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Virtual power plant models and electricity markets - A review

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ABSTRACT

In recent years, the integration of distributed generation in power systems has been accompanied by new facility operations strategies. Thus, it has become increasingly important to enhance management capabilities regarding the aggregation of distributed electricity production and demand through different types of virtual power plants (VPPs). It is also important to exploit their ability to participate in electricity markets to maximize operating profits.

This review article focuses on the classification and in-depth analysis of recent studies that propose VPP models including interactions with different types of energy markets. This classification is formulated according to the most important aspects to be considered for these VPPs. These include the formulation of the model, techniques for solving mathematical problems, participation in different types of markets, and the applicability of the proposed models to real case studies. From the analysis of the studies, it is concluded that the most recent models tend to be more complete and realistic in addition to featuring greater diversity in the types of electricity markets in which VPPs participate. The aim of this review is to identify the most profitable VPP scheme to be applied in each regulatory environment. It also highlights the challenges remaining in this field of study.

1. Introduction

Most countries are currently promoting renewable growth policies to achieve a stable, sustainable, and affordable energy system and mitigate the effects of climate change. Hydroelectricity is the most important renewable energy source on the planet, supplying approximately 17% of global electricity demand. However, hydroelectric projects must be properly planned and studied to avoid negative impacts on ecosystems [1,2]. In addition, the global growth of solar and wind energy is accelerating due to cost reductions and technological advancements.

The transformation of the electricity sector is mainly based on the digitalization of the power system, such as the installation of smart meters that establish bidirectional communications between consumers and the system operator. This transformation also results from the emergence of new agents, such as demand aggregators, storage systems, and virtual power plants (VPPs), which ensure the security and quality of the electricity supply given the growing introduction of renewable energy [3].

Virtual power plants represent the most immediate future of electricity generation, as they allow for intelligent consumption of energy in a distributed environment through the optimal management of demand and power generation. This means that users produce and consume their own energy, which leads to more active consumer participation in decision-making. Moreover, VPPs are useful tools for the integration of renewable energy in contributing to the balance of the grid. They better compensate for possible deviations from predicted production and demand. In addition, reducing prediction errors decreases economic penalties for deviations. The generators that compose VPPs have better access to electricity markets as a collective than they do individually, in which case it would be more difficult to reach the minimum market entry constraints. In addition, their access and operation costs are reduced, while their visibility in electricity markets is greater. Another important advantage of VPPs is the integration of electric vehicle load management, as this combines the storage systems and controllable loads offered by the vehicle-to-grid (V2G) service [4,5].

Study [6] reviews the scheduling of distributed energy resources according to different aspects, such as modeling techniques, reliability, environmental impact, and uncertainties. This review is based on the comparison of microgrids and VPPs. Paper [7] focuses on the principles of microgrid control and briefly analyzes the different types of VPPs. Reference [8] presents the different types of VPPs and their characteristics, communication technologies, and optimization and prediction algorithms. References [9,10] provide an overview of microgrid and VPP operations. Similarly, study [11] analyzes the differences between these two concepts. The authors of [12,13] classify and describe

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Abbreviations

ADMM	Alternating direction method of multipliers
CHP	Combined heat and power plant
CVPP	Commercial virtual power plant
EV	Electric vehicle
FCAS	Frequency control ancillary services
GA	Genetic algorithm
LP	Linear programming
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
NLP	Nonlinear programming
PBUC	Price-based unit commitment
PPA	Power purchase agreement
PSO	Particle swarm optimization
PV	Photovoltaic energy
TVPP	Technical virtual power plant
VPP	Virtual power plant
V2G	Vehicle-to-grid
WPP	Wind power plant

uncertainties regarding VPP problems and the optimization techniques used. Study [14] describes the components (generation resources, storage, and flexible loads) that compose a VPP. Articles [15,16] provide an overview of VPP composition and the optimization of its energy resources. The authors of [17] present arguments regarding the structure and control methods of VPPs. Other papers focus on the analysis of tools for the design and assessment of renewable energy systems. References [18,19] propose the modeling and technical-economic optimization of hybrid renewable energy systems by using HOMER software, a powerful tool for the design of renewable energy sites.

In conclusion, most review articles focus on comparing VPPs and microgrids according to various aspects, such as modeling techniques and problem solving methods, to determine their differences. These works tend to provide general descriptions without delving into further details, focusing on a specific aspect of VPP modeling.

Given the current evolution in electricity markets regarding renewable energy, it is essential to study the contributions of VPP models in maximizing operating profits and guaranteeing the security of the electricity supply in relation to different types of electricity markets, such as the day-ahead market, balancing services, and power purchase agreements (PPAs). The main objectives of this review article are to consider VPP models that include interactions with electricity markets and to identify and analyze in depth the relevant aspects in this field of study, such as the type of mathematical formulation and solving methods, the types of electricity markets, and the application of the proposed models to real case studies.

The regulation of the power sector allows for more active participation of distributed generation and demand in electricity markets. As a result, new tools are being developed to address unique technical and economic challenges derived from the optimal integration of available resources. This review contributes to the field by classifying and providing a detailed analysis of recent papers that model VPPs and their interactions with energy markets.

Identifying relevant articles to include in a review is a substantial challenge, as it involves an exhaustive search of a large number of articles in different journals and databases that focus on the chosen topic. In this case, the selection was based mainly on articles published in indexed journals. These articles are generally more reliable and of higher quality because they completed a peer review process. However, this study also includes articles presented at conferences due to the relevance of their content. In addition, the selection criteria account for the topic and novelty of papers, focusing on articles related to the objective of this review: the proposal of VPP models that include interactions with different types of electricity markets.

Nevertheless, there are certain limitations regarding the selection criteria of this study. This review considers aspects that have not been deeply evaluated before regarding the modeling and calculation of VPPs for participation in energy markets. These aspects include the type of problem, problem solving methods, energy markets, and real case studies. However, this article does not consider other aspects, such as VPP composition [6,14,15] and the management of uncertainties [6,12,13], due to their analysis in previous papers. Finally, this review also considers the year of publication when selecting studies, as it only includes articles published in the last ten years.

2. Objective of the problem

The development of VPPs is accelerating worldwide through the penetration of distributed generation in electricity systems, the massive introduction of ICT technologies, and the advancement of competitive electricity markets. This all offers new tools for the integrated management of energy resources.

By definition, a VPP consists of the integration of a group of distributed generation facilities managed by a single control system with bidirectional communications between its components to achieve more efficient operation. An important characteristic of VPPs is their ability to participate directly in electricity markets to obtain greater economic and technical profits. There are two types of VPPs that are distinguished by the objective of their aggregation: commercial virtual power plants (CVPPs) and technical virtual power plants (TVPPs). First, CVPPs fundamentally focus their operation on participation in the electricity market by optimizing the production and electrical demand of their components. Second, TVPPs offer ancillary services to the operator of the transmission grid by controlling the voltage and frequency levels of the system and thus improving the quality of the electricity supply. Unlike for CVPPs, TVPP modeling includes the constraints of the distribution network.

Next, the works in this review are classified according to the main objective of VPP modeling in relation to its interaction with wholesale electricity markets.

2.1. Energy management

The main aim of reviewed studies [20–50, 51-78] is to optimize the management and scheduling of different generation facilities, storage systems, and electricity demand to maximize the final VPP profit. The development of these models is primarily based on typical problems of technical-economic dispatch. To maximize economic profit, these models create an objective function formulated as the difference between system income and costs. In addition, each model is subject to compliance with the energy balances and technical constraints associated with different factors. These mainly include the available generation, state of charge of the storage systems, and electricity purchase and sale transactions. Within this type of problem, the authors of [68–70] propose the modeling of a cooperation system among neighboring CVPPs to maximize opportunities for the commercialization of electricity. Other articles, such as [72–75], include other aspects in the formulation of the VPP optimization model in addition to the economic profit, such as the environmental impact and the risk management of the variability of the VPP profit while participating in competitive markets. These studies propose a multiobjective problem for the management of VPP energy resources that seeks to maximize profits and minimize both carbon emissions and operational risk. In other words, the aim of these papers is to achieve an optimal balance among the economy, reliability, and environment. It should be noted that problems in the real world generally involve more than one objective at a time. Given the growing development of more efficient techniques for solving these problems, multiobjective optimization problems have been proposed for the realistic management of VPPs in recent years.

Fig. 1 presents a typical diagram of a VPP and its interaction with electricity markets and networks.

2.2. Bidding strategy

All the articles reviewed are listed in Table 1. Almost half of these studies examine optimal VPP bidding in different energy market structures [79–129]. The aim is to maximize the operating profit while reducing energy production forecast errors and economic penalties due to these deviations. In these problems, the objective function is subject to a series of technical and temporal constraints for the generators, such as reserve regulation requirements, state of the generator groups (connection-disconnection), ramp limits of the units, and compliance of energy balances. For this type of problem, some studies propose a price-based unit commitment (PBUC) model [120–126]. Other studies, such as [127,128], include the allocation of the VPP profit among the distributed energy sources of which it is composed. In addition, some of these works, such as [79,81,82,85,88,94–96,122], and [126–128], exploit the arbitrage opportunities among the different electricity markets to maximize VPP profit.

Fig. 2 presents the methodology used to obtain the optimal bidding strategy in a VPP. It is based on the articles classified in this section, such as [88,121].

As the figure shows, most of the studies reviewed focus on highlighting the management power of different models of VPPs. Given the importance of transforming the current energy model towards a distributed system, it is essential to optimize the control and coordination between the power generation sources and storage systems of the VPP. This should satisfy the electricity demand at any time and obtain greater profits by providing access to the same electricity markets as traditional power plants. For this reason, VPPs eliminate an important barrier to maximizing the integration of renewable energy into the grid and achieving sustainable development.

3. Methods of problem solving

As the previous section shows, most of the studies reviewed formulate a mathematical problem for maximizing the profit of a VPP, including all the characteristics of the hourly energy balance of the production and consumption of electricity, along with the costs of the supply and sale of electricity. The objective function is defined as the difference between income and costs, and technical constraints for the variables are imposed. Once the mathematical model is developed, the appropriate selection of the problem solving method becomes essential. The studies use different optimization techniques to obtain both an optimal solution to the VPP management problem and optimal selection of the bidding strategy in different electricity markets. In addition, due to the growing importance of multiobjective optimization problems, this section also addresses the most important characteristics of the approaches used for their resolution.

3.1. Types of optimization problems

The optimization problems are divided into the following categories according to the type of variable (continuous, integer) and the linear or nonlinear nature of the constraints:

- Linear programming (LP) [57,60,65,82,113,115],
- Mixed-integer linear programming (MILP) [20–24,27–47,49,51–55,58,61–63,68,69,71,76–78,81,83–100,106–108,110,119,127,128],
- Nonlinear programming (NLP) [66,72,74,79,101,103–105,112,116–118,129],
- Mixed-integer nonlinear programming (MINLP) [25,26,48,50,56,59,64,67,70,73,75,80,102,109,111,114,120–126],

Most of the studies reviewed formulate a mixed-integer linear mathematical problem. This problem involves integer decision variables associated with the hourly import/export of electricity during the established period of time or the state of charge/discharge of the storage systems, among other factors, in addition to continuous variables that represent the values of energy exchanged in the VPP model. The

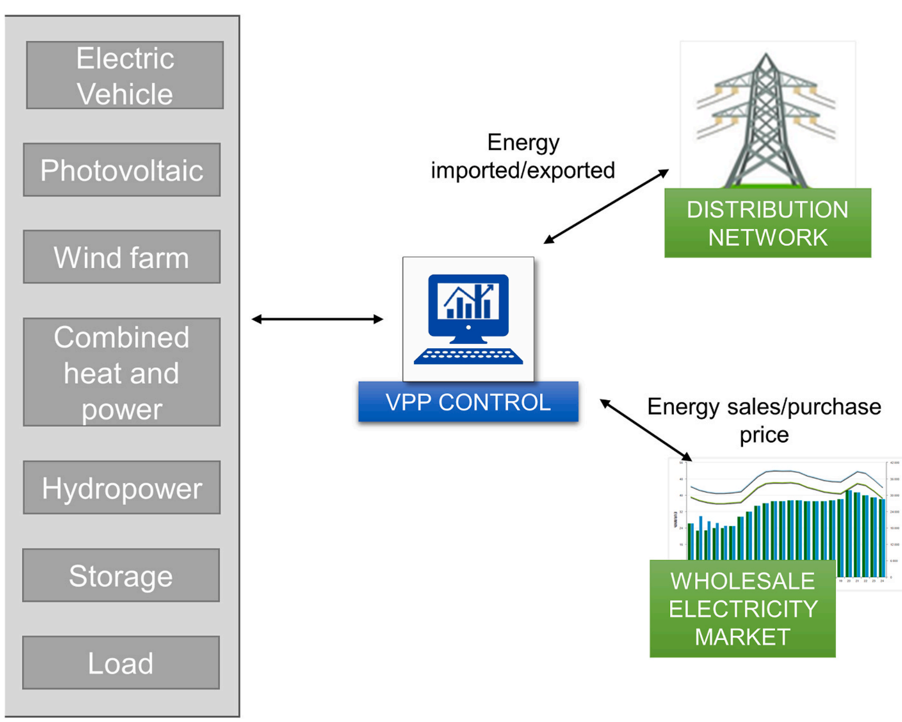

Fig. 1. Diagram of a VPP and its interaction with electricity markets and networks.

Table 1
Summary of advantages and limitations of VPP model types and resolution methods.

	Method	References	Advantages	Limitations
Types of optimization problems	Linear programming	[57,60,65,82,113,115]	Simplicity of implementation	Linear objective function and constraints/Does not allow uncertainty
	Mixed-integer linear programming	[20–24,27–47,49,51–55,58,61–63,68,69,71,76–78,81,83–100,106–108,110,119,127,128]	Simplicity of implementation and obtainment of a unique optimal solution	Does not consider the evolution of the variables, since only linear decision variables can be considered
	Nonlinear programming	[66,72,74,79,101,103–105,112,116–118,129]	More complete model	Difficulty of resolution/Previous use of linearization techniques
	Mixed-integer nonlinear programming	[25,26,48,50,56,59,64,67,70,73,75,80,102,109,111,114,120–126]	More complete and realistic model	High resolution difficulty/Cannot guarantee a global optimal solution
Heuristic methods	Particle swarm optimization	[26,72,78,117,120]	Simplicity of implementation and calculation efficiency	Local optimums
	Genetic algorithms	[56,100,117,124,125]	Flexibility and mode of operation, as they simultaneously determine several solutions	Local optimums
	Big bang big crunch	[51]	Application to complex models	Local optimums
	Imperialist competitive	[54]	Application to complex models	Local optimums
Mathematical methods	Simplex method	[57,60,65,82,113,115]	Ease of implementation	When increasing the number of variables, too many iterations are needed to obtain the optimal solution
	Branch-and-bound method	[20–25,28,29,31,34,35,37–40,43,45,47,52,55,68,69,71,76,81,83–85,87–91,93–99,119]	Convergence to the global optimum of the problem	Memory usage
	Quadratic programming	[49,101,104]	Faster convergence/Convexity	High execution time
	Interior-point method	[77,110]	Application to linear and nonlinear problems with a large number of variables	More efficient for linear problems/Longer processing time for nonlinear problems
	Dynamic programming	[80]	Efficient mode of operation	Inefficient with large models
	Column generation method	[30,32,58,86]	Calculation efficiency in linear problems with a large number of variables	Memory usage
	Game theory	[58,66,67,107,127,128]	Optimal analysis of the strategic behavior of VPP in different electricity markets	When increasing the number of participants, additional techniques should be used to reduce the computation-al load
	Fuzzy simulation	[56,102]	Appropriate for solving multiobjective optimization problems	Difficulty with solving
	Point estimate method	[27,121,123]	High accuracy, computational efficiency, and variable correlation	Mathematical assumptions
	Area-based observe and focus algorithm	[62]	Ability to find the global optimum	Increase in the number of search points
	ADMM and consensus optimization	[53]	Improves convergence ratio and scalability	Complex mathematical formulation

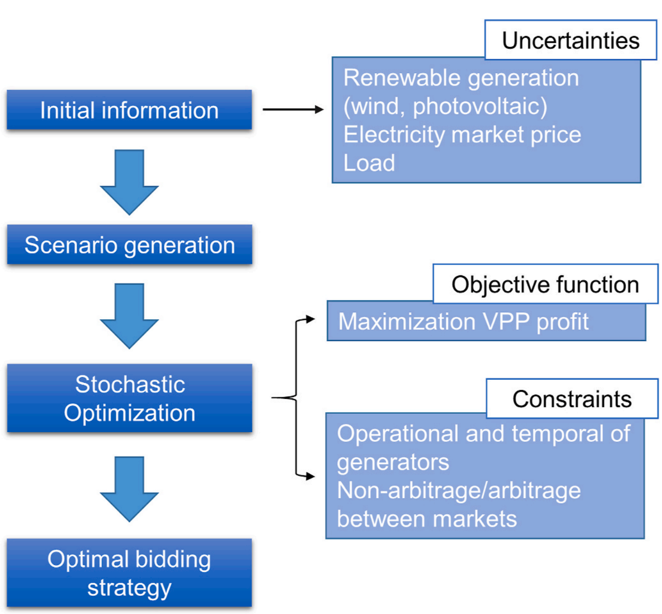

Fig. 2. Methodology for solving for the optimal bidding strategy of a VPP.

simplicity of this problem's implementation is notable, and it has a fast execution time for finding the optimal solution. Currently, the majority of calculation software incorporates efficient solvers to obtain the optimal solution of mixed-integer linear problems. However, some authors formulate the VPP problem with nonlinear constraints, which makes it difficult to solve because the feasible region does not necessarily have to be convex. For this reason, before proceeding to its resolution, the problem is transformed into a mixed-integer linear model using the Karush-Kuhn-Tucker optimality conditions and duality theory. In addition, other articles formulate the model with integer variables and nonlinear constraints, making the problem a mixed-integer nonlinear model that is difficult to solve. Due to the nonlinearity of these problems, they are generally nonconvex, which implies the existence of several local solutions without being able to guarantee an optimal global solution. To obtain an optimal solution, the authors use various problem solving techniques that can be classified mainly into mathematical and heuristic methods. Next, the main advantages and disadvantages of each method will be analyzed in depth.

3.1.1. *Mathematical methods*

Mathematical methods ensure convergence to an optimal solution (if any). For this reason, many authors use these techniques to obtain the optimal management of the energy resources that compose the VPP.

- Simplex method [57,60,65,82,113,115].
- Branch-and-bound technique [20–25,28,29,31,34,35,37–40,43,45,47,52,55,68,69,71,76,81,83–85,87–91,93–99,119].
- Quadratic programming [49,101,104].
- Interior-point method [77,110].
- Dynamic programming [80].
- Column generation and constraint method [30,32,58,86].
- Game theory [58,66,67,107,127,128].
- Fuzzy simulation [56,102].
- Point estimate method [27,121,123].
- Area-based observe and focus algorithm [62].
- The alternating direction method of multipliers (ADMM) and consensus optimization [53].

When solving LP models, the authors mainly use the simplex method, which is the most common method. It offers a wide range of applications due to its easy implementation and computational efficiency, meaning that it requires little time to find an optimal solution.

In contrast, when solving integer programming models, articles fundamentally consider branch-and-bound techniques that implicitly list feasible integer solutions. Important advances have been made in solving MINLP problems through the use of advanced optimization algorithms such as branch-and-bound or heuristic methods. However, some works propose linearizing the model equations before solving them due to the complexity of MINLP, the need for high calculation times, and the difficulty of obtaining an optimal solution.

The branch-and-bound method used in references such as [25,83,93], and [97] provides an intelligent search for the optimal solution. This is done by evaluating the different alternatives based on the value of the integer variables, eliminating the combinations that do not meet certain constraints, and determining the optimal conditions according to their bounds. It facilitates convergence to the global optimum of the problem since it has different strategies for exploring the field of solutions and, thus, is able to significantly limit the search for the optimum, ultimately yielding efficiency. However, this method requires a large use of memory, as each possible solution must be autonomous, which means that it must contain all the information for the branch-and-bound process. This then makes it impossible to have a global structure to build the solution.

Study [80] uses dynamic programming to solve the VPP bidding problem in different electricity markets. The short execution times obtained demonstrate the practical viability of this approach to rebalance decisions in intraday markets. The advantage of this method is its ability to manage discrete variables, constraints, and uncertainty at the level of each subproblem instead of considering all aspects simultaneously in a complete decision model. This method increases the resolution efficiency by avoiding repeating the same calculation several times.

To obtain optimal scheduling for the VPP, the authors of [56] use fuzzy programming and propose the transformation of fuzzy probability constraints in their equivalent forms to improve the calculation efficiency. The aim of this work is to find the optimal balance between economy and reliability in VPP operation. Study [62] uses an iterative procedure based on the area-based observation and focus algorithm, which is divided into two parts. First, this method provides a general description of the search field with possible random solutions. Subsequently, it undergoes a more detailed local search on the best point obtained in the first part of the procedure. This approach reduces the possibility of obtaining a local optimum.

In reality, however, distributed energy resources participate in a cooperative game in electricity markets to maximize the joint operating profit of the VPP. As a result, several studies [67,127,128] use procedures based on cooperative game theory to analyze the influence that each energy resource has on obtaining this profit and propose an appropriate distribution of profits. In contrast, other studies [58,66,107] use procedures based on the theory of noncooperative games, specifically the Stackelberg game. This type of model is applied to study the interaction between the market operator and the VPP operator. This method establishes an optimal two-stage decision process. First, the leader announces his strategy and has an idea about the response action of the follower. In the second stage, the follower performs a receptive strategy to respond to the leader. Once the leader receives this strategy, the final strategy is established.

Game theory is appropriate for analyzing the strategic behavior of VPPs in different electricity markets and competition among different VPPs. However, the information of all participants must be considered. In addition, one must account for the fact that as the number of participants and strategies increases, the degree of mathematical complexity for their resolution also increases.

3.1.2. Heuristic methods

Heuristic methods can provide a good solution to the problem, but they do not necessarily obtain an optimal solution. However, the resolution time is much shorter than in the case of mathematical methods. In addition, another important feature of these methods is their flexibility, as this allows for the incorporation of difficult modeling conditions. Heuristic methods are useful when the problem involves a large number of integer variables in addition to nonlinear constraints, where it is difficult to find an efficient solution using exact mathematical methods. Increasingly, articles have proposed heuristic procedures to solve problems of energy resource optimization in VPPs to either minimize the operating cost or maximize profit. The most common techniques that obtain the best solutions are as follows:

- Particle swarm optimization algorithm (PSO) [26,72,78,117,120].
- Genetic algorithms (GAs) [56,100,117,124,125].

The PSO algorithm is inspired by birds' social behavior in flight. Each particle is characterized by a position and velocity vector that directs its movement in the search space. This movement is guided by the optimal particles in the current moment. This algorithm is simple to implement, as there are few parameters that need adjustment. In addition, it produces an efficient search for the optimal solution with a shorter calculation time and less memory usage. On the other hand, GAs simulate biological evolution and natural selection based on learning, adaptation, and evolution. In each iteration, these algorithms consider a series of starting solutions. The main advantages are their flexibility and mode of operation, as they simultaneously determine several solutions instead of determining them sequentially, as done in common mathematical techniques. In other words, they explore the solution space quickly and intelligently. In addition, they more strongly avoid local optimal solutions even with highly complex problems. However, obtaining appropriate solutions demands that special attention be paid to the selection of the algorithm parameters, such as the population size and mutation rate. For example, if the population size is very small, the algorithm does not adequately explore the entire solution space, which may result in a local optimum.

In contrast, study [51] uses a metaheuristic method based on the big bang big crunch algorithm that seeks to minimize the purchase of electricity from the grid by managing the energy resources of the VPP in unbalanced distribution networks. Study [54] uses the metaheuristic imperialist competitive algorithm to minimize the operational cost of a VPP.

3.1.3. Summary of methods

As previously mentioned, most authors formulate the VPP problem as a mixed-integer linear model, and they mainly use mathematical methods to solve it. The application of branch-and-bound techniques is particularly popular due to their rapid convergence to a single optimal solution. However, the success of applying heuristic methods (approximation algorithms) rests on studying models of great mathematical complexity in a simple way and obtaining sufficiently strong solutions with a reasonable calculation time.

Table 1 summarizes the main advantages and limitations of the optimization problem types and the methods used for VPP model resolution.

3.2. Multiobjective optimization

Studies such as [46,72–75] propose the simultaneous minimization (or maximization) of different influential criteria in the operation of VPPs to achieve the optimal balance between them. As discussed in section 2, the authors of previous studies have proposed different objectives as subfunctions to analyze the multiobjective problem in VPPs. Study [46] seeks to maximize the profit of a VPP and minimize the cost of VPP self-consumption. Other studies, such as [72,74], seek to maximize the profit of a VPP and minimize carbon emissions, while the authors of [73,75] propose maximizing the economic profit of a VPP and minimizing the economic risk of the VPP by participating in electricity markets. In addition, different methods have been used for the appropriate resolution of the problem (see Table 2).

The authors of [73,75] transform the multiobjective model into a single objective problem to solve it by using weight coefficients. They first define a payoff table that decides the attributes for the calculation of the weight coefficients of the different objective functions. Subsequently, they use the fuzzy method to analyze the distance between the value of the objective function and the ideal value. Finally, they determine the optimal weight coefficients to solve the problem and thus reveal the best VPP operation strategy. These weight coefficients indicate the relative importance of each objective, and they are determined by using the entropy weight [73] and rough set [75] methods. Both methods are based on objective data to overcome the shortcomings of subjective methods. The weighting method stands out for its simple implementation of the problem and its efficiency. Study [72] uses an approach based on the Pareto optimum. The real Pareto frontier must be determined, which includes the set of optimal solutions (nondominated solutions) in the objective space. Once the Pareto frontier is generated, the VPP selects the best compromise solution according to the carbon emission constraints and the economic constraints related to the operation in the distribution system. In contrast, study [74] uses the epsilon-constraint method, which basically consists of maintaining an objective and restricting the rest of the objectives to an epsilon value. This method can be applied to convex and nonconvex problems. However, the difficulty with this approach is knowing the appropriate range of values to select the epsilon vector for the objective functions. It also has a high calculation time due to the level of variability required for the epsilon values.

Table 2
Characteristics of multiobjective optimization problems.

Ref.	Objective	Method	Best compromise solution	Characteristics
[46]	Maximizing the profit of the VPP and minimizing the cost of self-consumption of the VPP	Iterative process using CPLEX solver	–	Division of the original problem to make it more manageable
[72]	Maximizing the profit of VPP and minimizing operating emissions	PSO	Fuzzy technique	Reduction of execution time
[73]	Maximizing VPP profit and minimizing operating risk and emissions	Weighting method	Payoff table/ Fuzzy linearization/ Weight calculation	Efficiency and simplicity of implementation
[74]	Maximizing the profit of the VPP and minimizing operating emissions	Augmented epsilon-constraint method	Fuzzy technique	Selection of the appropriate range of epsilon vector values
[75]	Maximizing VPP profit and minimizing operation risk	Weighting method	Payoff table/ Fuzzy linearization/ Weight calculation	Efficiency and simplicity of implementation

4. Participation in electricity markets

Currently, most countries have already implemented processes of liberalization and openness to competition in their respective electricity markets. One reason that liberalization has been promoted is to improve the economic efficiency of the activities of electricity companies, finance new investments in the electricity infrastructure, and especially reduce the final prices of electricity supply. This change in the electricity sector brought about a transformation from a vertical structure, where all activities were integrated, to another organization where generation, transmission, distribution, and retailing operate independently.

At the beginning of liberalization towards the end of the 20th century, the majority of electricity markets were organized around a short-term wholesale market. This involved a large number of buyers and sellers of the system attending and conducting auctions for the purchase and sale of electricity. However, some markets, such as Texas (following the proposals of the Federal Energy Regulatory Commission), Scandinavian countries (NordPool), and the English market (New Electricity Trading Agreements), sought to promote the use of bilateral transactions and avoid all energy being traded in a single pool. Currently, mature electricity markets have both day-ahead markets and forward and futures markets, which allow for diversifying the price risk in the purchase and sale of energy in electricity markets.

In addition, the current energy context characterized by the massive introduction of renewable energy in the power system implies a greater use of the balancing mechanisms of the system due to deviations from the generation program of renewable sources.

An important advantage of VPPs is that they sell energy on behalf of the owners of the distributed energy resources when accessing the wholesale electricity markets and thus increase their joint profit. This section addresses the participation of VPPs in different electricity markets.

4.1. Futures and forward market

The futures market consists of purchase and sale contracts of firm energy for a specified period of time at a fixed price. This market allows for the acquisition of a quantity of energy on a determined date that can be within a week or even years. Futures are typically traded on a standardized exchange, whereas forward markets are self-regulated.

Studies [41–43,47], and [100] propose VPP models that allow energy purchase and sales transactions through futures markets. Participation in this market allows the VPP to avoid the risks derived from the high uncertainty of prices in the day-ahead electricity market. The VPPs presented in studies [42,43], and [100] exploit the arbitrage opportunities between the day-ahead electricity market and the futures market to increase their operating profit.

4.2. Bilateral contracts (PPAs)

Bilateral contracts consist of a direct agreement for the sale of electricity between a power generator and a buyer of that power. Both parties agree on a series of characteristics, such as the price, volume of power delivery, and duration of the contract, in addition to the minimum power to be supplied/consumed. The strong growth of renewable energy sources in recent years has boosted this type of contract intended to avoid price uncertainty and, thus, ensure long-term price stability to make both investment in the construction of the generation plant and the productive process of the consumer profitable. In the reviewed literature, articles [20,22,33,40,42,43,62,69–71,94], and [126] propose a VPP model that must supply part or all of the demand through a bilateral contract in a time horizon of one week. This contract offers a strong opportunity to guarantee VPP income due to the volatility of the market price and possible constraints of the transmission system operator.

4.3. Day-ahead market

The day-ahead market is designed to conduct electricity transactions for each hour of the following day through the presentation of sale and purchase bids by market agents. The VPPs allow generators direct access to the electricity markets for the sale of their production and allow consumers to self-produce energy, the sale of excess energy from generation facilities that they cannot self-consume. At a higher market price, the general trend of generation facilities is to produce the maximum generation available to maximize the operating profit of the VPP due to the sale of surplus energy generated. As a result, research papers incorporate this capacity to participate in the day-ahead electricity market in their VPP models to maximize their operating profit [20–129]. In addition, a flexible electrical system is achieved, encouraging self-consumption and reducing the environmental impact.

Although the VPP generally acts as a price-taker in electricity markets, in some reviewed works, the VPP acts as a price-maker [79,80,82,84,87,100,103,107,116,118], and [119]. This condition is advantageous given that the bidding decisions can influence the resulting day-ahead electricity market prices for VPPs' own profit.

4.4. Ancillary services market

The main objective of the ancillary services market is to guarantee the security and reliability of the electricity generation and transmission system. The role of ancillary services is to provide the system with the capacity to maintain a balance between generation and demand at all times. With the improvement of the liquidity of ancillary services markets, the participation of VPPs will likely increase considerably, and their economic viability may improve. From a technical perspective, the progressive growth of renewable generation facilities in current power systems can weaken them, as poor management can lead to the collapse of the grid, thereby failing to guarantee the reliability of the electricity supply. As a result, several studies have incorporated the capacity to participate in ancillary services markets into VPP modeling to allow for frequency-power control that guarantees the quality and security of the electricity supply [21,33,37,38,44,61,74,88,90,95,110,118], and [122]. These VPP models also incorporate storage systems, which are essential elements to overcome electricity grid stability problems that may appear due to deviations of renewable energy resources.

4.5. Reserve market

The reserve market is a mechanism that allows additional generation reserves to ensure demand coverage and the security of the electricity supply. Usually, generators that present offers are remunerated at a marginal price. This mechanism is increasingly necessary given the frequency of situations in which reduced margins of power reserves in the electrical system are identified due to the growth of nondispatchable renewable energy (mainly wind and photovoltaic). Several works in the literature reviewed [27,29,30,32,33,57,64,73,86,91,98,119,120,122,124,125], and [127], propose different methodologies for the VPP to make the optimal decisions in the day-ahead and reserve electricity markets, maximize the economic profit, and ensure adequate levels of security and reliability. According to the results obtained from these studies, the reserve market is more important in periods of maximum demand because a contingency can have a greater impact. In addition, when a greater amount of renewable generation is produced, it is more profitable for the VPP to sell energy in the day-ahead market or recharge the storage systems than to participate in the reserve market. Therefore, the profit of the VPP associated with this market does not necessarily increase. There are electricity markets where the scheduling of energy and reserves is separated, as in the case of the Iberian Electricity Market (Spain), while this scheduling is done together for others, such as the California Independent System Operator (California, USA).

4.6. Intraday market

Intraday markets are designed to adjust the energy traded in the day-ahead market with greater precision, as there is more information than in that session. In these markets, a lower volume of energy is traded than in the day-ahead electricity market. Intraday markets are gaining greater importance due to the increase in renewable energy and its unpredictable nature, making it essential to correct offers and adjust the imbalances in the availability of expected generation. In addition, this market can also be highly useful for the agents that participate in it. For example, if there is a breakdown in a generator group, agents can repurchase the energy that it sold in the day-ahead market session in an intraday session. Studies [36,44,55,59,80,93,95,100,104,106], and [113] include the commercialization of VPP energy in intraday markets to increase profits.

4.7. Real-time balancing market

The real-time balancing market is the last market opportunity for balancing production and consumption. The gate closure of this market typically ranges between five and 30 min before actual energy delivery.

Although intraday markets allow VPPs to adjust the scheduled energy after the day-ahead market, exchange power imbalance may still occur as the dispatch time approaches. Thus, to avoid penalties, VPPs can participate in real-time balancing markets. The objective in the reviewed papers is to minimize the imbalance error and associated cost. In other words, this refers to the difference between the actual electric output and the forecasted output, covered either by the VPP or through the electricity from the balancing market [26,45,58–60,67,70,82–86,91–93,99,102,103,107–109,111], and [127–129]. Due to the intermittent nature of renewable energy sources, VPP access to these markets is essential to balance generation and consumption.

4.8. Summary of electricity markets in which VPP models participate

Table 3 summarizes the main characteristics of the different electricity markets in which the VPP models reviewed in the literature participate. Fig. 3 graphically depicts the sequence of market types.

In conclusion, the VPP models proposed in the articles reviewed participate in the day-ahead market for the purchase and sale of energy to maximize their operating profit. Due to the integration of distributed energy resources in VPPs, they can participate more actively in electricity markets, as they would have greater difficulties accessing markets individually due to their small capacities.

In recent years, power systems have experienced substantial growth in generation plants with renewable energy. To favor these plants' integration into the electricity system, market mechanisms should be promoted that provide greater flexibility to the electricity system and improve its capacity to cope with the variability and uncertainty of renewable generation. This should ultimately ensure the security of the electricity supply. For this reason, the growing development of ancillary services markets and bilateral contracts is notable.

There is an important current trend regarding the signing of bilateral energy sales contracts by electricity producers with renewable sources. This type of contract represents a strong opportunity for electricity consumers to manage and minimize the risk of high future prices. In addition, these contracts reduce environmental impacts by opting for a long-term and stable renewable source. Moreover, this type of contract allows for the financing of new renewable projects.

Table 3
Main characteristics of the types of markets.

Ref.	Electricity market	Characteristics
[41–43,47,100]	Futures market	Purchase and sales contracts of firm energy for a period of time and fixed price Avoid electricity market price uncertainty
[20,22,33,40,42,43,62,69–71,94,126]	Bilateral contracts	Direct agreement on the sale of electricity between a power generator and the buyer of said energy Avoidance of price uncertainty Long-term price stability to make profitable both the investment in the construction of the generation plant and the production process of the possible consumer
[20–129]	Day-ahead market	Offers of sale and purchase of energy for each hour of the following day Flexibility of the electrical system Greater self-consumption and operating profit
[21,33,37,38,44,61,74,88,90,95,110,118,122]	Ancillary services market	Security and reliability of the electricity generation and transmission system Balance of generation and demand at all times
[27,29,30,32,33,57,64,73,86,91,98,119,120,122,124,125,127]	Reserve market	Management of additional generation reserves to ensure demand coverage and the security of electricity supply
[36,44,55,59,80,93,95,100,104,106,113]	Intraday market	Precise adjustment of the energy traded in the day-ahead market Reduction of imbalance costs
[26,45,58–60,67,70,82–86,91–93,99,102,103,107–109,111,127–129]	Real-time balancing market	Management of deviations between generation and demand Electrical system balance Security of electricity supply

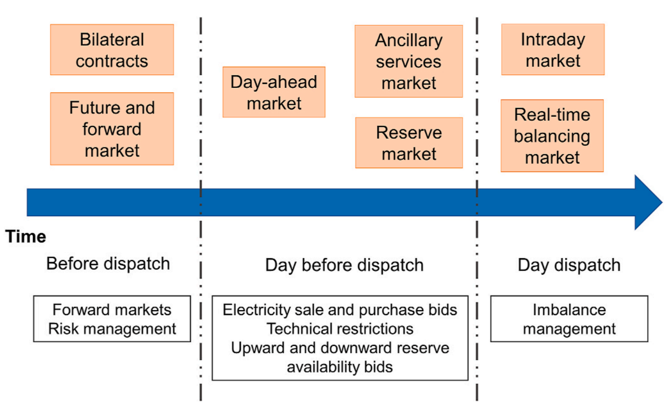

Fig. 3. Sequence of electricity market types.

At the same time, there must be a constant balance between generation and consumption to ensure the stability of the network. Many of the articles reviewed include VPPs' participation in the real-time balancing market to reduce generation deviations and possible subsequent economic penalties.

As a result of electricity market volatility, good risk management of both electricity sales and purchases must adequately combine futures markets, bilateral contracts, and the day-ahead (spot) market. In addition, simultaneous participation in different markets can provide additional profits to VPPs. However, only a few studies reviewed acknowledge this idea, and they have only combined day-ahead and futures markets [42,43], and [100].

5. Real case studies

To validate the efficiency of the mathematical optimization model of a VPP, some papers apply the model to a real case study to analyze the real scope of the implementation of VPPs. This is done through the optimal coordination of power generation and storage sources available to cover a given load at any time during the established study period. In addition, studies have analyzed different electricity markets to clarify their interaction with the model proposed and maximize their operating profit.

Older models applied to a real case study include few components and do not study the impact of storage system integration [40,45]. The authors of [40] use real data from generation facilities of both renewable and conventional origin in addition to data from the electrical demand of Sibenik County, located on the coast of Croatia. Market prices are determined from historical data of the EEX market. Reference [45] proposes a case study of a VPP with residential tariffs and the generation profile of a fixed photovoltaic installation located on the roof of the KU Leuven campus in Belgium. Regarding cogeneration components, this study details the technical data of real models existing in the market. In addition, it uses the energy purchase and sale prices in the day-ahead market of Belpex recorded in 2012.

Other articles include pumped hydrostorage [20,88], as it is a mature technology with an infinite technical life and a fast response capacity. Recent papers have studied the joint management of water and energy [24,25]. The authors of [24,25] apply the VPP model to a large irrigation system located in Aragon (Spain) with their own data of only renewable generation (hydroelectric, self-consumption photovoltaic, wind) and electricity demand. The studies use the hourly prices of the OMIE wholesale electricity market for the purchase and sale of energy in 2017.

The reviewed models mainly incorporate batteries to store renewable energy [21,33,52,60,82,83,86], and [107]. Energy storage is a key factor for managing renewable production and ensuring the stability of the electrical system against the massive introduction of this intermittent production. In these works, the VPP can reduce the risks of volatile market prices and operating risks of stochastic wind and/or photovoltaic generators. Nevertheless, the study periods are quite short, generally spanning a day or week, which allows for minimal analysis of the VPP operation. Study [21] analyzes data related to wind speed, solar radiation, and market prices of the PJM market for the area of Virginia (USA) on a summer day in 2005 to obtain a solution for the proposed model. Similarly, study [86] uses real data on the day-ahead market price, reserve, and real time of the PJM electricity market in July 2017. It also uses data related to the production and installed capacity of the generation facilities. The authors of [52] present a small-scale VPP project in Guizhou (China) that includes a wind farm (WPP), photovoltaic installations (PV), batteries, electric vehicles (EVs), combined heat and power plants (CHP), and a boiler. In addition, this study uses real data on the purchase and sales prices of energy and the operation and maintenance costs of the components. Articles [60,82], and [83] obtain the optimal bidding strategy of a VPP by analyzing historical data on the hourly prices of the electricity market in the area of Massachusetts (USA) for a day in May 2011. They also analyze historical wind production data obtained from the Bishop and Clerk wind farms. Once the wind speed is known, the hourly wind energy production curve is obtained from the power curve provided by the wind turbine manufacturer.

The authors of [33] analyze the feasibility of a VPP based on data from the new engineering campus at the University of Melbourne (Australia). The VPP consists mainly of photovoltaic installations and batteries in addition to controllable loads. The research includes investment costs and fixed and variable operating costs. For market prices, the study accounts for how the VPP participates in various markets, such as electricity, FCAS, and cap contracts. Study [107] uses the electricity market transaction rules of the Electric Reliability Council of Texas (USA) for the optimal operation of a VPP comprising large-scale photovoltaic installations with a storage system.

Note that the optimal management of renewable resources and electricity demand is achieved with the incorporation of storage systems in the VPP model. This produces greater energy autonomy and a better correlation between production curves and electricity demand. In addition, greater economic profit is achieved by participating in electricity markets through purchasing energy at low prices and selling it at high prices. The VPP makes the best decisions that maximize its operating profit. For example, the VPP might buy or sell additional energy in the real-time market or use the storage system to compensate for prediction errors, ensuring compliance with market operations. The incorporation of storage systems reduces both the risk of volatility in the price of the electricity market and the risk of operating renewable resources.

Table 4 summarizes the main characteristics of the VPP model applied to real case studies.

6. Discussion

This section compares the VPP models and their temporal evolution over the last ten years. This review classifies the articles according to several significant criteria, such as the type of problem, resolution methods, and electricity markets. Older articles propose simpler VPP models with fewer components that participate only in the day-ahead market by selling production of the generators. Most articles use a linear or mixed-integer linear mathematical model without high computational complexity [20–24,27–47,83–100], etc. Over time, however, there has been an evolution towards more complete and realistic models.

Fig. 4 shows the participation of the reviewed VPP models in different markets (day-ahead, intraday, futures, ancillary services, reserve, real-time balancing, and bilateral contracts). The most recent models show greater diversity in the types of electricity markets in which VPPs participate. First, this is because the legal regulation of the countries has allowed distributed generation to participate in ancillary services of the electricity system, which was previously reserved for classical power plants. Moreover, the greater maturity of electricity markets encourages consumers and generators to participate more actively in other types of markets, with the objective of obtaining additional profits from their participation in the day-ahead market or in bilateral contracts.

Fig. 5 graphically summarizes the mathematical models used for the optimal management of VPP resources. The figure confirms that most of the reviewed works formulate a mixed-integer mathematical problem with continuous and integer variables. This type of formulation is characteristic of problems regarding the optimal dispatch of resources, wherein decisions are made to produce/not produce, export/import energy, etc. However, in recent years, the complexity of mathematical models has been growing, and more nonlinear problems have been formulated. This is the result of incorporating more realistic approximations of the VPPs and including more complex interactions in the mathematical models between agents and markets. To resolve these models, articles, such as [26,56], and [72], usually use heuristic methods given that they allow greater flexibility and robustness for handling the problem characteristics.

Regarding the composition of the VPP, the most current models already integrate storage systems, EVs, and their interaction with electricity markets to maximize the VPP's operating profit.

Note that increasingly more research has focused on the proposal of multiobjective problems that account not only for economic profits but also for the environment and other aspects [46,72–75]. However, there is an area for improvement here, and other models can be developed to include additional aspects, such as investment costs and more distribution network constraints.

This review's findings indicate that only a few studies consider the ability of arbitrage between day-ahead and futures markets [42,43,100].

Table 4
Characteristics of VPP models applied to real case studies.

Ref.	Components	Location	Technical data	Study period
[20]	Gas turbine/ WPP/PV/Pumped storage hydro	Sibenik County (Croatia)	Gas turbine capacity = 5.67 MW WPP capacity = 9.6 MW PV capacity = 6 MW Pumped storage accumulation = 40 MWh	1 week
[21]	WPP/PV/Diesel/ Microturbine/ Batteries	Virginia (USA)	WPP capacity = 25 kW PV capacity = 12 MW Min/max capacity Diesel generator = 5/30 MW Micro turbine min/max capacity = 5/28 MW 220 V 16 A lithium-ion batteries	1 day
[24, 25]	Hydroelectric/ WPP/PV	Irrigation system in Aragon (Spain)	Hydroelectric capacity = 14.7 MW WPP capacity = 30 MW PV capacity = 15.5 MW Annual demand = 39 MWh	1 year
[33]	PV/Gas generator/ Batteries	New engineering campus of the University of Melbourne (Australia)	PV capacity = 1.1 MW Gas generator capacity range = 0–4 MW Battery capacity range = 0–4 MW Load = 14 MW	1 year
[40]	PV/WPP/Gas turbine	Sibenik County (Croatia)	WPP capacity = 9.6 MW Min/max gas turbine capacity = 2.5/5.67 MW PV capacity = 6 MW	1 week
[45]	PV/CHP/Boiler	KU Leuven Campus (Belgium)	Small PV capacity = 32 kW Boiler efficiency = 90%	1 day
[52]	PV/WPP/CHP/ Boiler/Storage/ EV	Guizhou (China)	WPP capacity = 300 kW PV capacity = 305 kW CHP capacity = 600 kW Boiler capacity = 500 kW Storage capacity = 200 kWh, SOC = 20–80% EV capacity = 324 kWh	1 day
[60]	WPP/Storage	Massachusetts (USA)	WPP capacity = 100 MW Storage capacity = 200 MWh, efficiency = 90%	1 day
[82]	WPP/Storage	Massachusetts (USA)	WPP capacity = 100 MW Storage capacity	1 day

(continued on next page)

Table 4 (*continued*)

Ref.	Components	Location	Technical data	Study period
			= 200 MWh, efficiency = 90%	
[83]	Gas turbine/ WPP/Storage	Massachusetts (USA)	WPP capacity = 100 MW Min/max gas turbine capacity = 20/180 MW Storage capacity = 200 MWh, efficiency = 90% Maximum charge/ discharge capacity = 100 MW	1 day
[86]	PV/Storage/ Flexible load/ Dispatchable generating units	PJM market (USA)	PV capacity = 6 MW Storage charge/discharge capacity = 0.3/ 0.5 MW Flexible load capacity = 2 MW DGUs capacity = 5 MW	1 day
[88]	WPP/Pumped storage hydro/ Gas turbine	Sibenik County (Croatia)	WPP capacity = 9.6 MW Pumped storage hydro capacity = 40 MWh Gas turbine capacity = 5.67 MW	1 day
[107]	PV/Storage/EV	Texas (USA)	PV capacity = 100 MW Battery capacity = 25 MWh, efficiency = 98% Max charge/ discharge capacity = 12.5 MW EV capacity = 70 kWh Max EV charge/ discharge capacity = 10 kW	1 day

This shows how there are still pending challenges related to the modeling of CVPPs, such as the simultaneous consideration of multiple electricity purchase and sales strategies in wholesale markets. In other words, the CVPP models decide how to diversify the risk of the acquisition or sale of energy among the different instruments available: spot market, futures market, PPAs, etc.

The papers reviewed have rarely considered distribution network constraints in VPP operation [64]. More research should be conducted to study the technical and economic viability of electricity exchanges in distribution networks, including the interaction between CVPPs and TVPPs in the model.

Some authors have begun to introduce artificial intelligence techniques for wind generation prediction [62]. Nevertheless, these methods need to be investigated properly. Incorporating artificial intelligence can allow the VPP models to learn to maximize the profit of the operation as they train with more real data, from the perspectives of both demand and the management of VPP energy resources.

VPP models have rarely been applied to real cases, and they include few components [45,60,82]. Future research should focus on the application of the proposed models to real case studies to analyze the integration of new types of agents (storage systems, demand aggregators, etc.) in the framework of current power systems and its contribution to competitive electricity markets.

7. Conclusions

The purpose of this review is to analyze the interaction of VPP models with different types of electricity markets. This article clearly identifies the relevant aspects of the research conducted in this field of study, how the models have evolved in recent years, and the challenges that remain for future research. This review classifies and analyzes 110 papers according to the definition of the main objective, formulation of the model, selection of the solving method, participation in different electricity markets, and application of the proposed VPP model to real case studies. This review evaluates in detail the advantages and disadvantages of each aspect analyzed to provide useful knowledge for further research.

The four main conclusions of this review are as follows:

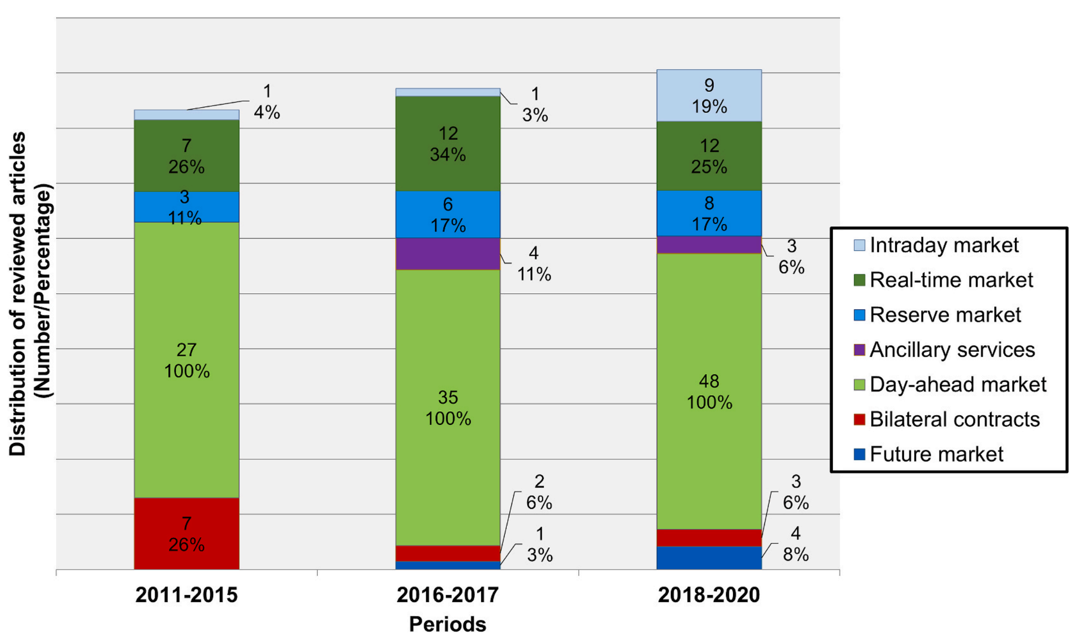

Fig. 4. Distribution of the types of markets included in the VPPs (2011–2020).

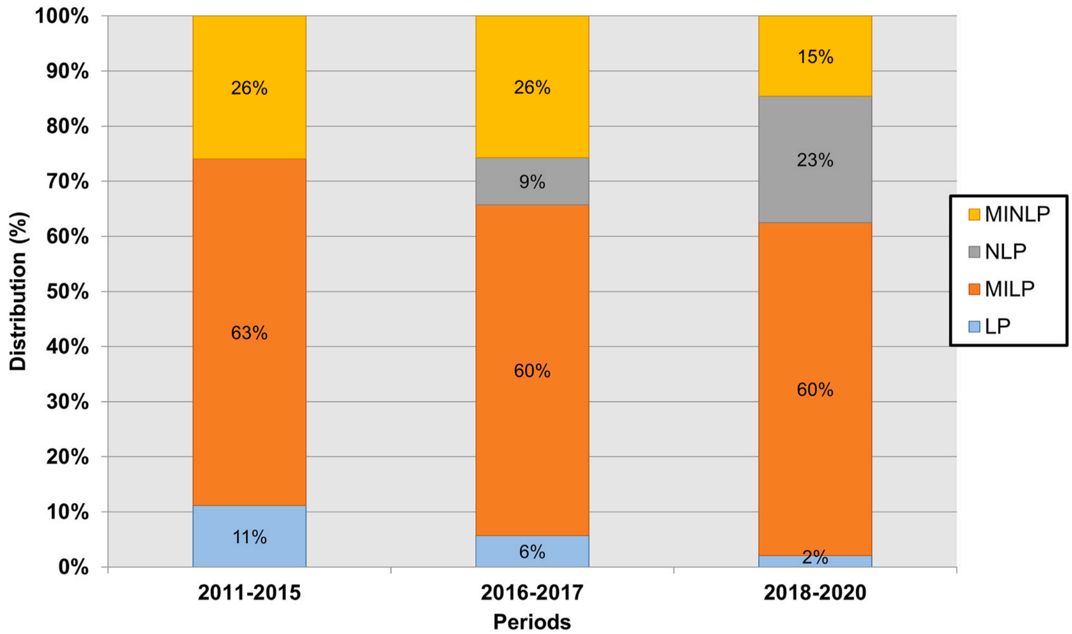

Fig. 5. Distribution of the mathematical models used for VPPs (2011–2020).

- Most of the research has focused on the development of VPP models to achieve optimal control and coordination among the components and thus maximize the operating profit.
- As time has progressed, models have become more complete and complex and include more operating constraints. As a result, more advanced optimization techniques are required to achieve an optimal solution.
- From the perspective of participation in electricity markets, the integration of distributed generation in the VPP has contributed to more active participation in different types of markets. In addition to the day-ahead spot market, recent articles have included bilateral contracts, futures, and balancing markets in the models. This shows how greater profits can be obtained in the operation of VPPs.
- Proposed models have rarely been applied to real cases, such as in industrial processes that require the management of electricity consumption and its own generation facilities.

In addition, the review establishes that there is a paucity of research that uses real-world case studies. Furthermore, the review identifies other pending challenges, such as the combination of multiple VPP electricity purchase and sales strategies and the use of artificial intelligence techniques to provide learning tools for VPP models to anticipate the best decisions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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