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Review article

Virtual power plant for energy management: Science mapping approach

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A R T I C L E I N F O

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A B S T R A C T

A bibliometric analysis was conducted to examine the trends and developments in the field of Virtual Power Plants (VPPs) from 2000 to June 2022. The selection and identification of data involved a systematic search resulting in 1245 articles for bibliometric analysis after applying the inclusion and exclusion criteria. Strategic diagrams, overlay graphs, and evolution maps were used to analyze the trends and themes in different periods. The analysis reveals the emergence and evolution of various themes and their interconnections. In the early periods, the focus was on energy market issues, distributed generation, and the control of Distributed Energy Resources. Themes such as microgrids, renewable energy, electric vehicles, and economic analysis have gained prominence over time. The present study also identified the introduction of new concepts such as prosumers, collaborative networks, and dynamic power plants in later periods. The performance analysis for the last period (2022) highlighted the centrality and density of themes such as power plants, renewable power plants, battery energy storage systems, and robust optimization. These themes are considered both fundamental and transverse in the research field. This study discusses the importance of VPPs and battery energy storage systems in addressing grid intermittency issues and providing auxiliary market services. The analysis also emphasized the management of the demand side and the integration of electric vehicles and Building Energy Management Systems in VPPs. Therefore, future directions for VPP research include innovative structures and topologies, big-data analysis, and diversified optimization techniques. This study provides insights into the evolution and current state of research in the field of VPPs and identifies areas for further exploration and development.

1. Introduction

Currently, the global energy demand is increasing daily because of economic and population growth, particularly in emerging market economies [1]. Since the invention of alternating current (AC) electrical systems capable of transferring electrical energy over long distances, the vertical paradigm has dominated electricity generation and supply. Currently, the paradigm of centralized power

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Nomenclature

AC	Alternating Current
AI	Artificial Intelligence
ASM	Ancillary Services Market
BEMS	Building Energy Management Systems
BESS	Battery Energy Storage Systems
CL	Controllable Loads
CN	Collaborative Networks
DERs	Distributed Energy Resources
DG	Distributed Generation
DVPP	Dynamic Virtual Power Plant
ESS	Energy Storage Systems
EVs	Electric Vehicles
IoT	Internet of Things
PVS	Photovoltaic Systems
Q1, Q2, Q3 and Q4	Quadrants in the Strategic Map
RES	Renewable Energy Sources
VPPs	Virtual Power Plants

systems is being replaced by distributed generation (DG), which is connected to distribution [2]. Therefore, the conventional centralized power grid has become a decentralized smart grid characterized by the following components: DG, energy storage, and smart electrical charges.

Virtual Power Plants (VPPs) are innovative power systems that leverage advanced technologies to integrate and optimize the operation of Distributed Energy Resources (DERs) within a unified platform. VPPs enable the efficient management and utilization of various energy sources such as solar panels, wind turbines, battery storage systems, and demand response programs. VPPs incorporate DER, monetize them, and cope with the variability in renewable generation. In addition, VPPs are a new type of coordinated control and energy management technology that includes DER, energy storage systems (ESS), and controllable loads (CL) integrated into different energy markets [3]. Alternatively, the VPP can be used as a power supplier to sell power or as a load demander to buy power [4]. In contrast, the VPP can also supply the DER, ESS, and CL to participate in the Ancillary Services Market (ASM) as system support [5].

The following are the most important innovations, focused topics, and VPP-based methods. VPPs, for example, allow the integration of demand response programs, which allow users to adjust their electricity consumption patterns in response to grid conditions or price signals, providing flexibility, and aiding in the balance of supply and demand [6]. VPPs can optimize the delivery of renewable power generation and balance it with other power resources by monitoring weather forecasts and power production in real-time. As a result, VPPs are critical in integrating intermittent renewable energy sources such as solar and wind into the grid. Therefore, VPPs can optimize the use of energy storage, smooth intermittent renewable generation, and provide network services such as frequency regulation and peak reduction using intelligent control algorithms [7].

Similarly, Blockchain technology and smart contracts can be employed to enable secure and transparent energy transactions within the VPP ecosystem, allowing individuals and communities to exchange energy directly. This also enables VPPs to improve grid stability and resilience through active management of distributed energy resources [8]. To achieve this, AI-powered algorithms are used to continuously learn from historical data and adapt to changing conditions, thereby improving the overall performance and efficiency of VPPs. Finally, VPPs can participate in flexibility markets by offering their aggregate energy resources, such as demand response capacity or stored energy, to grid operators or energy markets [9,10]. Similarly, VPPs can be integrated with microgrids, which are localized power systems that can operate independently or in coordination with the main grid.

Different contexts and approaches to VPPs have been discussed in the existing literature. For example, a review [11] discussed DER programming problems in microgrids related to VPPs, optimization methods, dispatch strategies, and objective functions. Similarly, in Ref. [12], programming problems in VPP, reliability, and multi-objective optimization studies were identified. In another study [13], the architecture and optimization techniques of VPPs were reviewed, and optimization techniques based on operation strategies were synthesized. Similarly [3], reviewed and verified the communication structure, optimization techniques, and development of different aspects of VPP.

In addition, a review [14] on the integration of electric vehicles as VPP was reviewed [14], and the configuration structures for vehicle-to-grid integration concepts were determined. Similarly, the types and modes of electric vehicle (EV) integration in power plants have been compared and analyzed [15]. Finally, a review [16] of the scheduling programs used in VPPs was presented, considering the joint techno-economic constraints and various types of uncertainties at different network levels, including smart homes and home area networks. Furthermore, the application of VPP models to different electricity markets has been analyzed [17]. Thus, the advantages and limitations of the optimization methods for the revised VPP models were studied.

Although these reviews have contributed significantly to the field of VPP, they have primarily focused on specific aspects of VPP, such as scheduling problems and uncertainties. Moreover, most of these studies are literature reviews. However, this study provides knowledge that has not been previously evaluated. Bibliometric indicators were adopted and research on VPP was conceptually mapped. Compared with traditional literature review methods, bibliometric analysis offers objective criteria for evaluating the development of the field under study [18].

In addition, bibliometric methods provide systematic and replicable processes that enhance our understanding of knowledge dissemination within a specific field, thereby contributing to its development [19]. Therefore, the objective of this study is to conduct a comprehensive analysis of the scientific evolution of Virtual Power Plants (VPPs) using a scientific mapping approach applied to the relevant literature between 2000 and 2022. This will provide a comprehensive understanding of the advancements in this field of research and identify emerging topics that can provide researchers with valuable insights.

2. Materials and methods

This study employed a mixed-method approach to assess the impact of VPPs by reviewing a collection of published articles that addressed the main issue. A bibliometric analysis was conducted on the articles published between 2000 and June 2022. Additionally, a detailed review was conducted specifically for the year 2022 to identify emerging research trends. This study encompassed three distinct phases, as illustrated in Fig. 1.

2.1. Materials

The researchers carefully selected the Scopus multidisciplinary database for the purpose of this review, citing its comprehensive collection of relevant articles pertaining to the topic under investigation [20–23]. To ensure a comprehensive search, they employed the following search syntax: ("virtual power plant" or VPP) in the Article Title field. This method identifies documents within a database that are directly relevant to the subject matter. To establish a reasonable timeframe for the review, the search was limited to the period from 2000 to June 2022. This time was chosen to encompass the most recent developments in the field, while still capturing a significant body of literature.

Additional filters were applied to refine the search results and focus on the most pertinent research. They selected articles from engineering, energy, computer science, mathematics, environmental science, decision science, and other multidisciplinary fields. By incorporating these filters, they aimed to ensure that the articles included in the analysis were from relevant fields and provided valuable insights for the review.

Finally, to conduct a comprehensive bibliometric analysis [24–27], the researchers decided to conduct a search in both the "Conference Paper" and "Article" categories. This decision was made to encompass a broad range of scholarly contributions, including peer-reviewed journal articles and conference-presented research. Considering these two categories, researchers sought to compile a diverse and comprehensive set of sources for their analyses.

2.2. Bibliometric analysis

Bibliometric analysis is critical for comprehending the thematic evolution of research over time. This study focused on obtaining a precise understanding of development trends in VPPs, using the methodology proposed by Cobo et al. [28]. To assist in this analysis, we used the SciMAT software tool that has been recommended for identifying thematic evolution in previous studies [29]. Notably, the SciMAT tool has been successfully applied in various scientific and engineering fields [30–32], demonstrating its versatility and reliability. We can generate an evolution map in the form of a superimposed graph using bibliometric analysis, providing valuable insights into research trends and their evolution. In addition, we developed a strategic map (Fig. 2) to visually represent the findings and improve comprehension and interpretation.

The evolution map obtained through the bibliometric analysis allowed us to observe the trajectory and changes in research topics over time, thereby facilitating a comprehensive understanding of the subject. The strategic map depicted in Fig. 2 serves as a visual representation of the key findings and provides a comprehensive overview of the relationships and connections between different research areas. Collectively, the combination of bibliometric analysis and the SciMAT software tool enabled us to investigate the thematic evolution of VPP research, yielding valuable information that contributes to the development of this field.

a) Strategy diagram

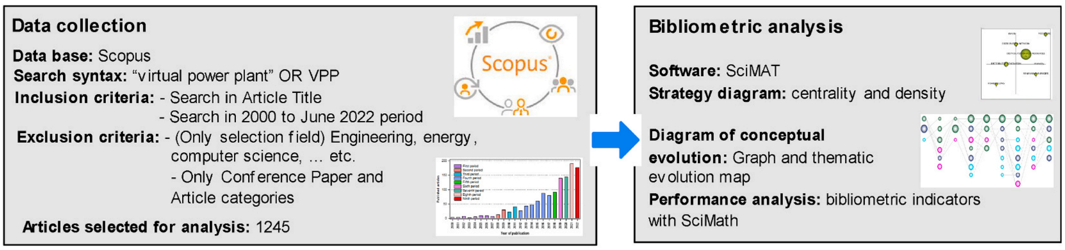

Fig. 1. Sequence methodological applicate.

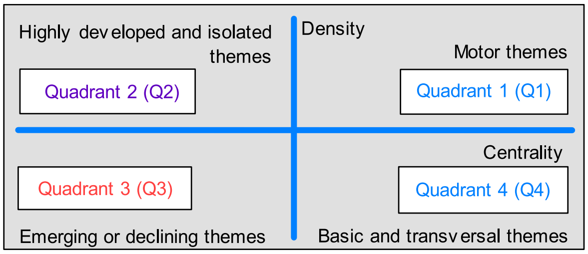

Fig. 2. Strategic diagram for bibliometric analysis.

Before using the single-center approach, SciMAT created an equivalence index to identify relevant topics [33]. To achieve this, the concepts of centrality and density, which define strategic diagrams, were used. Centrality measures the degree of interaction between themes and other thematic networks to demonstrate the strength of external links. Therefore, centrality (c) is defined as

$$c = 10\sum e_{uv}, \tag{1}$$

where u is an element or keyword that belongs to the topic, and v is an element that belongs to another theme [27]. Similarly, density measures the level of internal development between a study's main topic and the related research topics. In this case, density (d) is defined as:

$$d = 100\sum e_{ij} \Big/ n, \tag{2}$$

where i and j are the elements or keywords associated with the topic and n is the number of elements [27]. To illustrate the different categories of the study topics, the diagrams were divided into four quadrants, as shown in Fig. 2.

The motor themes, shown in Fig. 2, represent well-developed and fundamental concepts in the selected scientific discipline, exhibiting high density and strong centrality because they were categorized under Q1. The field of study is expected to expand into these topics.

The highly developed and isolated themes in Q2 in Fig. 2 represent themes that differ from the previous themes because they exhibit low centrality but high density. That is, internally, they are highly developed because they are shown in Q2, becoming specialized topics in auxiliary areas of the research field.

The emerging or declining themes in Q3 in Fig. 2 represent those that lack development and relevance to the field studied because they exhibit low centrality and density.

The basic and transversal themes in Q4 represent additional essential concepts for the field of research. However, they are not yet completely developed because they exhibit high centrality and medium density.

b) Diagram of conceptual evolution

The inclusion index was used to identify the conceptual relationships between the research topics over the established periods. Similarly, the strength of the association between different themes was considered as described in Ref. [34]. This was obtained using a superimposed graph and thematic evolution map. In the overlay graph, the number of words shared between periods is indicated by a horizontal arrow. The upper arrow indicates the number of new words in the current period, and the upper output arrow indicates the number of words that disappear and are not included in the subsequent period. However, the thematic evolution map shows the links between concepts in different continuous periods. The main elements are connected by continuous lines, whereas the dotted lines represent the links among topics that share nonessential elements. Additionally, the volume of the spheres was proportional to the number of published documents related to the topics, and the thickness of each border was proportional to the inclusion index.

c) Performance analysis

SciMat uses quantitative and qualitative standards to comprehensively measure the contribution of a study to a field of research. Similarly, performance analysis allows for the identification of the most productive, notable, and high-effect subfields through bibliometric indicators such as the number of citations, published articles, and h-index.

3. Results and discussion

3.1. Selection and identification of data

The initial search identified 1656 articles based on the keywords used in the "Article Title" field of the database. Subsequently, the search was limited to the period from 2000 to June 2022, resulting in 1621 results. After selecting documents following the inclusion and exclusion criteria, 1371 articles were obtained. Finally, by selecting only articles related to "Conference Paper" and "Article," 1245 results were obtained for the bibliometric analysis, as shown in Fig. 3. These results were divided based on the publication year, according to the most important milestones of the VPP, and the search for selected articles.

3.2. Bibliometric analysis

a) Strategic diagram, overlay graph, and evolution map

Fig. 4 shows the strategic diagrams classified according to different periods, portraying the thematic groups in the map quadrants. Fig. 5(a) depicts the number of new keywords is high in the overlapping graph. Thus, the number of words varied between 29 and 180 for different periods. Similarly, the number of shared keywords was high, ranging between 53% and 85% in different periods. As keywords reappear with equal or greater magnitude in successive periods, the number of keywords can be considered an indicator of the consolidation of the progressive form of the evaluated field of research. Fig. 5(b) presents an evolution map of the themes identified in the strategy map. The concept of a VPP was introduced in 1997 by Dr. Shimon Awerbuch using the term “virtual utility” [35]. This concept has led to the creation of small energy systems that take advantage of the benefits of DER. Consequently, several studies have contributed to the development of this conceptual definition by managing key research milestones, as shown in Fig. 5(b).

In the first period (2000–2007), VPPs improved their visibility by providing an interface that focused on controlling DERs [36]. Therefore, energy market issues were considered the driving theme during this period, as shown in Fig. 4. Similarly, DG is considered a specialized issue because it is located at Q2 in the strategic map. For this period, the fundamental and transversal themes were analyzed with respect to the distribution network, which is important for the evaluated period. These themes exhibited direct and indirect links to the themes of the subsequent period, as shown in Fig. 5(b).

In the second period (2008–2009), the profitable integration of DERs through the microgrid and VPPs [37] (2009) was observed. In addition, the aggregation of a plant with a VPP has been proposed to directly control the distributed energy units with respect to the active and reactive powers [38]. Moreover, microgrids appeared as topics with high centrality and density in the strategic map, that is, in Q1. However, it was not directly related to the themes of the following period, according to the evolution map (Fig. 5(b)). The microgrid concept is based on the principle that connecting several microgenerators to a grid can reduce the requirements for high-voltage transmission and distribution assets. Furthermore, VPPs facilitate the selection of several DERs with different technologies and operating parameters, and availabilities. These DERs are connected to various points in the distribution network, with the advantage of trading electrical energy and providing system support services. This is the primary basis for the issues of microgrids, distribution networks, and distributed energy resources categorized under Q1 in the strategic map for this period. Renewable energy appears as a fundamental and cross-cutting theme for the field, with high centrality and moderate density, which renders it a developing and important topic in this field of study. However, the theme of a distributed generation emerged as specialized, whereas power flows exhibited an emerging or declining theme during this period.

In the third study period (2010–2011), the following approaches were identified for integrating electric vehicles through VPP: direct, hierarchical, and distributed control approaches [39]. The most relevant issues corresponding to high density and centrality in the strategic map are V PPs and bidding strategies, which are categorized under Q1 of the strategic map. The linear programming theme was considered an emerging or declining theme during this period because of its low centrality and density. During this period, researchers have generally focused on the contribution of the VPP to a joint rotating reserve power and service market. In other words, a deterministic equilibrium model was proposed to simultaneously design the VPP bidding strategy. In addition to the DER constraints, the approach identified VPP security and supply–demand balancing constraints. This concept can integrate several DERs in the same geographical area by considering the influence of the local network in real-time. Therefore, the VPP integration approach can injure/absorb power to/from the main grid, including the rotating standby service. Thus, this approach integrates the DER for visibility

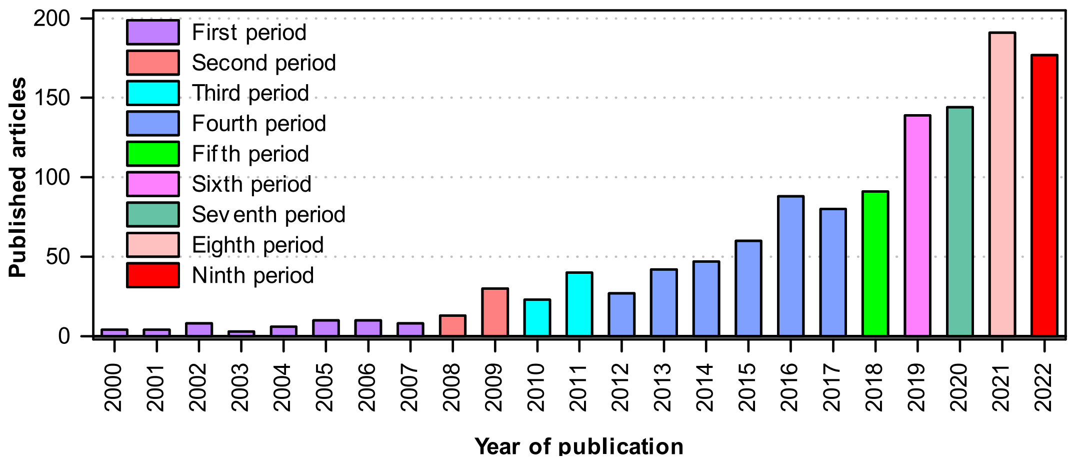

Fig. 3. Articles selected for bibliometric analysis.

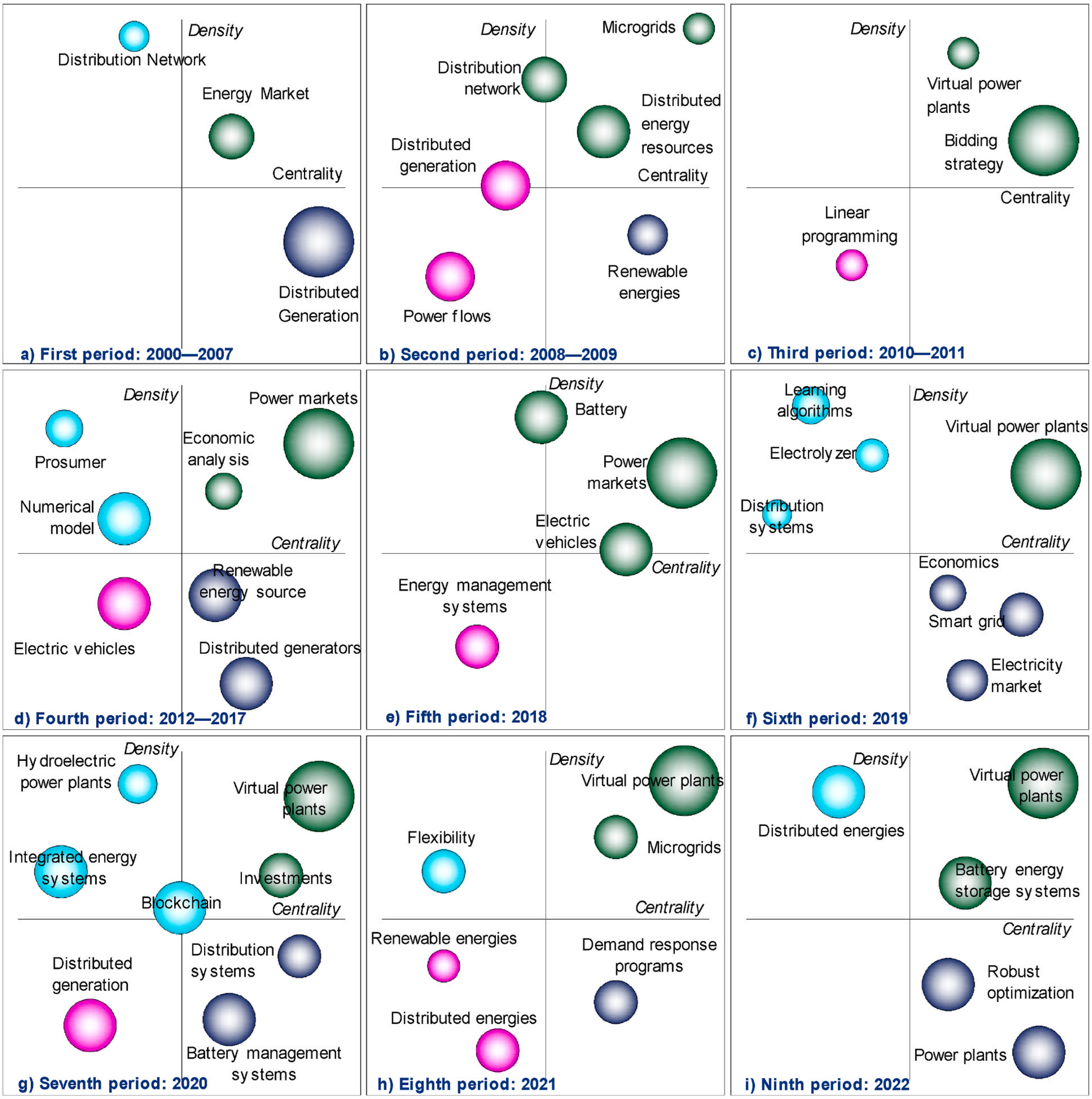

Fig. 4. Strategy diagram for various Periods:(a) First period (2000–2007); (b) second period (2008–2009; (c) third period (2010–2011); (d) fourth period (2012–2017); (e) fifth period (2018); (f) sixth period (2019); (g) seventh period (2020); (h) eighth period (2021); (i) ninth period (2022).

in the energy market and by the system operator.

During the fourth period (2012–2017), the operation control of DERs with VPP in the transmission and distribution systems was investigated [40]. Consequently, during this period, power markets and economic analysis were considered the driving themes, exhibiting high centrality and density, as they were categorized under Q1. Similarly, two topics related to the numerical model and the prosumer were shown to be specialized, as they exhibited high density and low centrality, and were categorized under Q2. Following the evolution map, the prosumer appears for the first time and is not linked to the previous themes (Fig. 5(b)). Similarly, the topics of renewable energy sources, electric vehicles, and DGs were considered fundamental and transverse within the field of research and the period evaluated.

Typically, during this period, the development of electricity market models was distinct in the daily (spot), intraday, and regulated energy markets. This can assist virtual powerhouse traders to increase their profits through daily trading in various markets. The VPP optimal energy management problem was solved using metaheuristic optimization algorithms to demonstrate unlimited energy exchange between the public network and the VPP. This strategy has been proposed as a more economical method than the limited

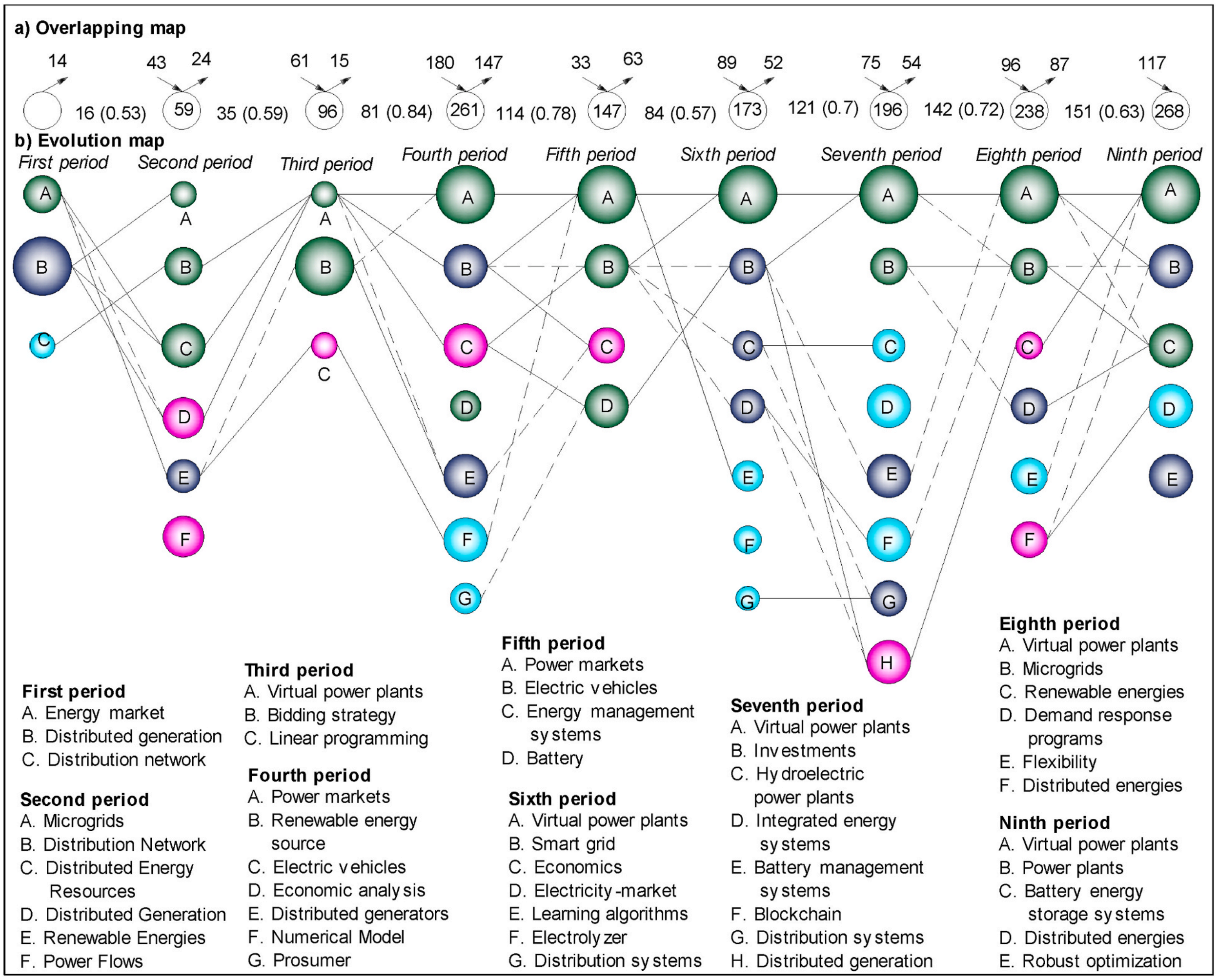

Fig. 5. Overlay graph and evolution map for VPP from 2000–June 2022.

energy exchange. The approaches in this period focused on maximizing economic benefits by suggesting virtual gas-electric power plants [41]. Thus, a robust optimization foundation was used to solve the deficiencies of the system operation risk based on the price and intensity of the energy load of the system.

In the fifth period (2018), VPPs exhibited a new technological convergence trend in electricity distribution networks with DER [42]. The driving and fundamental issues studied in this field are power markets, electric vehicles, and batteries. Energy-management systems are considered to have emerged during this period. Therefore, the technology of collaborative networks (CN) possesses a certain level of penetration in the energy industry, and consequently, in intelligent networks and VPPs. However, the penetration rate should be increased to improve the maturity of the VPP concept using the knowledge of the CN domain. Therefore, VPPs form various collaborative, strategic, and dynamic connections identical to the organizational forms of the CN. Therefore, the adoption of CN concepts in the collaborative environment of a VPP improves system performance.

In the sixth period (2019), VPPs were defined as dispatchable virtual units offering complementary services to the network [43]. The strategic map shows that VPPs were the primary research topic during this period. Learning algorithms, electrolyzers, and distribution systems were the isolated topics found in Q2. According to thematic evolution, the electrolyzer appeared as a theme that did not present direct connections or links with other themes, as shown in Fig. 5(b). Similarly, the strategic map shows the smart grid, economics, and electricity market as fundamental and transverse themes in the sixth period. Therefore, real-time economic dispatch methods have been proposed for different levels of VPP, including various types of DER. Considering the demands of the VPP and system operator, real-time economic dispatch was appropriately approached as a two-level scheduling problem. Considering the uncertainties of the DER, the loads, system operators, and VPPs at different levels can make efficient decisions based on their risk preferences.

In the seventh period (2020), management based on the virtual cloud concept was proposed [44]. Virtual power plants, blockchain, and investments were shown to be the driving or primary themes, owing to their high centrality and density, following the strategic map in Fig. 4. Similarly, hydroelectric power plants and integrated energy systems were isolated themes, as they were categorized under Q2. Similarly, DG is considered an emerging or declining topic, owing to its low centrality and density. Finally, battery management and distribution systems were fundamental and transversal research themes with high centrality and moderate density. During this period, researchers focused on cloud-computing technologies to control computational tasks centrally. For example, edge computing has been used to reduce the complexity of implementing decision-making controls for decentralized VPP [45].

In the eighth period (2021) the concept of a dynamic virtual power plant (DVPP) was addressed [46]. Coordinated frequency control strategies for VPP have been proposed to improve the short-term dynamic response of electrical systems. Thus, the themes of the VPP microgrids are shown as the driving or primary themes in the field of research, as shown in Fig. 4. Subsequently, in Q2 of the strategic map, flexibility is shown as an isolated theme with highly developed external links, not presenting links with previous themes, according to the thematic evolution shown in Fig. 5(b). Similarly, renewable, and distributed energy sources either emerged or declined during this period. Finally, the demand response programs were shown to be fundamental and transversal research themes. The control approach is based on an adaptive strategy that addresses the desired voltage and frequency control of the DVPP aggregated using adaptive dynamic participation matrices. Furthermore, the local linear parameter variables of the control were designed to best fit local requirements.

Finally, the ninth period (2022) focuses on the programming and operation of a VPP based on renewable energy sources (RES) with electric mobility (e-mobility) [47]. VPPs and battery energy storage systems (BESS) have been the subject of primary research due to their centrality and density. Subsequently, the distributed energies were shown to be isolated themes owing to the topic's low centrality and high density. Finally, as categorized under Q4, power plants, and robust optimization were shown to be fundamental and cross-cutting issues that are important for the field of research.

During this period, real-time distributed clustering algorithms were proposed for aggregating energy storage systems in heterogeneous power plants. Currently, the energy market necessitates that consumers become producers, and simultaneously requires greater control based on small-scale technological progress. However, when they choose to become VPP, changes in network management and control are required. Consequently, VPPs can substantially alter the network demands by reducing or halting EVs charging. Similarly, with bidirectional flow capabilities, EVs can allow VPPs to implement smart offloading and transfer stored energy from the EVs battery to reduce the load on the grid within seconds. Therefore, the BESS plays a fundamental role in the implementation of a VPP to provide reliability and quality to the energy supply. This neutralizes the power imbalance in intermittent RES.

b) Performance analysis

Table 1 presents the performance of the themes in the last period (2022). Recent studies related to power plants have highlighted four relevant topics in this field: renewable power plants, BESS, distributed energy, and robust optimization. BESS, which is categorized under Q1, was considered the main theme because of its high centrality and density. Similarly, renewable power plants and robust optimization were considered fundamental and transversal themes because they exhibited high centrality and moderate density. These topics are emerging in this research field. However, distributed energy is an isolated topic in this field of research. Therefore, more emphasis was placed on fundamental and cross-cutting themes, future driving, and the main themes in the research field.

The BESS and VPP concepts are considered important in electrical systems. These new approaches were referenced and exploited in terms of their ability to address grid intermittency issues. Similarly, the BESS was proposed to increase the performance and economic viability if it is operated by a VPP. Therefore, BESS can be considered to provide auxiliary market services, operate in response to demand, and solve problems related to the regulation of peaks and frequencies. However, this would only be feasible if the policies and incentives defined by the regulator ensure that the services and roles of the BESS are present.

In contrast, robust optimization models were proposed to identify VPP parameters that are not directly related to information from daily energy markets. However, the identification is limited to stochastic variables such as time-varying power limits. Moreover, these models involve uncertainties related to the energy dispatch and DER outputs. Therefore, the approaches suggested for the energy management of VPPs consider contingency conditions as a robust stochastic optimization model. Consequently, the uncertainty in the availability of the different components in the VPP and market prices were modeled through scenarios. Thus, variability in renewable energy production was achieved through prediction intervals. In addition, the conditional value of risk was incorporated into the model to determine the impact of risk aversion on the management decisions of the electricity grid. However, robust daily optimization models have also been proposed to analyze the flexibility of different local resource configurations.

Similarly, demand-side management was considered to modify the load at predefined intervals related to the production forecasts of renewable components. In addition, robust multistage optimization models based on the risk-control approach of VPP alliances and market bidding strategies have been proposed. Similarly, multiple adjustable resources such as electric vehicles and BESS were

Table 1
Performance of virtual power plant (VPP) in 2022.

Cluster or theme	Centrality	Density
Virtual power plants	72.66	28.84
Renewable power plants	35.51	6.07
Battery energy storage systems	11.9	8.96
Distributed energies	5.77	24
Robust optimization	8.97	6.19

considered. Therefore, a robust dual-dynamic programming algorithm is proposed as the recommended model. The purpose of the two-stage stochastic robust optimization is to maximize the VPP gain in the power market and minimize the total system cost in the reserve market.

The perspectives of VPP can proceed in the following directions: Innovative VPP structures and topologies can be proposed in parallel with changes in the energy system and its components. Compatibility, universality, and competitiveness are relevant to VPPs; therefore, big data analysis can be used to obtain adequate information. Diversified and hybrid optimization techniques can be considered for the further exploration of internal power dispatch, external markets, risk identification, bidding strategies, and decision-making. DER, market price, and load uncertainties must be considered to achieve optimal VPP scheduling. Electric vehicles may exhibit a promising future for possible utilization as energy reserves with bidirectional flow. Finally, data transmission protocols using Information and Communication Technologies (ICTs) are necessary to enable faster scheduling, dispatch, and hierarchical registration activities in VPPs.

3.3. Discussion

The results revealed the evolution and key themes in the field of VPPs over time. This study identified different periods and their associated themes, such as the control of DER, integration of DER through microgrids and VPPs, integration of electric vehicles through VPPs, research on DER operation control with VPPs, convergence of VPPs with DERs, management approaches based on virtual cloud concepts, dynamic virtual power plants, programming, and operation of VPPs using renewable energy sources, and electric mobility.

Previous studies that provide valuable information through the review process can be found in the literature. For example [11], highlighted the importance of considering various factors such as uncertainty, reliability, reactive power, control, emissions, stability, and demand response in the DER programming problem in the microgrid and VPP concepts. In Ref. [12], the topic of uncertainty in VPP optimization was analyzed, and uncertainties were classified into renewable energy generation uncertainty, market price uncertainty, and load demand uncertainty [13]. focuses on the integration of EVs as virtual power plants and highlights the importance of EVs as alternative energy sources. This suggests that the integration of EVs into the power grid is a promising solution for balancing energy production and consumption.

Although different concepts are shared in the findings, this study contributes to the existing literature by providing a comprehensive analysis of the scientific evolution of VPPs. It identifies key themes and periods in the field, highlights advancements and areas of focus over time, and establishes the importance of each topic for researchers throughout the established period. Each of them is placed on the strategic map, classifying them into motor themes, highly developed and isolated themes, emerging or declining themes, and basic and transversal themes. This study provides information on the integration of different energy resources, including DERs, microgrids, electric vehicles, and renewable energy sources, within VPPs. It also emphasized the importance of considering uncertainties, reliability, and emissions in VPP optimization.

Analysis of the strategic diagram, overlay plot, and evolution map revealed the evolution of VPPs over different periods. In the early years (2000–2007), VPPs primarily focused on controlling DERs and addressing energy market issues. This specialized problem is in quadrant Q2 of the strategic map. In subsequent periods, the integration of DERs through microgrids and VPPs was highlighted. Renewable energy has emerged as a fundamental theme, and the concept of aggregating a plant with a VPP to control distributed energy units has been proposed. The research then shifted towards the integration of electric vehicles through VPPs and the exploration of different control approaches. The operational control of DERs with VPPs in transmission and distribution systems has gained attention with a focus on energy markets and economic analyses. The concepts of collaborative networks and technology convergence in distribution networks with DERs were discussed later. Finally, management approaches based on the concept of virtual clouds were explored, and the concept of dynamic VPPs was introduced.

Performance analysis indicated that VPPs were a major research topic in 2022. Renewable power plants, BESS, distributed energy, and robust optimization are also important topics. BESS exhibits high centrality and density, making it a major theme in the field. Robust optimization models have been proposed to address the uncertainties and risk aversion in VPP management. The analysis also highlighted the importance of considering demand-side management, electric vehicles, and data transmission protocols in future research. Innovative VPP structures and topologies and diversified and hybrid optimization techniques for internal energy dispatch, external markets, risk identification, bidding strategy, and decision-making in VPPs should be considered. Uncertainties related to DERs, market prices, and loads should be incorporated into optimal VPP programming. Furthermore, the potential of electric vehicles as bidirectional energy reserves should be further investigated. Finally, the development of efficient data transmission protocols using ICTs is crucial for streamlining programming, dispatch, and hierarchical registration activities in VPPs.

The findings of this study can serve as the basis for future research and development in the field of VPPs. In addition, the findings of this study have implications for practical applications of VPPs in energy management. Identifying the key themes and periods in the field can help policymakers, energy companies, and researchers understand the evolution of VPPs and make informed decisions regarding their implementation. This study highlighted the potential of VPPs to integrate different energy resources, optimize energy management, and address challenges related to renewable energy integration, demand response, and market dynamics. Practical applications of VPPs include improved control and optimization of energy systems, increased reliability and efficiency, and the potential to utilize electric vehicles as energy reserves.

3.4. Future directions for research

Based on the results and analyses of previous studies, several directions for future research were identified. First, there is a need for further exploration of innovative VPP structures and topologies that align with evolving energy systems and their components. The compatibility, universality, and competitiveness of VPPs can be enhanced through big data analysis and the establishment of appropriate information. Additionally, diversified and hybrid optimization techniques should be considered for internal energy dispatch, external markets, risk identification, bidding strategies, and decision-making in VPPs. Uncertainties related to DERs, market prices, and loads should be incorporated into optimal VPP programming. Furthermore, the potential of electric vehicles as bidirectional energy reserves should be further investigated. Finally, the development of efficient data transmission protocols using ICTs is essential for streamlining programming, dispatch, and hierarchical registration activities in VPPs.

4. Conclusions

This study conducted a comprehensive analysis of the scientific evolution of VPPs using a scientific mapping approach applied to the relevant literature.

After applying the inclusion and exclusion criteria, 1245 articles were selected for bibliometric analysis. Bibliometric analysis involves applying a strategic diagram, overlay graph, and evolution map to gain insights into the development and trends of VPP research across different time periods.

- Period 1 (2000–2007): The focus was on controlling DERs and addressing energy market issues. Distribution networks emerged as a significant theme during this period.
- Period 2 (2008–2009): The focus has shifted towards integrating DERs via microgrids and VPPs. Microgrids are considered specialized issues, whereas renewable energy has emerged as a fundamental and cross-cutting theme.
- Period 3 (2010–2011): The integration of EVs into VPPs was explored using different control approaches. Important themes included VPPs and bidding strategies.
- Period 4 (2012–2017): This investigation focuses on the operational control of DERs using VPPs in transmission and distribution systems. The research was driven by power markets and economic analyses, with prosumers and renewable energy sources emerging as fundamental and cross-cutting themes.
- Period 5 (2018): Technological convergence of VPPs with electricity distribution networks and DERs was observed. Power markets, EVs, and batteries play key roles in driving these research themes.
- Period 6 (2019): VPPs are dispatchable virtual units that offer complementary services. Smart grids, economics, and electricity markets are fundamental and cross-cutting themes.
- Period 7 (2020): Management based on the virtual cloud concept was proposed. VPPs, blockchains, and investments are the driving themes. Battery management and distribution systems are fundamental cross-cutting themes.
- Period 8 (2021): Dynamic VPPs and coordinated frequency control strategies are addressed, with VPP microgrids serving as driving themes.
- Period 9 (2022): The programming and operation of VPPs based on RES with e-mobility were explored with VPPs and BESS as the driving themes.
- BESS, renewable power plants, and robust optimization have emerged as important themes in the field. BESS, due to its high centrality and density, BESS was considered the main theme.

Thus, prospects for VPP research include exploring innovative structures and topologies, utilizing big data analysis, and considering diverse and hybrid optimization techniques. This study provides insights for future VPP research and practical applications. It identifies the key themes, periods, and implications for policymakers and energy companies. VPPs have the potential to integrate energy resources, optimize management, and address renewable energy challenges. These benefits include improved control, efficiency, and the utilization of EVs as energy reserves.

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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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