‘components of microgrid energy markets’’ are mentioned in a diagram that describes the ‘‘energy management trading system’’, providing useful information with which to understand at what point and under what conditions the VPP could integrate the power systems. Furthermore, it is also recommended that the reader analyze the case study of ‘‘Smart contract architecture for decentralized energy trading’’, as it establishes and complements concepts that relate a P2P strategy with the power distribution network integrated by VPP and its interaction with EVs, solar power, wind power, DSOs and the power market through the application of blockchain technology [120]. The case study of ‘‘Exploring blockchain for the energy transition in Japan’’ shows the structures and technologies applied to a system implemented in Japan, in which the opportunities and challenges related to economic, environmental and institutional aspects are described [28].

VII. CONCLUSION

This paper provides a literature review of more than 180 scientific papers related to VPPs. The mention of key strategies of VPPs and their strong factors as regards making decisions in power systems have been collected organizing the information according to: i) the evolutionary frequency of the concepts and definitions related to VPPs within the analyzed papers; ii) the operation, planning and interaction of VPPs with the internal and external system elements, agents and power markets; iii) the programming methods, math techniques and software tools used to solve the production, distribution and profit issues proposed; and iv) the international VPP projects as reference for the development of new power systems integrated by VPPs.

The power systems analyzed mention VPP interaction in the operation and synchronization of DERs, power operators, EVs, consumers, producers, prosumers or batteries, among others, along with the integration with other power systems and power markets. Moreover, they analyze the behavior of the combination between sources of traditional power production and sources of power production derived from renewable energies.

In the analyzed papers, it is mentioned that VPPs carry out trading operations in power and CO_2 markets, acting as intermediaries for the big and small producers, consumers and prosumers, considering in some papers the bidirectional power transactions carried out by models such as P2P, V2G and M2M. In addition, it is also mentioned that the international VPP projects involve Industry 4.0, such as IoT, AI, blockchain and cloud computing, thus facilitating the integration of small consumers, producers and prosumers into power systems, and even making their interaction easier with the power market.

The papers cited suggest that the issues and challenges analyzed in the power systems may be overcome interpreting and modeling systematically each of the elements within the system, as well as the featured geographic and meteorological characteristics of each environment in which they perform. Therefore, the issues proposed by researchers consider factors such as uncertainty, reliability, DR, reactive power, or the use of heat and waste gases, among others, to formulate the models whose objectives are: i) to optimize power consumption by establishing incentive and penalty parameters at peak and off-peak hours; ii) to maximize profits from power trading in power and CO_2 markets, establishing predictions according to DR, real-time and time-of-use programs; and iii) to minimize operating costs for power production, distribution and storage, establishing control and storage nodes according to the BESS, the state of charge and the characteristics of power batteries.

REFERENCES

[1] European Environment Agency. *Sources of Air Pollution in Europe*. Accessed: May 27, 2021. [Online]. Available: https://www.eea.europa.eu/signals/signals-2013/infographics/sources-of-air-pollution-in-europe/view

[2] European Environment Agency. *Total Greenhouse Gas Emission Trends and Projections in Europe*. Accessed: May 27, 2021. [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends-7/assessment

[3] European Commission. *Energy Policies*. Accessed: May 27, 2021. [Online]. Available: https://ec.europa.eu/info/policies/energy_en

[4] European Commission. *Energy Strategy*. Accessed: May 27, 2021. [Online]. Available: https://ec.europa.eu/energy/topics/energy-strategy-and-energy-union_es

[5] United Nations. *Sustainable Development Goals*. Accessed: May 27, 2021. [Online]. Available: https://sdgs.un.org/

[6] J. Gong, D. Xie, C. Jiang, and Y. Zhang, "Multiple objective compromised method for power management in virtual power plants," *Energies*, vol. 4, no. 4, pp. 700–716, Apr. 2011.

[7] M. Brenna, M. C. Falvo, F. Foiadelli, L. Martirano, and D. Poli, "From virtual power plant (VPP) to sustainable energy microsystem (SEM): An opportunity for buildings energy management," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, Oct. 2015, pp. 1–8.

[8] D. Koraki and K. Strunz, "Wind and solar power integration in electricity markets and distribution networks through service-centric virtual power plants," *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 473–485, Jan. 2018.

[9] B. Moreno and G. Díaz, "The impact of virtual power plant technology composition on wholesale electricity prices: A comparative study of some European Union electricity markets," *Renew. Sustain. Energy Rev.*, vol. 99, pp. 100–108, Jan. 2019.

[10] P. Pal, P. A. Krishnamoorthy, D. K. Rukmani, and S. J. Antony, "Optimal dispatch strategy of virtual power plant for day-ahead market framework," *Appl. Sci.*, vol. 11, no. 9, p. 3814, 2021.

[11] N. Shaukat, S. M. Ali, C. A. Mehmood, B. Khan, M. Jawad, U. Farid, Z. Ullah, S. M. Anwar, and M. Majid, "A survey on consumers empowerment, communication technologies, and renewable generation penetration within smart grid," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 1453–1475, Jan. 2018.

[12] K. O. Adu-Kankam and L. M. Camarinha-Matos, "Towards collaborative virtual power plants: Trends and convergence," *Sustain. Energy, Grids Netw.*, vol. 16, pp. 217–230, Dec. 2018.

[13] J. Shen, C. Jiang, and B. Li, "Controllable load management approaches in smart grids," *Energies*, vol. 8, no. 10, pp. 11187–11202, Oct. 2015.

[14] S. A. A. Kazmi, M. K. Shahzad, A. Z. Khan, and D. R. Shin, "Smart distribution networks: A review of modern distribution concepts from a planning perspective," *Energies*, vol. 10, no. 4, p. 501, Apr. 2017.

[15] M. H. Rehmani, A. Davy, B. Jennings, and C. Assi, "Software defined networks-based smart grid communication: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2637–2670, 3rd Quart., 2019.

[16] Z. Ullah, G. Mokryani, F. Campean, and Y. F. Hu, "Comprehensive review of VPPs planning, operation and scheduling considering the uncertainties related to renewable energy sources," *IET Energy Syst. Integr.*, vol. 1, no. 3, pp. 147–157, Sep. 2019.

[17] S. M. Nosratabadi, R. Hooshmand, and E. Gholipour, "A comprehensive review on microgrid and virtual power plant concepts employed for distributed energy resources scheduling in power systems," *Renew. Sustain. Energy Rev.*, vol. 67, pp. 341–363, Jan. 2017.

[18] S. Yu, F. Fang, Y. Liu, and J. Liu, "Uncertainties of virtual power plant: Problems and countermeasures," *Appl. Energy*, vol. 239, pp. 454–470, Apr. 2019.

[19] M. Farmanbar, K. Parham, Ø. Arild, and C. Rong, "A widespread review of smart grids towards smart cities," *Energies*, vol. 12, no. 23, p. 4484, Nov. 2019.

[20] K. Mahmud, B. Khan, J. Ravishankar, A. Ahmadi, and P. Siano, "An internet of energy framework with distributed energy resources, prosumers and small-scale virtual power plants: An overview," *Renew. Sustain. Energy Rev.*, vol. 127, Jul. 2020, Art. no. 109840.

[21] M. Andoni, V. Robu, D. Flynn, S. Abram, and D. Geach, "Blockchain technology in the energy sector: A systematic review of challenges and opportunities," *Renew. Sustain. Energy Rev.*, vol. 100, pp. 143–174, Feb. 2019.

[22] A. S. Musleh, G. Yao, and S. M. Muyeen, "Blockchain applications in smart grid–review and frameworks," *IEEE Access*, vol. 7, pp. 86746–86757, 2019.

[23] M. F. Zia, M. Benbouzid, E. Elbouchikhi, S. M. Muyeen, K. Techato, and J. M. Guerrero, "Microgrid transactive energy: Review, architectures, distributed ledger technologies, and market analysis," *IEEE Access*, vol. 8, pp. 19410–19432, 2020.

[24] M. A. Hossain, H. R. Pota, M. J. Hossain, and F. Blaabjerg, "Evolution of microgrids with converter-interfaced generations: Challenges and opportunities," *Int. J. Elect. Power Energy Syst.*, vol. 109, pp. 160–186, Jul. 2019.

[25] A. Colmenar-Santos, C. Reino-Rio, D. Borge-Diez, and E. Collado-Fernández, "Distributed generation: A review of factors that can contribute most to achieve a scenario of DG units embedded in the new distribution networks," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1130–1148, Jun. 2016.

[26] C. Rae, S. Kerr, and M. M. Maroto-Valer, "Upscaling smart local energy systems: A review of technical barriers," *Renew. Sustain. Energy Rev.*, vol. 131, Oct. 2020, Art. no. 110020.

[27] G. Dileep, "A survey on smart grid technologies and applications," *Renew. Energy*, vol. 146, pp. 2589–2625, Feb. 2020.

[28] A. Ahl, M. Yarime, M. Goto, S. S. Chopra, N. M. Kumar, K. Tanaka, and D. Sagawa, "Exploring blockchain for the energy transition: Opportunities and challenges based on a case study in Japan," *Renew. Sustain. Energy Rev.*, vol. 117, Jan. 2020, Art. no. 109488.

[29] M. Lv, S. Lou, B. Liu, Z. Fan, and Z. Wu, "Review on power generation and bidding optimization of virtual power plant," in *Proc. Int. Conf. Electr. Eng. Informat. (ICELTICs)*, Oct. 2017, pp. 66–71.

[30] O. Palizban, K. Kauhaniemi, and J. M. Guerrero, "Microgrids in active network management—Part I: Hierarchical control, energy storage, virtual power plants, and market participation," *Renew. Sustain. Energy Rev.*, vol. 36, pp. 428–439, Aug. 2014.

[31] S. Kumar V., J. Prasad, and R. Samikannu, "Overview, issues and prevention of energy theft in smart grids and virtual power plants in Indian context," *Energy Policy*, vol. 110, pp. 365–374, Nov. 2017.

[32] G. Plancke, K. De Vos, R. Belmans, and A. Delnooz, "Virtual power plants: Definition, applications and barriers to the implementation in the distribution system," in *Proc. 12th Int. Conf. Eur. Energy Market (EEM)*, May 2015, pp. 1–5.

[33] T. Morstyn, N. Farrell, S. J. Darby, and M. D. McCulloch, "Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants," *Nature Energy*, vol. 3, no. 2, pp. 94–101, Feb. 2018.

[34] E. Mashhour and S. M. Moghaddas-Tafreshi, "Bidding strategy of virtual power plant for participating in energy and spinning reserve markets—Part I: Problem formulation," *IEEE Trans. Power Syst.*, vol. 26, no. 2, pp. 949–956, May 2010.

[35] J. Zhang, B.-C. Seet, and T. Lie, "An event-based resource management framework for distributed decision-making in decentralized virtual power plants," *Energies*, vol. 9, no. 8, p. 595, Jul. 2016.

[36] J. Wang, W. Yang, H. Cheng, L. Huang, and Y. Gao, "The optimal configuration scheme of the virtual power plant considering benefits and risks of investors," *Energies*, vol. 10, no. 7, p. 968, Jul. 2017.

[37] L. Dong, S. Fan, Z. Wang, J. Xiao, H. Zhou, Z. Li, and G. He, "An adaptive decentralized economic dispatch method for virtual power plant," *Appl. Energy*, vol. 300, Oct. 2021, Art. no. 117347.

[38] A. F. Raab, M. Ferdowsi, E. Karfopoulos, I. G. Unda, S. Skarvelis-Kazakos, P. Papadopoulos, E. Abbasi, L. M. Cipcigan, N. Jenkins, N. Hatziargyriou, and K. Strunz, "Virtual power plant control concepts with electric vehicles," in *Proc. 16th Int. Conf. Intell. Syst. Appl. Power Syst.*, Sep. 2011, pp. 1–6.

[39] G. Neglia, L. Giarré, I. Tinnirello, and G. Di Bella, "Teletraffic engineering for direct load control in smart grids," *Sustain. Energy, Grids Netw.*, vol. 16, pp. 167–176, Dec. 2018.

[40] H. Eisazadeh, M. Mirhosseini Moghaddam, and B. Alizadeh, "Optimal frequency response of VPP-based power systems considering participation coefficient," *Int. J. Electr. Power Energy Syst.*, vol. 129, Jul. 2021, Art. no. 106881.

[41] K. E. Bakari and W. L. Kling, "Fitting distributed generation in future power markets through virtual power plants," in *Proc. 9th Int. Conf. Eur. Energy Market*, May 2012, pp. 1–7.

[42] A. Karabiber, C. Keles, A. Kaygusuz, and B. B. Alagoz, "An approach for the integration of renewable distributed generation in hybrid DC/AC microgrids," *Renew. Energy*, vol. 52, pp. 251–259, Apr. 2013.

[43] E. Mashhour and S. M. Moghaddas-Tafreshi, "The opportunities for future virtual power plant in the power market, a view point," in *Proc. Int. Conf. Clean Electr. Power*, Jun. 2009, pp. 448–452.

[44] F. Nazari, A. Zangeneh, and A. Shayegan-Rad, "A bilevel scheduling approach for modeling energy transaction of virtual power plants in distribution networks," *Iranian J. Elect. Electron. Eng.*, vol. 13, no. 1, pp. 1–9, 2017.

[45] M. H. Nazari, M. Bagheri Sanjareh, A. Khodadadi, M. Torkashvand, and S. H. Hosseinian, "An economy-oriented DG-based scheme for reliability improvement and loss reduction of active distribution network based on game-theoretic sharing strategy," *Sustain. Energy, Grids Netw.*, vol. 27, Sep. 2021, Art. no. 100514.

[46] Z. Ma, J. D. Billanes, and B. N. Jørgensen, "Aggregation potentials for buildings—Business models of demand response and virtual power plants," *Energies*, vol. 10, no. 10, p. 1646, 2017.

[47] Z. Luo, S. Hong, and Y. Ding, "A data mining-driven incentive-based demand response scheme for a virtual power plant," *Appl. Energy*, vol. 239, pp. 549–559, Apr. 2019.

[48] A. Beguin, C. Nicolet, B. Kawkabani, and F. Avellan, "Virtual power plant with pumped storage power plant for renewable energy integration," in *Proc. Int. Conf. Electr. Mach. (ICEM)*, Sep. 2014, pp. 1736–1742.

[49] J. Luo, Y. Gao, W. Yang, Y. Yang, Z. Zhao, and S. Tian, "Optimal operation modes of virtual power plants based on typical scenarios considering output evaluation criteria," *Energies*, vol. 11, no. 10, p. 2634, Oct. 2018.

[50] H. Wang, S. Riaz, and P. Mancarella, "Integrated techno-economic modeling, flexibility analysis, and business case assessment of an urban virtual power plant with multi-market co-optimization," *Appl. Energy*, vol. 259, Feb. 2020, Art. no. 114142.

[51] F. Nadeem, M. A. Aftab, S. M. S. Hussain, I. Ali, P. K. Tiwari, A. K. Goswami, and T. S. Ustun, "Virtual power plant management in smart grids with XMPP based IEC 61850 communication," *Energies*, vol. 12, no. 12, p. 2398, Jun. 2019.

[52] H. Han, H. Cui, S. Gao, Q. Shi, A. Fan, and C. Wu, "A remedial strategic scheduling model for load serving entities considering the interaction between grid-level energy storage and virtual power plants," *Energies*, vol. 11, no. 9, p. 2420, Sep. 2018.

[53] A. Khodaei, S. Bahramirad, and M. Shahidehpour, "Microgrid planning under uncertainty," *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2417–2425, Sep. 2015.

[54] R. Ko, D. Kang, and S.-K. Joo, "Mixed integer quadratic programming based scheduling methods for day-ahead bidding and intra-day operation of virtual power plant," *Energies*, vol. 12, no. 8, p. 1410, Apr. 2019.

[55] M. C. Buth, A. J. Wieczorek, and G. P. J. Verbong, "The promise of peer-to-peer trading? The potential impact of blockchain on the actor configuration in the Dutch electricity system," *Energy Res. Social Sci.*, vol. 53, pp. 194–205, Jul. 2019.

[56] L. Che, X. Zhang, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, "Optimal interconnection planning of community microgrids with renewable energy sources," *IEEE Trans. Smart Grid*, vol. 8, no. 3, pp. 1054–1063, May 2017.

[57] K. Zafred, J. Nieto-Martin, and E. Butans, "Electric vehicles—Effects on domestic low voltage networks," in *Proc. IEEE Int. Energy Conf. (ENERGYCON)*, Apr. 2016, pp. 1–6.

[58] Z. Liu, W. Zheng, F. Qi, L. Wang, B. Zou, F. Wen, and Y. Xue, "Optimal dispatch of a virtual power plant considering demand response and carbon trading," *Energies*, vol. 11, p. 1488, Jun. 2018.

[59] F. Imbault, M. Swiatek, R. de Beaufort, and R. Plana, "The green blockchain: Managing decentralized energy production and consumption," in *Proc. IEEE Int. Conf. Environ. Electr. Eng. IEEE Ind. Commercial Power Syst. Eur. (EEEIC/I&CPS Europe)*, Jun. 2017, pp. 1–5.

[60] S. Wassermann, M. Reeg, and K. Nienhaus, "Current challenges of Germany's energy transition project and competing strategies of challengers and incumbents: The case of direct marketing of electricity from renewable energy sources," *Energy Policy*, vol. 76, pp. 66–75, Jan. 2015.

[61] L. Lehmbruck, J. Kretz, J. Aengenvoort, and F. Sioshansi, "Aggregation of front- and behind-the-meter: The evolving VPP business model," in *Behind and Beyond the Meter: Digitalization, Aggregation, Optimization, Monetization*, F. Sioshansi, Ed. New York, NY, USA: Academic, 2020, ch. 10, pp. 211–232.

[62] D. Shropshire, A. Purvins, I. Papaioannou, and I. Maschio, "Benefits and cost implications from integrating small flexible nuclear reactors with off-shore wind farms in a virtual power plant," *Energy Policy*, vol. 46, pp. 558–573, Jul. 2012.

[63] R. Chakraborty, A. Samanta, K. M. Agrawal, and A. Dutta, "Towards smarter grid: Policy and its impact assessment through a case study," *Sustain. Energy, Grids Netw.*, vol. 26, Jun. 2021, Art. no. 100436.

[64] W. S. W. Abdullah, M. Osman, M. Z. A. A. Kadir, R. Verayiah, N. F. A. Aziz, and M. A. Rasheed, "Techno-economics analysis of battery energy storage system (BESS) design for virtual power plant (VPP)–A case study in Malaysia," *J. Energy Storage*, vol. 38, Jun. 2021, Art. no. 102568.

[65] R. D. Rappaport and J. Miles, "Cloud energy storage for grid scale applications in the U.K.," *Energy Policy*, vol. 109, pp. 609–622, Oct. 2017.

[66] P. Asmus, "Microgrids, virtual power plants and our distributed energy future," *Electr. J.*, vol. 23, no. 10, pp. 72–82, Dec. 2010.

[67] Y. M. Kim, D. Jung, Y. Chang, and D. H. Choi, "Intelligent micro energy grid in 5G era: Platforms, business cases, testbeds, and next generation applications," *Electronics*, vol. 8, no. 4, p. 468, Apr. 2019.

[68] N. K. Meena, J. Yang, and E. Zacharis, "Optimisation framework for the design and operation of open-market urban and remote community microgrids," *Appl. Energy*, vol. 252, Oct. 2019, Art. no. 113399.

[69] W. Li, M. Ferdowsi, M. Stevic, A. Monti, and F. Ponci, "Cosimulation for smart grid communications," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2374–2384, Nov. 2014.

[70] G. I. Pereira, J. M. Specht, P. P. Silva, and R. Madlener, "Technology, business model, and market design adaptation toward smart electricity distribution: Insights for policy making," *Energy Policy*, vol. 121, pp. 426–440, Oct. 2018.

[71] A. J. Conejo, J. M. Morales, and L. Baringo, "Real-time demand response model," *IEEE Trans. Smart Grid*, vol. 1, no. 3, pp. 236–242, Dec. 2010.

[72] M. H. Abbasi, M. Taki, A. Rajabi, L. Li, and J. Zhang, "Coordinated operation of electric vehicle charging and wind power generation as a virtual power plant: A multi-stage risk constrained approach," *Appl. Energy*, vol. 239, pp. 1294–1307, Apr. 2019.

[73] N. D. Hatziargyriou and G. E. Asimakopoulou, "DER integration through a monopoly DER aggregator," *Energy Policy*, vol. 137, Feb. 2020, Art. no. 111124.

[74] A. Tascikaraoglu, O. Erdinc, M. Uzunoglu, and A. Karakas, "An adaptive load dispatching and forecasting strategy for a virtual power plant including renewable energy conversion units," *Appl. Energy*, vol. 119, pp. 445–453, Apr. 2014.

[75] R. Campaner, M. Chiandone, V. Arcidiacono, G. Sulligoi, and F. Milano, "Automatic voltage control of a cluster of hydro power plants to operate as a virtual power plant," in *Proc. IEEE 15th Int. Conf. Environ. Electr. Eng. (EEEIC)*, Jun. 2015, pp. 2153–2158.

[76] M. Kolenc, P. Nemček, C. Gutschi, N. Suljanović, and M. Zajc, "Performance evaluation of a virtual power plant communication system providing ancillary services," *Electr. Power Syst. Res.*, vol. 149, pp. 46–54, Aug. 2017.

[77] A. Vicente-Pastor, J. Nieto-Martin, D. W. Bunn, and A. Laur, "Evaluation of flexibility markets for retailer–DSO–TSO coordination," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 2003–2012, May 2019.

[78] M. Shabanzadeh, M.-R. Haghifam, and M.-K. Sheikh-El-Eslami, "An interactive cooperation model for neighboring virtual power plants," *Appl. Energy*, vol. 200, pp. 273–289, Aug. 2017.

[79] P. L. Querini, O. Chiotti, and E. Fernádez, "Cooperative energy management system for networked microgrids," *Sustain. Energy, Grids Netw.*, vol. 23, Sep. 2020, Art. no. 100371.

[80] S. E. Ahmadi, N. Rezaei, and H. Khayyam, "Energy management system of networked microgrids through optimal reliability-oriented day-ahead self-healing scheduling," *Sustain. Energy, Grids Netw.*, vol. 23, Sep. 2020, Art. no. 100387.

[81] H. Cui, F. Li, Q. Hu, L. Bai, and X. Fang, "Day-ahead coordinated operation of utility-scale electricity and natural gas networks considering demand response based virtual power plants," *Appl. Energy*, vol. 176, pp. 183–195, Aug. 2016.

[82] M. Pasetti, S. Rinaldi, and D. Manerba, "A virtual power plant architecture for the demand-side management of smart prosumers," *Appl. Sci.*, vol. 8, no. 3, p. 432, Mar. 2018.

[83] N. Mazzi, A. Trivella, and J. M. Morales, "Enabling active/passive electricity trading in dual-price balancing markets," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 1980–1990, May 2019.

[84] I. Worighi, A. Maach, A. Hafid, O. Hegazy, and J. Van Mierlo, "Integrating renewable energy in smart grid system: Architecture, virtualization and analysis," *Sustain. Energy, Grids Netw.*, vol. 18, Jun. 2019, Art. no. 100226.

[85] T. Sikorski, M. Jasiński, E. Ropuszyńska-Surma, M. Węglarz, D. Kaczorowska, P. Kostyła, Z. Leonowicz, R. Lis, J. Rezmer, W. Rojewski, M. Sobierajski, J. Szymańda, D. Bejmert, P. Janik, and B. Solak, "A case study on distributed energy resources and energy-storage systems in a virtual power plant concept: Technical aspects," *Energies*, vol. 13, no. 12, p. 3086, Jun. 2020.

[86] T. Sikorski, M. Jasiński, E. Ropuszyńska-Surma, M. Węglarz, D. Kaczorowska, P. Kostyła, Z. Leonowicz, R. Lis, J. Rezmer, W. Rojewski, M. Sobierajski, J. Szymańda, D. Bejmert, and P. Janik, "A case study on distributed energy resources and energy-storage systems in a virtual power plant concept: Economic aspects," *Energies*, vol. 12, no. 23, p. 4447, Nov. 2019.

[87] S. Seyyed Mahdavi and M. H. Javidi, "VPP decision making in power markets using benders decomposition," *Int. Trans. Electr. Energy Syst.*, vol. 24, no. 7, pp. 960–975, Jul. 2014.

[88] G. Sun, W. Qian, W. Huang, Z. Xu, Z. Fu, Z. Wei, and S. Chen, "Stochastic adaptive robust dispatch for virtual power plants using the binding scenario identification approach," *Energies*, vol. 12, no. 10, p. 1918, May 2019.

[89] S. Stepanescu, C. Rehtanz, S. Arad, I. Fotau, M. Marcu, and F. Popescu, "Implementation of small water power plants regarding future virtual power plants," in *Proc. 10th Int. Conf. Environ. Electr. Eng.*, May 2011, pp. 1–4.

[90] M. A. Salmani, A. Anzalchi, and S. Salmani, "Virtual power plant: New solution for managing distributed generations in decentralized power systems," in *Proc. Int. Conf. Manage. Service Sci.*, Aug. 2010, pp. 1–6.

[91] J. M. Xu, Y. Sun, Q. Sun, and J. W. Ma, "A comprehensive evaluation index system of virtual power plant participating in power coordination and optimal dispatching," in *Proc. IEEE Int. Conf. Appl. Supercond. Electromagn. Devices (ASEMD)*, Apr. 2018, pp. 1–2.

[92] C. Pop, M. Antal, T. Cioara, I. Anghel, and I. Salomie, "A fog computing enabled virtual power plant model for delivery of frequency restoration reserve services," *Sensors*, vol. 19, no. 21, p. 4688, Oct. 2019.

[93] R. Iacobucci, B. McLellan, and T. Tezuka, "The synergies of shared autonomous electric vehicles with renewable energy in a virtual power plant and microgrid," *Energies*, vol. 11, no. 8, p. 2016, Aug. 2018.

[94] Z. Su, Y. Wang, Q. Xu, M. Fei, Y.-C. Tian, and N. Zhang, "A secure charging scheme for electric vehicles with smart communities in energy blockchain," *IEEE Internet Things J.*, vol. 6, no. 3, pp. 4601–4613, Jun. 2019.

[95] M. Maanavi, A. Najafi, R. Godina, M. Mahmoudian, and E. M. G. Rodrigues, "Energy management of virtual power plant considering distributed generation sizing and pricing," *Appl. Sci.*, vol. 9, no. 14, p. 2817, Jul. 2019.

[96] J. Liu, J. Li, Y. Xiang, X. Zhang, and W. Jiang, "Optimal sizing of cascade hydropower and distributed photovoltaic included virtual power plant considering investments and complementary benefits in electricity markets," *Energies*, vol. 12, no. 5, p. 952, Mar. 2019.

[97] H. Pandžić, I. Kuzle, and T. Capuder, "Virtual power plant mid-term dispatch optimization," *Appl. Energy*, vol. 101, pp. 134–141, Jan. 2013.

[98] E. Handschin, F. Neise, H. Neumann, and R. Schultz, "Optimal operation of dispersed generation under uncertainty using mathematical programming," *Int. J. Electr. Power Energy Syst.*, vol. 28, no. 9, pp. 618–626, Nov. 2006.

[99] C. Schulz, G. Roder, and M. Kurrat, "Virtual power plants with combined heat and power micro-units," in *Proc. Int. Conf. Future Power Syst.*, 2005, p. 5.

[100] A. Hany Elgamal, G. Kocher-Oberlehner, V. Robu, and M. Andoni, "Optimization of a multiple-scale renewable energy-based virtual power plant in the U.K.," *Appl. Energy*, vol. 256, Dec. 2019, Art. no. 113973.

[101] J. Zhang, Z. Xu, W. Xu, F. Zhu, X. Lyu, and M. Fu, "Bi-objective dispatch of multi-energy virtual power plant: Deep-learning-based prediction and particle swarm optimization," *Appl. Sci.*, vol. 9, no. 2, p. 292, Jan. 2019.

[102] F. Fang, S. Yu, and M. Liu, "An improved Shapley value-based profit allocation method for CHP-VPP," *Energy*, vol. 213, Dec. 2020, Art. no. 118805.

[103] H. Pandžić, J. M. Morales, A. J. Conejo, and I. Kuzle, "Offering model for a virtual power plant based on stochastic programming," *Appl. Energy*, vol. 105, pp. 282–292, May 2013.

[104] K. Honghui, G. Shaoqing, and N. Hui, "Virtual power plant optimization decision method considering the interaction between combined cooling-heating and power and electric heating equipment," in *Proc. IEEE Innov. Smart Grid Technol.-Asia (ISGT Asia)*, May 2019, pp. 4351–4355.

[105] S. Pazouki, M.-R. Haghifam, and S. Pazouki, "Transition from fossil fuels power plants toward virtual power plants of distribution networks," in *Proc. 21st Conf. Electr. Power Distrib. Netw. Conf. (EPDC)*, Apr. 2016, pp. 82–86.

[106] B. Behi, A. Baniasadi, A. Arefi, A. Gorjy, P. Jennings, and A. Pivrikas, "Cost–benefit analysis of a virtual power plant including solar PV, flow battery, heat pump, and demand management: A western Australian case study," *Energies*, vol. 13, no. 10, p. 2614, 2020.

[107] Y. Gao, X. Zhou, J. Ren, X. Wang, and D. Li, "Double layer dynamic game bidding mechanism based on multi-agent technology for virtual power plant and internal distributed energy resource," *Energies*, vol. 11, no. 11, p. 3072, Nov. 2018.

[108] X. Li, D. Zhao, and B. Guo, "Decentralized and collaborative scheduling approach for active distribution network with multiple virtual power plants," *Energies*, vol. 11, no. 11, p. 3208, 2018.

[109] A. Raab, E. Lauth, K. Strunz, and D. Göhlich, "Implementation schemes for electric bus fleets at depots with optimized energy procurements in virtual power plant operations," *World Electric Vehicle J.*, vol. 10, no. 1, p. 5, Jan. 2019.

[110] J. Duan, X. Wang, Y. Gao, Y. Yang, W. Yang, H. Li, and A. Ehsan, "Multi-objective virtual power plant construction model based on decision area division," *Appl. Sci.*, vol. 8, no. 9, p. 1484, Aug. 2018.

[111] C. Wei, J. Xu, S. Liao, Y. Sun, Y. Jiang, D. Ke, Z. Zhang, and J. Wang, "A bi-level scheduling model for virtual power plants with aggregated thermostatically controlled loads and renewable energy," *Appl. Energy*, vol. 224, pp. 659–670, Aug. 2018.

[112] D. M. Anand, R. T. de Salis, Y. Cheng, J. Moyne, and D. M. Tilbury, "A hierarchical incentive arbitration scheme for coordinated PEV charging stations," *IEEE Trans. Smart Grid*, vol. 6, no. 4, pp. 1775–1784, Jul. 2015.

[113] J. Thomsen, N. Saad Hussein, C. Senkpiel, N. Hartmann, and T. Schlegl, "An optimized energy system planning and operation on distribution grid level—The decentralized market agent as a novel approach," *Sustain. Energy, Grids Netw.*, vol. 12, pp. 40–56, Dec. 2017.

[114] R. Gao, H. Guo, R. Zhang, T. Mao, Q. Xu, B. Zhou, and P. Yang, "A two-stage dispatch mechanism for virtual power plant utilizing the CVaR theory in the electricity spot market," *Energies*, vol. 12, no. 17, p. 3402, Sep. 2019.

[115] P. M. De Oliveira-De Jesus and C. H. Antunes, "Economic valuation of smart grid investments on electricity markets," *Sustain. Energy, Grids Netw.*, vol. 16, pp. 70–90, Dec. 2018.

[116] Q. Yang, H. Wang, T. Wang, S. Zhang, X. Wu, and H. Wang, "Blockchain-based decentralized energy management platform for residential distributed energy resources in a virtual power plant," *Appl. Energy*, vol. 294, Jul. 2021, Art. no. 117026.

[117] L. Xiao, L. Lin, and Y. Liu, "Discussions on the architecture and operation mode of future power grids," *Energies*, vol. 4, no. 7, pp. 1025–1035, Jul. 2011.

[118] X. Lyu, Z. Xu, N. Wang, M. Fu, and W. Xu, "A two-layer interactive mechanism for peer-to-peer energy trading among virtual power plants," *Energies*, vol. 12, no. 19, p. 3628, Sep. 2019.

[119] S. R. Dabbagh and M. K. Sheikh-El-Eslami, "Risk-based profit allocation to DERs integrated with a virtual power plant using cooperative game theory," *Electr. Power Syst. Res.*, vol. 121, pp. 368–378, Apr. 2015.

[120] D. Han, C. Zhang, J. Ping, and Z. Yan, "Smart contract architecture for decentralized energy trading and management based on blockchains," *Energy*, vol. 199, May 2020, Art. no. 117417.

[121] S. Rahmani-Dabbagh and M. K. Sheikh-El-Eslami, "A profit sharing scheme for distributed energy resources integrated into a virtual power plant," *Appl. Energy*, vol. 184, pp. 313–328, Dec. 2016.

[122] J. Ali and F. Silvestro, "Conventional power plants to TSO frequency containment reserves–A competitive analysis for virtual power Plant's role," in *Proc. IEEE 5th Int. Forum Res. Technol. Soc. Ind. (RTSI)*, Sep. 2019, pp. 6–11.

[123] A. G. Zamani, A. Zakariazadeh, and S. Jadid, "Day-ahead resource scheduling of a renewable energy based virtual power plant," *Appl. Energy*, vol. 169, pp. 324–340, May 2016.

[124] A. Laur, J. Nieto-Martin, D. W. Bunn, and A. Vicente-Pastor, "Optimal procurement of flexibility services within electricity distribution networks," *Eur. J. Oper. Res.*, vol. 285, no. 1, pp. 34–47, Aug. 2020.

[125] F. Rahimi and A. Ipakchi, "Demand response as a market resource under the smart grid paradigm," *IEEE Trans. Smart Grid*, vol. 1, no. 1, pp. 82–88, Jun. 2010.

[126] J. Hu, C. Jiang, and Y. Liu, "Short-term bidding strategy for a price-maker virtual power plant based on interval optimization," *Energies*, vol. 12, no. 19, p. 3662, Sep. 2019.

[127] S. Li, F. Luo, J. Yang, G. Ranzi, and J. Wen, "A personalized electricity tariff recommender system based on advanced metering infrastructure and collaborative filtering," *Int. J. Electr. Power Energy Syst.*, vol. 113, pp. 403–410, Dec. 2019.

[128] A. Baringo and L. Baringo, "A stochastic adaptive robust optimization approach for the offering strategy of a virtual power plant," *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 3492–3504, Sep. 2017.

[129] H. Bai, S. Miao, X. Ran, and C. Ye, "Optimal dispatch strategy of a virtual power plant containing battery switch stations in a unified electricity market," *Energies*, vol. 8, no. 3, pp. 2268–2289, Mar. 2015.

[130] J. Qiu, J. Zhao, D. Wang, and Y. Zheng, "Two-stage coordinated operational strategy for distributed energy resources considering wind power curtailment penalty cost," *Energies*, vol. 10, no. 7, p. 965, Jul. 2017.

[131] S. R. Dabbagh and M. K. Sheikh-El-Eslami, "Risk assessment of virtual power plants offering in energy and reserve markets," *IEEE Trans. Power Syst.*, vol. 31, no. 5, pp. 3572–3582, Sep. 2016.

[132] M. Shabanzadeh, M.-K. Sheikh-El-Eslami, and M.-R. Haghifam, "A medium-term coalition-forming model of heterogeneous DERs for a commercial virtual power plant," *Appl. Energy*, vol. 169, pp. 663–681, May 2016.

[133] T. Wang, X. Jiang, Y. Jin, D. Song, M. Yang, and Q. Zeng, "Peaking compensation mechanism for thermal units and virtual peaking plants union promoting curtailed wind power integration," *Energies*, vol. 12, no. 17, p. 3299, Aug. 2019.

[134] L. Baringo, M. Freire, R. García-Bertrand, and M. Rahimiyan, "Offering strategy of a price-maker virtual power plant in energy and reserve markets," *Sustain. Energy, Grids Netw.*, vol. 28, Dec. 2021, Art. no. 100558.

[135] M. Shafiekhani, A. Badri, M. Shafie-khah, and J. P. S. Catalão, "Strategic bidding of virtual power plant in energy markets: A bi-level multi-objective approach," *Int. J. Elect. Power Energy Syst.*, vol. 113, pp. 208–219, Dec. 2019.

[136] N. Pourghaderi, M. Fotuhi-Firuzabad, M. Moeini-Aghtaie, and M. Kabirifar, "Commercial demand response programs in bidding of a technical virtual power plant," *IEEE Trans. Ind. Informat*, vol. 14, no. 11, pp. 5100–5111, Nov. 2018.

[137] M. Foroughi, A. Pasban, M. Moeini-Aghtaie, and A. Fayaz-Heidari, "A bi-level model for optimal bidding of a multi-carrier technical virtual power plant in energy markets," *Int. J. Electr. Power Energy Syst.*, vol. 125, Feb. 2021, Art. no. 106397.

[138] M. Freire-Lizcano, L. Baringo, and R. Garcia-Bertrand, "Offering strategy of a price-maker virtual power plant," in *Proc. Int. Conf. Smart Energy Syst. Technol. (SEST)*, Sep. 2019, pp. 1–6.

[139] A. Bagchi, L. Goel, and P. Wang, "An optimal virtual power plant planning strategy from a composite system cost/worth perspective," in *Proc. IEEE Milan PowerTech*, Jun. 2019, pp. 1–6.

[140] C. Cao, J. Xie, D. Yue, C. Huang, J. Wang, S. Xu, and X. Chen, "Distributed economic dispatch of virtual power plant under a non-ideal communication network," *Energies*, vol. 10, no. 2, p. 235, Feb. 2017.

[141] R. R. Appino, H. Wang, J. Á. González Ordiano, T. Faulwasser, R. Mikut, V. Hagenmeyer, and P. Mancarella, "Energy-based stochastic MPC for integrated electricity-hydrogen VPP in real-time markets," *Electr. Power Syst. Res.*, vol. 195, Jun. 2021, Art. no. 106738.

[142] X. Kong, J. Xiao, C. Wang, K. Cui, Q. Jin, and D. Kong, "Bi-level multi-time scale scheduling method based on bidding for multi-operator virtual power plant," *Appl. Energy*, vol. 249, pp. 178–189, Sep. 2019.

[143] M. Shabanzadeh, M.-K. Sheikh-El-Eslami, and M.-R. Haghifam, "The design of a risk-hedging tool for virtual power plants via robust optimization approach," *Appl. Energy*, vol. 155, pp. 766–777, Oct. 2015.

[144] W. Hou, L. Guo, and Z. Ning, "Local electricity storage for blockchain-based energy trading in industrial Internet of Things," *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3610–3619, Jun. 2019.

[145] L. Ju, Z. Tan, J. Yuan, Q. Tan, H. Li, and F. Dong, "A bi-level stochastic scheduling optimization model for a virtual power plant connected to a wind–photovoltaic–energy storage system considering the uncertainty and demand response," *Appl. Energy*, vol. 171, pp. 184–199, Jun. 2016.

[146] S. W. Park and S. Y. Son, "Interaction-based virtual power plant operation methodology for distribution system operator's voltage management," *Appl. Energy*, vol. 271, Aug. 2020, Art. no. 115222.

[147] S. Arefi Ardakani and A. Badri, "Cooperative decision making of DERs in a joint energy and regulation market in presence of electric vehicles," *Iranian J. Elect. Electron. Eng.*, vol. 13, no. 4, pp. 374–384, 2017.

[148] E. Hajipour, M. Bozorg, and M. Fotuhi-Firuzabad, "Stochastic capacity expansion planning of remote microgrids with wind farms and energy storage," *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 491–498, Apr. 2015.

[149] L. Ju, R. Zhao, Q. Tan, Y. Lu, Q. Tan, and W. Wang, "A multi-objective robust scheduling model and solution algorithm for a novel virtual power plant connected with power-to-gas and gas storage tank considering uncertainty and demand response," *Appl. Energy*, vol. 250, pp. 1336–1355, Sep. 2019.

[150] A. Baringo, L. Baringo, and J. M. Arroyo, "Day-ahead self-scheduling of a virtual power plant in energy and reserve electricity markets under uncertainty," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 1881–1894, May 2019.

[151] A. Khayatian, M. Barati, and G. J. Lim, "Integrated microgrid expansion planning in electricity market with uncertainty," *IEEE Trans. Power Syst.*, vol. 33, no. 4, pp. 3634–3643, Jul. 2018.

[152] X. Cao, J. Wang, and B. Zeng, "A chance constrained information-gap decision model for multi-period microgrid planning," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2684–2695, May 2018.

[153] E. G. Kardakos, C. K. Simoglou, and A. G. Bakirtzis, "Optimal offering strategy of a virtual power plant: A stochastic bi-level approach," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 794–806, Mar. 2016.

[154] X. Cao, J. Wang, and B. Zeng, "Networked microgrids planning through chance constrained stochastic conic programming," *IEEE Trans. Smart Grid*, vol. 10, no. 6, pp. 6619–6628, Nov. 2019.

[155] S. M. Nosratabadi, R.-A. Hooshmand, and E. Gholipour, "Stochastic profit-based scheduling of industrial virtual power plant using the best demand response strategy," *Appl. Energy*, vol. 164, pp. 590–606, Feb. 2016.

[156] S. Fan, J. Liu, Q. Wu, M. Cui, H. Zhou, and G. He, "Optimal coordination of virtual power plant with photovoltaics and electric vehicles: A temporally coupled distributed online algorithm," *Appl. Energy*, vol. 277, Nov. 2020, Art. no. 115583.

[157] J. Hu, H. Morais, T. Sousa, S. You, and R. D'hulst, "Integration of electric vehicles into the power distribution network with a modified capacity allocation mechanism," *Energies*, vol. 10, no. 2, p. 200, 2017.

[158] N. Naval and J. M. Yusta, "Water-energy management for demand charges and energy cost optimization of a pumping stations system under a renewable virtual power plant model," *Energies*, vol. 13, no. 11, p. 2900, Jun. 2020.

[159] X. Han, M. Zhou, G. Li, and K. Lee, "Optimal dispatching of active distribution networks based on load equilibrium," *Energies*, vol. 10, no. 12, p. 2003, Dec. 2017.

[160] L. Ju, P. Li, Q. Tan, Z. Tan, and G. De, "A CVaR-robust risk aversion scheduling model for virtual power plants connected with wind-photovoltaic-hydropower-energy storage systems, conventional gas turbines and incentive-based demand responses," *Energies*, vol. 11, no. 11, p. 2903, Oct. 2018.

[161] C. Zhang, J. Wu, C. Long, and M. Cheng, "Review of existing peer-to-peer energy trading projects," *Energy Proc.*, vol. 105, pp. 2563–2568, May 2017.

[162] Q. Zhao, Y. Shen, and M. Li, "Control and bidding strategy for virtual power plants with renewable generation and inelastic demand in electricity markets," *IEEE Trans. Sustain. Energy*, vol. 7, no. 2, pp. 562–575, Apr. 2016.

[163] Y. Gao, H. Cheng, J. Zhu, H. Liang, and P. Li, "The optimal dispatch of a power system containing virtual power plants under fog and haze weather," *Sustainability*, vol. 8, no. 1, p. 71, Jan. 2016.

[164] J. Nieto-Martin, T. Kipouros, M. Savill, J. Woodruff, and J. Butans, "Technoeconomic distribution network planning using smart grid techniques with evolutionary self-healing network states," *Complexity*, vol. 2018, pp. 1–18, Oct. 2018.

[165] Build Up. *European Virtual Fuel Cell Power Plant—Best Practice Sheet—Germany*. Accessed: Aug. 21, 2021. [Online]. Available: https://www.buildup.eu/en/practices/cases/european-virtual-fuel-cell-power-plant-best-practice-sheet-germany

[166] M. Kenzhina, I. Kalysh, I. Ukaegbu, and S. K. Nunna, "Virtual power plant in industry 4.0: The strategic planning of emerging virtual power plant in Kazakhstan," in *Proc. 21st Int. Conf. Adv. Commun. Technol. (ICACT)*, Feb. 2019, pp. 600–605.

[167] D. Coll-Mayor, M. Paget, and E. Lightner, "Future intelligent power grids: Analysis of the vision in the European Union and the United States," *Energy Policy*, vol. 35, no. 4, pp. 2453–2465, Apr. 2007.

[168] European Commission. *Flexible Electricity Networks to Integrate the Expected 'energy Evolution' | FENIX Project | FP6 | CORDIS*. Accessed: Aug. 21, 2021. [Online]. Available: https://cordis.europa.eu/project/id/518272/es

[169] Europena Commission. *Smart Watts | JRC Smart Electricity Systems and Interoperability*. Accessed: Aug. 23, 2021. [Online]. Available: https://ses.jrc.ec.europa.eu/smart-watts

[170] DTU Orbit. *Electric Vehicles in a Distributed and Integrated Market Using Sustainable Energy and Open Networks*. Accessed: Aug. 22, 2021. [Online]. Available: https://orbit.dtu.dk/en/projects/electric-vehicles-in-a-distributed-and-integrated-market-using-su

[171] F. W. Bliek, A. van den Noort, B. Roossien, R. Kamphuis, J. de Wit, J. van der Velde, and M. Eijgelaar, "The role of natural gas in smart grids," *J. Natural Gas Sci. Eng.*, vol. 3, no. 5, pp. 608–616, Oct. 2011.

[172] Energy Research Centre of The Netherlands (ECN). *PowerMatching City: The First European City Test for a Smart Power Grid*. Accessed: Aug. 23, 2021. [Online]. Available: https://www.ecn.nl/nl/nieuws/item/powermatching-city-the-first-european-city-test-for-a-smart-power-grid/

[173] web2Energy. *The Intelligent Energy Network of the Future*. Accessed: Aug. 23, 2021. [Online]. Available: https://www.web2energy.com/

[174] Western Power Distribution. *What is FALCON?*. Accessed: Aug. 23, 2021. [Online]. Available: https://www.westernpower.co.U.K./projects/falcon

[175] POWER Magazine. *Large China Energy Storage Project Begins Operation*. Accessed: Aug. 23, 2021. [Online]. Available: https://www.powermag.com/large-china-energy-storage-project-begins-operation/

[176] German Research Center for Artificial Intelligence. *PeerEnergyCloud—Cloud Enabled Smart Energy Micro Grid*. Accessed: Aug. 23, 2021. [Online]. Available: https://www.dfki.de/en/web/research/projects-and-publications/projects-overview/projekt/show/Project/peerenergycloud/

[177] Center for Electric Power and Energy (CEE). *iPower Demonstration of the Future FLECH House on 8 April 2014—CEE*. Accessed: Aug. 23, 2021. [Online]. Available: https://www.cee.elektro.dtu.dk/News/2014/04/iPower-Demonstration-on-8-April-2014

[178] Open Utility. *Piclo—Building Software for a Smarter Energy Future*. Accessed: Aug. 23, 2021. [Online]. Available: https://piclo.energy/

[179] Universal Smart Energy Framework Foundation. *Universal Smart Energy Framework Project (USEF)*. Accessed: Aug. 23, 2021. [Online]. Available: https://www.usef.energy/

[180] Vandebron. *Duurzame Energie Van Nederlandse Bodem*. Accessed: Aug. 23, 2021. [Online]. Available: https://vandebron.nl/

[181] Mobile Loaves & Fishes. *Community First! Village*. Accessed: Aug. 23, 2021. [Online]. Available: https://mlf.org/community-first/

[182] Electron. *Empowering Distributed Energy Markets*. Accessed: Aug. 24, 2021. [Online]. Available: https://electron.net/

[183] Mosaic Energy. *Commercial, Residential and Energy Solutions*. Accessed: Aug. 24, 2021. [Online]. Available: https://www.mosaicenergy.com/

[184] Sonnen. *Sonnencommunity*. Accessed: Aug. 23, 2021. [Online]. Available: https://sonnengroup.com/sonnencommunity/

[185] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, "Designing microgrid energy markets: A case study: The Brooklyn microgrid," *Appl. Energy*, vol. 210, pp. 870–880, Jan. 2018.

[186] M. Foti and M. Vavalis, "Blockchain based uniform price double auctions for energy markets," *Appl. Energy*, vol. 254, Nov. 2019, Art. no. 113604.

[187] Brooklyn Microgrid (BMG). *Community Powered Energy*. Accessed: Aug. 24, 2021. [Online]. Available: https://www.brooklyn.energy/

[188] Y. Li, W. Gao, and Y. Ruan, "Feasibility of virtual power plants (VPPs) and its efficiency assessment through benefiting both the supply and demand sides in Chongming country, China," *Sustain. Cities Soc.*, vol. 35, pp. 544–551, Nov. 2017.

[189] Australian Renewable Energy Agency (ARENA). *AGL Virtual Power Plant*. Accessed: Aug. 24, 2021. [Online]. Available: https://arena.gov.au/projects/agl-virtual-power-plant/

[190] U. Rehman, K. Yaqoob, and M. Adil Khan, "Optimal power management framework for smart homes using electric vehicles and energy storage," *Int. J. Electr. Power Energy Syst.*, vol. 134, Jan. 2022, Art. no. 107358.

[191] P. H. Andersen, J. A. Mathews, and M. Rask, "Integrating private transport into renewable energy policy: The strategy of creating intelligent recharging grids for electric vehicles," *Energy Policy*, vol. 37, no. 7, pp. 2481–2486, Jul. 2009.

[192] S. Kulkarni, Q. Gu, E. Myers, and L. Polepeddi, "Enabling a decentralized smart grid using autonomous edge control devices," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 7406–7419, Oct. 2019.

[193] H. Zhou, S. Fan, Q. Wu, L. Dong, Z. Li, and G. He, "Stimulus-response control strategy based on autonomous decentralized system theory for exploitation of flexibility by virtual power plant," *Appl. Energy*, vol. 285, Mar. 2021, Art. no. 116424.

[194] C. Alcaraz, J. E. Rubio, and J. Lopez, "Blockchain-assisted access for federated smart grid domains: Coupling and features," *J. Parallel Distrib. Comput.*, vol. 144, pp. 124–135, Oct. 2020.

[195] C. Steinbrink, M. Blank-Babazadeh, A. El-Ama, S. Holly, B. Lüers, M. Nebel-Wenner, R. Ramírez Acosta, T. Raub, J. Schwarz, S. Stark, A. Nieße, and S. Lehnhoff, "CPES testing with mosaik: Co-simulation planning, execution and analysis," *Appl. Sci.*, vol. 9, no. 5, p. 923, Mar. 2019.

[196] L. Thomas, Y. Zhou, C. Long, J. Wu, and N. Jenkins, "A general form of smart contract for decentralized energy systems management," *Nature Energy*, vol. 4, pp. 140–149, Jan. 2019.

[197] H. Malik, A. Manzoor, M. Ylianttila, and M. Liyanage, "Performance analysis of blockchain based smart grids with ethereum and hyperledger implementations," in *Proc. IEEE Int. Conf. Adv. Netw. Telecommun. Syst. (ANTS)*, Dec. 2019, pp. 1–5.

[198] A. Khatoon, P. Verma, J. Southernwood, B. Massey, and P. Corcoran, "Blockchain in energy efficiency: Potential applications and benefits," *Energies*, vol. 12, no. 17, p. 3317, Aug. 2019.

[199] L. A. Hurtado, P. H. Nguyen, and W. L. Kling, "Smart grid and smart building inter-operation using agent-based particle swarm optimization," *Sustain. Energy, Grids Netw.*, vol. 2, pp. 32–40, Jun. 2015.

[200] S. Dorahaki, M. Rashidinejad, S. F. Fatemi Ardestani, A. Abdollahi, and M. R. Salehizadeh, "A peer-to-peer energy trading market model based on time-driven prospect theory in a smart and sustainable energy community," *Sustain. Energy, Grids Netw.*, vol. 28, Dec. 2021, Art. no. 100542.

[201] S. Wang, A. F. Taha, J. Wang, K. Kvaternik, and A. Hahn, "Energy crowdsourcing and peer-to-peer energy trading in blockchain-enabled smart grids," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 49, no. 8, pp. 1612–1623, Aug. 2019.

[202] X. Zhang and M. Fan, "Blockchain-based secure equipment diagnosis mechanism of smart grid," *IEEE Access*, vol. 6, pp. 66165–66177, 2018.

[203] S. Saxena, H. Farag, A. Brookson, H. Turesson, and H. Kim, "Design and field implementation of blockchain based renewable energy trading in residential communities," in *Proc. 2nd Int. Conf. Smart Grid Renew. Energy (SGRE)*, Nov. 2019, pp. 1–6.

[204] J. Lin, B. Xiao, H. Zhang, X. Yang, and P. Zhao, "A novel underfill-SOC based charging pricing for electric vehicles in smart grid," *Sustain. Energy, Grids Netw.*, vol. 28, Dec. 2021, Art. no. 100533.

[205] P. MacDougall, B. Ran, G. Huitema, and G. Deconinck, "Performance assessment of black box capacity forecasting for multi-market trade application," *Energies*, vol. 10, no. 10, p. 1673, Oct. 2017.

[206] M. Löschenbrand, "Modeling competition of virtual power plants via deep learning," *Energy*, vol. 214, Jan. 2021, Art. no. 118870.

[207] S. S. Gougheri, H. Jahangir, M. A. Golkar, A. Ahmadian, and M. Aliakbar Golkar, "Optimal participation of a virtual power plant in electricity market considering renewable energy: A deep learning-based approach," *Sustain. Energy, Grids Netw.*, vol. 26, Jun. 2021, Art. no. 100448.

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