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# Virtual power plants: an in-depth analysis of their advancements and importance as crucial players in modern power systems

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**Abstract**

**Background** Virtual power plants (VPPs) represent a pivotal evolution in power system management, offering dynamic solutions to the challenges of renewable energy integration, grid stability, and demand-side management. Originally conceived as a concept to aggregate small-scale distributed energy resources, VPPs have evolved into sophisticated enablers of diverse energy assets, including solar panels, wind turbines, battery storage systems, and demand response units. This review article explores the evolution of VPPs and their pivotal roles as major stakeholders within contemporary power systems. The review opens with a definition of VPPs that clarifies both their fundamental traits and technological foundations. A historical examination of their development highlights major turning points and milestones that illustrate their transforming journey.

**Main text** The methodology used for this article entailed a thorough examination to identify relevant studies, articles, and scholarly works related to virtual power plants. Academic databases were used to gather relevant literature. The literature was organized into categories helping to structure and present information in a logical flow based on the outline created for the review article**.** The discussions in the article show that the various functions that VPPs perform in power systems are of major interest. VPPs promote the seamless integration of renewable energy sources and provide optimum grid management by aggregating distributed energy resources, which improves sustainability. One of the important components of this evaluation involves taking market and policy considerations. Examining worldwide market patterns and forecasts reveals that VPP usage is rising, and that regulatory frameworks and incentives have a bigger impact on how well they integrate.

**Conclusion** Overcoming obstacles is a necessary step towards realizing full VPP potential. For VPPs to be widely adopted, it is still essential to address technological and operational challenges as they arise. Diverse stakeholders must work together to overcome market obstacles and promote the expansion of the VPP market. This analysis highlights the potential for VPPs to propel the evolution of contemporary power systems toward a more sustainable and effective future by highlighting areas for future research and development.

**Keywords** Contemporary power systems, Distributed energy resources, Renewable energy sources, Virtual power plants

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## Background

There is an urgent need for creative and sustainable alternatives as the world's need for energy rises, while fossil fuel-based power generation methods are increasingly scrutinized for their environmental effects [1]. Centralized alternating current power networks have been widely installed and used worldwide since the 1880s. Evaluations from the 2023 statistical global energy review [2] revealed that about 82% of the world's primary energy source comes from fossil fuels like coal oil, and natural gas but their utilization produces greenhouse gas emissions that harm the environment and cause climate warming which has triggered the current global climate crisis [3]. The contribution of the different sources to world energy consumption is shown in Fig. 1.

On the other hand, energy demand has grown significantly as a result of global economic growth. The demand for electricity has increased steadily over the past decades, by an average of 15%, and is anticipated to increase by 30% by 2040 [4]. This calls for innovative ideas to support the demand while looking out for the environment. Therefore, distributed energy resources (DERs) must be considered to lessen the detrimental environmental impacts of fossil fuels [1]. DERs are decentralized energy systems that produce, consume and store energy and are preferably located close to where electricity is consumed. These resources include batteries, wind turbines, solar panels, etc. DERs have been integrated in the power system networks (PSN) and have reduced the effects of energy generation from fossil fuels, furnishing stakeholders with economic and technical benefits [5]. While DERs offer power systems opportunities, they also bring with them challenges because of their intermittent and stochastic nature. DERs are often described as stochastic and intermittent due to their inherent characteristics and the factors that influence their generation. This nature of DERs is caused by elements including weather changes, operational uncertainties like maintenance, and equipment performance, which can result in unanticipated variations in DER generated or connected output. Instability in the grid is brought on by the rising use of DERs on the demand side, which worsens load demand fluctuations. As a result, real-time monitoring and dispatching are essential for the grid's safe operation [6–9]. Furthermore, the power system needs more adaptability, which can be provided by several mechanisms, such as demand-side management, and energy storage systems (ESS). The only way to properly use these sources to increase their grid contributions is through optimal coordination between different agents [10].

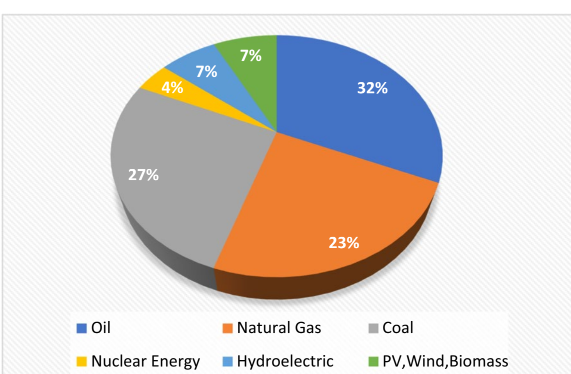


**Fig. 1** Global energy sources data

Over the years, various research has been conducted to address the above challenges and many solutions have been proposed. VPPs have emerged as a ground-breaking solution in an era of energy transition and growing emphasis on sustainable power generation, altering the landscape of contemporary power systems [11]. VPPs have evolved as key players in promoting efficiency, flexibility, and resilience in the energy industry thanks to their capacity to integrate a variety of energy supplies and improve grid management [12, 13].

A VPP is an energy management system that aggregates and coordinates diverse array of DERs, including photovoltaics, wind turbines, battery energy storage systems (BESS), and demand response technologies. The primary function of a VPP is to optimize the collection of these DERs in response to grid conditions, energy demand, and market signal. Through advanced control algorithms and real-time monitoring capabilities, VPPs dynamically adjust energy dispatch schedules, balances supply and demand, and enhance grid stability and reliability.

It is important to note that the concept of VPPs shares some basic similarities with that of the smart grid. However, unlike the VPP which focuses on the aggregation and optimization of DERs, smart grid, on the other hand, encompasses a broader range of functionalities aimed at modernizing the entire electricity supply chain. It can be said that the VPP augment the operation of the smart grid by providing ancillary support like supply and demand balancing to the smart grid.

The combination of these various resources enables the VPP to function as a cohesive and adaptable entity, to be able to react in real-time to grid signals and market conditions [14, 15]. In the late 1990s, a pioneering shift in energy research and innovation emerged with the exploration of aggregating distributed resources into a unified virtual power entity, laying the groundwork for the conceptualization and development of VPPs [13]. Since then, VPPs have evolved from theoretical notions to real-world applications owing to technical developments, and breakthroughs in communication technology. The adoption of VPPs has been hastened by the spread of smart grid technologies and the rise of renewable energy resources (RERs), making them a crucial component of contemporary power systems [12, 16].

It is impossible to overstate the importance of VPPs as significant participants in contemporary power systems. VPPs are essential for facilitating the seamless integration of intermittent renewable resources into power grids as they shift from fossil fuel-based generation to renewable-dominated systems [3, 17, 18]. In addition, VPPs can control electricity consumption patterns to correspond with variations in renewable generation. Demand-side management improves grid reliability and efficiency by lowering peak demand and reducing grid congestion [19, 20]. VPPs also significantly contribute to the optimization of the energy market. VPPs are crucial actors in the developing electricity market because of their involvement in energy trading and the provision of ancillary services, which help to stabilize prices and maintain system resilience [11, 21]. A typical architecture of a VPP is shown in Fig. 2. With the aid of technology like cloud computing, a VPP aggregates various power consumers, ESS, and power generators to provide flexible adjustments. A communication protocol is used by the components of a VPP to transfer data to the VPP communication system. This communication protocol enables efficient coordination for the VPP to adjust energy production which allows supply to the grid with dependable cost-effective electricity via the electricity market [22]. The data acquisition platform aids in gathering information about the generation, consumption, and state of charge of the portfolio of DERs for optimal decision-making.

From the above discussion, it is clear that VPPs have become an important player in modern power systems, providing a dynamic and revolutionary method of managing energy. The idea of VPPs has recently received a lot of interest in energy systems. Studies have provided insightful information by highlighting their potential to transform the way we produce, distribute, and use power. It is critical to understand that this dynamic and developing discipline poses several notable issues, gaps, and areas that require added research.

In the review presented in [23], an overview of VPP operations, including the integration of DERs, controlled loads, and EVs for resource aggregation and cooperative optimization as well as market and grid operations, is the goal. The evaluation did however not discuss regulatory and policy issues that might affect how widely VPPs are used and implemented in the power market.

Also, the difficulties, solutions, and prospects related to the conceptual review of the conversion of a microgrid to a VPP have also been covered by [24]. The overview examines RERs integration, opportunities for VPPs in the field of smart distribution systems, and effective management mechanisms. The management mechanism, however, did not discuss the optimization of the DERs for optimal operation. Authors in [25] gave a thorough overview of the VPP concept and its potential advantages in integrating DERs to assist grid security and stability. Resource optimization, as a main part of the VPP operation, is not covered in this study. Also, Ref. [11] provided an overview of VPP models and how they interacted with various energy markets. Finding the most profitable VPP scheme to be implemented in each regulatory environment is the focus. DER integration challenges, which

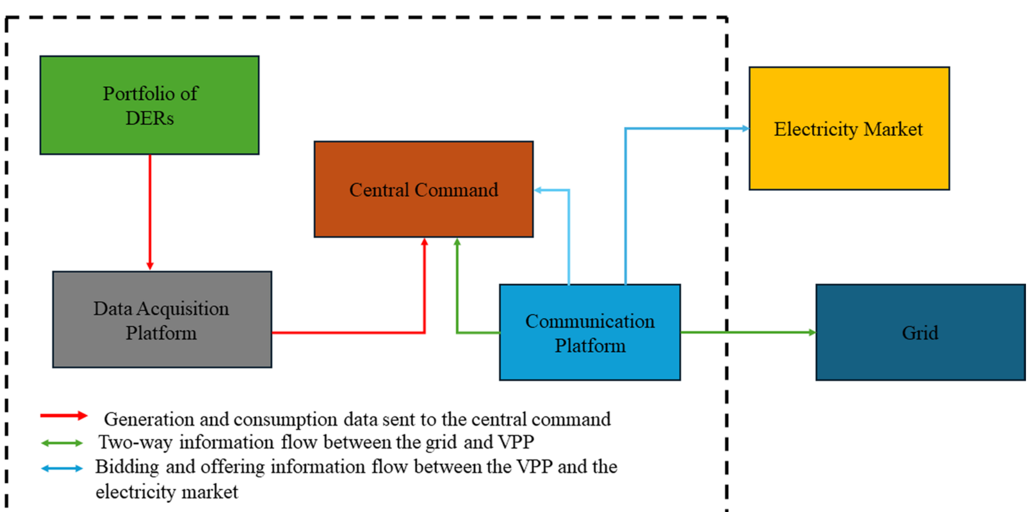


**Fig. 2** Architecture of a VPP

affect the operation of VPPs in the energy markets, are not considered in this study. In [26], the idea of VPPs to participate in various energy markets is proposed. The model evaluates the VPP's technical and commercial prospects. Engaging in various energy markets revolves around sharing of data between the VPP and operators of the markets. The issue of data privacy and cybersecurity was not included in this study. Authors in [27] provided a review with a focus on integrating DERs into the electricity grid. The assessment gave a summary of the development and use of VPP for carbon reduction in the Chinese power system. The study, however, did not cover technologies that can improve the management and operation of VPPs, notably in addressing the intermittent and volatile nature of DERs. In the domain of energy management, authors of [28] provided a summary of resource scheduling in VPPs and addressed questions on scheduling procedures. However, despite concentrating on both technical and economic elements of scheduling in VPPs, this analysis did not address potential influences like the state of the energy markets that could have an impact on the scheduling issue. The case of a multi-energy coupled VPP has been presented in [29]. The purpose of this study was to address the advantages of multi-energy linked VPPs engaging in various energy markets. The issue of enhanced communication technology, data privacy and cybersecurity are some of the challenges which were not featured in this study.

The idea and structure of VPPs are concisely described in [30] with regard to its two main goals—energy management and power markets. Solutions are suggested to alleviate the problems with DER uncertainties that were highlighted. In order to create future sustainable power grids, authors of [3] have presented a comprehensive overview of the cutting-edge VPP technology. The study discusses recent technological advancements as well as the significant economic benefits of VPPs. However, this study did not cover the legislation that specifies how VPPs can access and participate in the energy markets. Below are some of the gaps found in existing literature:

- Analysis of cybersecurity and data privacy as crucial elements in the VPP development.
- Environmental and sustainability focus. The SDGs that VPPs could support, and how the support can be achieved.
- Rigor analysis of legislation or regulations which will dictate the operation of the VPP.

Considering the above research gaps in literature, this review article advances the knowledge of energy systems by providing a thorough analysis of VPPs, their historical development, and their crucial roles as essential stakeholders in modern power systems. There will be focus on technical and market operations, real-world case studies, the identification of challenges and prospects, the emphasis on technical and market operations highlight the relevance and transformative potential of VPPs in creating sustainable and effective energy ecosystems. The contributions of this paper can be summarized as follows:

- Comprehensive understanding of VPPs to provide readers with a concise definition, key traits, and core values of VPPs.
- Tracing historical developments of VPPs from their theoretical roots to their current popularity.
- Emphasis on VPPs as key stakeholders in modern power systems. This emphasis highlights the vital role that VPPs play in ensuring grid stability, fostering the integration of RES, and promoting sustainability.
- Integration of technical and market aspects by providing a comprehensive analysis of VPP operation. This integration is crucial as it shows that VPPs actively participate in energy markets and actively optimize energy resources, which facilitates effective electricity trading and grid balancing.
- Application of cybersecurity and data privacy techniques that protect the VPP from cyber threats, assuring grid stability, data integrity, and consumer trust in the ever-changing energy sector.
- Real-world case studies of VPP deployments to offer insights and experiences.
- Discussion of the regulatory frameworks that control how VPP operates.
- Identification of challenges, providing recommendations, and prospects.

## Main text

### VPP advancements

The traditional centralized power generation model is being replaced by a decentralized, adaptable, and sustainable system thanks to VPP, which represents a revolutionary paradigm in the energy sector. Early theoretical ideas from the late twentieth century established the foundation for the development of VPPs and their eventual prominence in modern power systems [31, 32]. This part of the paper will focus on the evolutionary journey of VPPs, highlighting the early concepts, key milestones, and technological advancements that shaped their development into critical enablers of modern energy ecosystems.

#### The embryonic stage (1990s–2000s)

Although the idea of VPPs was initially put forth in the 1997 [13] by Dr. Shimon Awerbuch, it did not really take off until the early 2000s. Early academic publications proposed the idea of coordinating and optimizing a portfolio of distributed energy resources to increase operational effectiveness and grid reliability. However, due to limited technological capabilities and a lack of enabling legal frameworks, the practical deployment of VPPs remained primarily theoretical at this point. Also, the absence of developed distributed generating technology, the high cost of communication and control systems, and the regulatory uncertainties surrounding VPPs were some of the causes of lack of practical deployment. References [33–38] provides a description of the early years concept of the VPP, its difficulties, including consumer resistance to participating, economic viability in infrastructure setup, investors' perceptions of risk, and grid operators' reluctance to adopt the unique strategy.

#### The breakthrough stage (2010s–2020)

The growth years presented milestones and key turning points in VPP deployment from the early years. At this point, the VPP has encountered rapid growth as a result of increasing interest in adoption of distributed generation technology, decreasing communication and control system costs, and expanding regulatory backing for VPPs. In a declaration on the future of the European electricity market that was issued in 2011, the European Commission emphasized the potential of VPPs to increase grid flexibility and integrate renewable energy. This communication aided in increasing policymakers' and stakeholders' understanding of VPPs [39–45]. Later, in March 2023, it was amended in Strasbourg, France, by recommending an expansion of the EU electricity market structure to further integrate RESs, improve customer protection and industrial competitiveness [46]. Notable milestones of the growth years include grid integration [47], market participation [48], technological advancement, and demand response programs[49], allowing aggregated DERs to respond to grid signals and enhance grid stability [50]. This marked the initial practical application of VPPs, showcasing their ability to support grid operations.

#### The future (2021 and beyond)

The demand for flexible grids and the incorporation of RESs is anticipated to drive further growth of VPP. VPPs are viewed as one of the techniques to lower carbon emissions and increase energy efficiency [51]. The key drivers for this growth are the increasing deployment of distributed generation technologies (DGT), falling cost of communication and control systems, growing regulatory support for VPPs, and also prosumers who want to receive incentives for their surplus generation [45].

In summary, it is evident that early theoretical insights were followed by practical and revolutionary applications in modern power systems as VPPs evolved. The development of VPPs into essential enablers of decentralized, flexible, and sustainable energy ecosystems has been shaped by significant turning points and milestones, as well as technological development and innovations. A thorough summary is provided in Table 1 for further reading.

## VPP planning, roles, and sustainability

### Planning

VPP planning is a crucial and multifaceted process that entails strategic design, coordination, and optimization to provide effective and dependable energy management. The main goal of VPP planning is to maximize the advantages for both grid operators and consumers while optimizing the potential of varied DERs and guaranteeing their seamless integration with the power grid. The planning approach necessitates a thorough comprehension of the energy landscape, individual DER capabilities, market dynamics, and regulatory frameworks.

To ensure that VPPs perform as planned and expected, their technological constraints must be recognized and measured [55]. Before interacting with external and internal elements, the VPP schedules and plans its operations. It is also a good performance criterion for the VPP to keep accurate data to engage the electricity market and reap favorable effects by analyzing the uncertainties resulting from elements like weather and producing forecasts with a high level of assertiveness [56]. The issue of forecasting will be discussed later in the section dedicated to the roles of VPPs. The VPP operations may be constrained by infrastructure, technological, and technical limits [57]. The model shown in [26] emphasizes the importance of effectively measuring and managing controllable loads in heating, ventilation, and air conditioning (HVAC) systems. Also, it emphasizes the significance of photovoltaic (PV) and BESS influences in determining the viability and adaptability of a VPP. VPPs can improve their coordination with all stakeholders by developing a methodical technique for evaluating and controlling power availability at time intervals. Surely, this enhances the performance of the VPP and enables a more seamless interaction with the power grid.

VPP planning also includes economic and legal factors in addition to the technical ones. The aspects of technical and economic frameworks of the VPP will be delved deeper in the sections dedicated to the technical and economic aspects of VPPs. It is important to note that good operational planning directly affects good economic

**Table 1** Summary on the advancements of VPPs

| Refs. | Year | Brief explanation | Challenges |
|---|---|---|---|
| [33] | 1997 | VPPs idea was conceived in accordance with a flexible partnership between autonomous, market-driven enterprises for the provision of consumer-focused energy services | Limited technological capabilities |
| [34] | 2003 | The idea elevated from the previous definition to a system that will effectively integrate the VPPs into the energy market using cogeneration units, small-scale RES and EMS | High cost of communication and control systems |
| [35] | 2004 | A novel concept for providing heat and energy near the load involved grouping small generators | |
| [36] | 2007 | VPPs were defined as a flexible mix of DERs that would aggregate numerous different DERs and produce a single operational file for control and management depending on the specifications of each DER | Reluctance to adopting the idea |
| [37] | 2008 | The most efficient methods for integrating DERs into the power systems were frequently cited as VPPs and Microgrids (MGs), although they were distinct. Their differences will be discussed further in this paper | Regulatory uncertainties for grid integration |
| [38] | 2009 | DG and controllable loads took part in grid operations in real time as part of an open electricity market. To increase their usability and manageability in the market, DERs were integrated into the VPP concept | Investors' risk perceptions |
| [39] | 2010 | At this turn, software applications were implemented for remote dispatch and optimization within a secured network | Data management and analytics |
| [40] | 2011 | The advent of electric vehicles (EVs) paved the way for their incorporation into the VPPs DERs portfolio | Uncertainties with charging and discharging patterns |
| [41] | 2014 | Considering both market prices and demand-side projections for energy, the concept of thriving VPPs allowed for a reduction in operational expenses | Market price volatilities |
| [42] | 2017 | The idea was more widely used as a power source for distribution networks thanks to the cooperation of the transmission system operator (TSO) and distribution system operator (DSO) | Incorporating vast number of energy sources which causes grid disturbances |
| [43] | 2018 | Financial gains have become very feasible for prosumers. To maximize financial gains for all system participants, VPPs were termed as a group of DERs that participated as a single entity in the energy and reserve power market | Market price volatilities |
| [44] | 2019 | The growing use of DERs presented challenges to the grid. The stochastic nature of these DERs gained more traction and attention | Challenges with grid dependability |
| [45] | 2020 | A framework for the Internet of Energy for the various stakeholders of the VPP | Cybersecurity threats, cost in technological upgrade |
| [52–54] | 2021 and beyond | VPP energy production optimization, increased profit margin, and the issue of cybersecurity are well established for further absorption of the VPP concept into the present-day and future energy system | Cybersecurity threats, market price volatility, scalability |

outcomes [55]. The economic viability of the VPP and its prospective revenue streams, including energy trading [58], demand response participation [59], and the supply of ancillary services [21], are assessed using financial models and cost–benefit analysis [60]. Collaboration with grid operators, legislators, and other stakeholders is also necessary for successful VPP planning to overcome regulatory obstacles and build an environment that facilitates VPP integration. To ensure effective planning, the VPP should be continuously monitored and improved to respond to shifting grid conditions and market dynamics [61]:

- VPP planning opens the way for a more resilient, and sustainable energy future by integrating technological, economic, and regulatory factors. It has enormous potential to optimize resource use, improve grid stability, and contribute to the global quest for a reduction in carbon emissions produced by energy systems. It is therefore imperative that stakeholders comprehend the complexities of VPP planning to influence the energy industry's future and advance the cause for greener and a more sustainable and effective energy future. This planning

phase can be summarized as: aggregating existing and new energy resources.
- Ownership structure: The internal ownership structure of VPPs can vary depending on the specific implementation and stakeholders involved. It may involve collaboration between multiple stakeholders including energy producers, consumers, and aggregators.
- Regulating and market considerations governing energy markets and grid operations.
- Implementation of an energy management system to provide functionalities such as real-time monitoring, forecasting, dispatching, and scheduling energy resources to meet grid requirements and maximize economic benefits.
- Agreement formulation such as power purchase agreements.
- Profit sharing mechanisms taking into consideration factors such as investment contributions, operational cost, risk allocation, etc.
- Compensation structures for various stakeholders involved in the VPP including incentives for demand response participations from consumers.

## Roles

The way electricity is produced, controlled, and used has been revolutionized by VPPs as explained in the previous sections. VPPs are flexible and dynamic entities that perform a variety of roles in modern power systems. Because of the variety and importance of their tasks, they are key players in creating an energy ecosystem that is sustainable, effective, and resilient. The following are the main responsibilities of VPPs in power systems.

- Aggregation of DERs: Various DERs, such as solar panels, wind turbines, ESS, EVs, and demand response loads are gathered by VPPs. VPPs construct an adaptable and manageable portfolio of assets by combining these decentralized resources into a single virtual entity. Through this aggregation, grid management is improved, enabling the VPP to maximize DER usage in response to grid signals. The DERs' activity within the VPP is managed and coordinated by the VPP operators. The main responsibility is resource optimization and involvement in energy markets.

  The authors of [62] described the aggregator concept as a central control node that collects information from both the power grid and controlled loads. A load aggregator can also serve as a conduit between the controllable loads and the grid operator, allowing the regulated management to consider user and grid benefits simultaneously. When interfacing with the power market, aggregators are employed in power charging models for EVs to help optimize the batteries' charging as well as the modeling of driving patterns and price estimates [63]. As DERs are dispatched depending on compensation rates and power levels, an aggregator can stand in for them to maximize profits [64]. Furthermore, in [65], for a power market with bilateral contracts, the aggregator has the facility to select between various power plants based on power-cost-based offers.
- Grid stabilization and reliability: VPPs make a major contribution to the reliability and stability of the grid. VPPs maintain a stable and steady supply of electricity while minimizing the possibility of blackouts and voltage variations by balancing energy generation and consumption from various DERs [66]. They are able to provide ancillary services like frequency regulation and voltage management, which are essential for preserving grid stability [67]. The general stability and dependability of the electrical system are the responsibility of grid operators. In accordance with grid norms and standards, the grid operators work with VPP operators to incorporate DERs.
- Renewable energy integration: In 2016, in Paris, an emission reduction plan was enacted which has made the use of DERs very essential [68–70]. This integration is the VPP operator's responsibility. This is accomplished by coordinating the operation of diverse RERs, such as solar panels, wind turbines, and such that they work as a unified system. However, due to their erratic nature, integrating RESs into the power systems presents its own challenges [71, 72]. These challenges come about because of generation fluctuations due to weather conditions and time of the day. The variability adds complexity to power system operations. For instance, rapid changes in wind speed or cloud cover can result in fluctuations in generation, requiring grid operators to make quick adjustments to maintain system stability. VPPs take on this problem by combining several RESs and using intelligent management processes, they make it easier for the integration of the RESs effectively. They ensure the integration of these RESs to provide a steady supply of electricity while lowering reliance on conventional fossil fuel-based power plants.

Authors in [72] proposed a solution for integration of RESs into the grid to maintain power quality. This is important because RESs are becoming increasingly popular due to their environmental benefits, but they can also introduce power quality issues. This is a challenge that a VPP is sought to address. Large scale penetration of RESs means a hike in capital and operational cost. Authors in [73] discussed a mechanism that could aid in lowering the high cost of RESs integration and bringing electricity prices into affordable band. Spreading the benefits of renewable integration into the spheres of agriculture, where in [74], authors have created a mechanism to encourage energy-efficient agriculture by minimizing dependency on fossil fuels for water-table pumping. Through the aggregation and optimization of DERs, VPPs enable farmers to reduce their dependency on fossil fuels while enhancing energy efficiency and resilience in agricultural practices. This synergy not only fosters economic sustainability for farmers, but also contributes to the broader goal of renewable energy integration, paving the way for a greener energy future.

Successful integration depends on several important aspects. Forecasting methods that accurately estimate the patterns of RESs generation must be put in place [75, 76]. This allows better grid management and optimization of the DERs. The VPP employs such tools to better manage the generation of DERs. A summary of various forecasting techniques provided in the literature is listed in Table 2. Analysis of forecasting models to aid in the integration of RESs in the context of VPPs has been provided in [77].

Moreover, for optimal integration of RESs, the power grid must be modernized with smart technologies. Real-time monitoring, control, and communication between DERs and grid infrastructure are made possible using smart approaches like the VPP [16, 78, 79]. This improves the reliability and effectiveness of the grid. Additionally, VPPs provide beneficial grid functions, such as frequency regulation [67] and voltage control [80] in addition to balancing energy supply and demand [81]. These services boost the grid's dependability and resilience even more, promoting a stronger energy infrastructure that can handle the rising proportion of RESs.

The VPP approach to integrating RESs into the power grid is a cutting-edge strategy that is revolutionizing the way energy is produced, distributed, and consumed. VPPs offer an effective response to the problems caused by intermittent renewables by utilizing the combined potential of DERs and modern technology. VPPs will unquestionably be essential in advancing the transition to a cleaner, more dependable, and efficient energy system as the world progresses toward a sustainable energy future.

### DER technologies applied in VPPs

In VPPs, various DERs are used, including solar panels, wind turbines, ESS, EVs, and demand response loads. These DERs are aggregated and optimized within the VPPs, allowing for efficient management and coordination [55]. By harnessing the collective capacity of diverse DERs, VPPs enhance grid stability, enable renewable energy integration, and support demand response strategies, contributing to a more sustainable and flexible energy ecosystem. A VPP should ensure that DER integration keeps the system operating properly by ensuring

**Table 2** Forecasting techniques

| Refs. | Objective | Forecasting method used | Practical implications | Time scale | Software used |
|---|---|---|---|---|---|
| [82] | Probabilistic multi-period forecasting of DERs | CNN | Generate probabilistic forecasts | 24 h | N/A |
| [83] | Forecast DER production and consumption | ARIMA, Gradient boosting, random forest | Method can be used by TSOs and DSOs | 7 days ahead | N/A |
| [84] | Stochastic load and intermittency forecasting | | Optimizing the scheduling of DERs | N/A | MATLAB, |
| [85] | Focus on growth, development, and future of RESs | ANN, SVR | Power system planning | Real-time (15min) | N/A |
| [86] | Forecasting framework to predict electrical, thermal net load | Deep belief network-based | Design and develop efficient forecasting model | Day-ahead | N/A |
| [87] | Predicting wind power | Fuzzy logic, MPC | SG applications | Monthly | MATLAB, |
| [88] | Short-term load forecasting | Genetic algorithm | Future planning of the power system network | 24 h, 48 h | N/A |
| [89] | Wind speed forecasting | Neural network | Proper planning and operation | 24 h | MATLAB |
| [90] | To deal with the challenges of increased penetration of PV into the electric grid | Multi-layer perceptron | Smart grid and microgrid applications | 24 h | MATLAB |
| [91] | To predict accurate power generation from multiple RESs | CNN, LSTM, Auto regression | Power system planning | 24 h | N/A |

*CNN* Convolutional Neural Network, *ARIMA* autoregressive integrated moving average, *ANN* Artificial Neural Network, *SVR* support vector regression, *MPC* model predictive control, *LSTM* long short-term memory the stakeholders' continual consumption requirements [92]. Various DER technologies applied in VPPs in the reviewed literature are summarized in Table 3.

Out of the 15 References evaluated regarding DER technologies used in VPPs, it is evident from Table 3 that wind turbines and solar panels hold the largest share, as shown in Fig. 3. It proves how easily the technology of wind turbines and solar panels have been embraced. However, more renewables should be added to the energy mix to hasten the shift to a less carbon-oriented energy landscape.

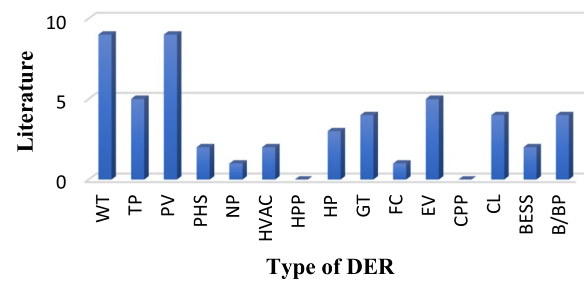

**Fig. 3** DER application in literature

#### VPP sustainability focus

One of the viable ways to address numerous Sustainable Development Goals (SDGs) of the United Nations (UN) and contribute to a more sustainable energy future is through VPPs. By encouraging the integration of RESs and boosting energy efficiency, VPPs, as a fundamental enabler of the energy transition, contribute significantly to achieving SDG 7 (Affordable and Clean Energy). VPPs promote the integration of sustainable energy into the power grid by aggregating and optimizing DERs thereby lowering greenhouse gas emissions and addressing climate change (SDG 13—Climate Action).

Additionally, through promoting technological advancements and innovation in the energy industry, VPPs provide a substantial contribution to SDG 9 (Industry, Innovation, and Infrastructure). VPPs promote grid modernization and improve overall energy infrastructure by integrating smart grid technologies, advanced analytics, and artificial intelligence. These developments result in more effective and adaptable energy systems, advancing the objectives of SDG 9 to develop robust infrastructure and encourage sustainable industrialization.

However, while VPPs offer considerable potential for achieving various SDGs, several challenges must be addressed to ensure their long-term sustainability. Access to VPP technologies must be equally available, as this can influence SDG 1 (No Poverty) and SDG 10 (Reduced Inequalities). For VPPs to be deployed in a way that supports SDG goals for eradicating poverty and minimizing inequality, marginalized people and neglected areas must be able to benefit from them. In simple terms, it is essential to make sure that everyone has an equal opportunity to profit from VPPs to realize SDG 1 and SDG 10. This calls for figuring out ways to make technology more accessible and inexpensive for everyone, especially those living in

**Table 3** DER technologies applied in VPP

| Refs. | WT | TP | PV | LU | PHS | NP | HVAC | HPP | HP | GT | FC | EV | CPP | CL | CHP | BESS | B/BP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [93] | – | – | – | – | – | – | – | – | – | – | – | ✓ | – | ✓ | – | – | ✓ |
| [94] | ✓ | ✓ | ✓ | – | ✓ | – | – | – | – | – | – | – | – | – | – | – | ✓ |
| [95] | – | – | – | – | – | – | – | – | – | – | – | ✓ | – | ✓ | – | – | – |
| [96] | ✓ | | ✓ | – | – | – | – | – | – | ✓ | – | ✓ | – | – | – | – | – |
| [97] | ✓ | – | – | – | –– | ✓ | – | – | – | – | – | ✓ | – | ✓ | – | – | – |
| [98] | – | – | – | – | – | – | – | – | – | – | – | ✓ | – | ✓ | – | – | – |
| [99] | ✓ | ✓ | ✓ | – | – | – | – | – | – | – | – | – | – | – | – | ✓ | – |
| [100] | ✓ | ✓ | ✓ | – | – | – | ✓ | – | – | ✓ | – | – | – | – | – | ✓ | – |
| [101] | – | ✓ | ✓ | – | – | – | – | – | ✓ | – | – | – | – | – | – | – | – |
| [102] | – | ✓ | ✓ | – | ✓ | – | – | – | – | ✓ | – | – | – | – | – | – | – |
| [103] | ✓ | – | ✓ | – | – | – | – | – | ✓ | ✓ | ✓ | – | – | – | ✓ | – | – |
| [104] | – | – | – | – | – | – | – | – | – | – | – | – | – | – | ✓ | – | ✓ |
| [105] | ✓ | – | | – | – | – | – | – | – | – | – | – | – | – | ✓ | – | ✓ |
| [106] | ✓ | – | ✓ | – | – | – | ✓ | – | ✓ | – | – | – | – | – | ✓ | – | – |
| [107] | ✓ | – | ✓ | – | – | – | – | – | – | – | – | – | – | – | ✓ | – | – |

*WT* wind turbine, *TP* turbine power, *PV* photovoltaic, *LU* load units, *PHS* pumped hydro system, *NP* nuclear plant, *HVAC* heating, ventilating, and air conditioning; *HPP* heat pump power, *HP* hydro power, *GT* gas turbine, *FC* fuel cell, *EV* electric vehicle, *CL* controlled load, *CHP* combined heat and power, *BESS* battery energy storage system; *B/BP* biogas/biomass power rural or underdeveloped areas. By doing this, VPPs may contribute to the development of a more just and sustainable energy future in which everyone, regardless of financial situation, has access to safe and dependable energy.

Furthermore, the environmental impact of VPPs [108] and their associated technologies require careful consideration to achieve SDG 12 (Responsible Consumption and Production). Lithium-ion batteries, which are used in ESS, are one example of a crucial mineral and material whose demand is on the rise, prompting questions regarding responsible sourcing, recycling, and end-of-life management. It is not a surprise that there has been extensive literature on ways to increase the lifespan of lithium-ion batteries [109]. Authors in [110] proposed a precise lifespan model for the battery cells used in VPP applications. To reduce the negative environmental and social effects of VPP deployment, sustainable methods must be implemented in material sourcing and VPP operation.

Moreover, numerous steps can be taken to guarantee the sustainability of a VPP itself. Stakeholders must work together to build supporting regulatory frameworks and financial incentives for VPP development. VPPs will become more widely available and long-lasting if investments are encouraged in their research, development, and implementation. This will also encourage technological breakthroughs and cost reductions. Also, a successful integration of VPPs into the energy economy depends on raising consumer awareness and engagement. The acceptance of VPP technology can be increased by educating consumers about the advantages of VPP participation, such as lower energy costs and increased grid reliability [111, 112].

To sum up, VPPs have a significant potential to help achieve several SDGs pertaining to renewable energy, tackling climate change, and sustainable infrastructure. They support SDGs 7 and 9 by fostering the integration of RESs and improving energy efficiency. To achieve more general sustainability goals, it is necessary to address issues with fair access to VPP advantages and responsible use and production. VPPs are critical enablers of a greener, more inclusive, and resilient energy future and can help accomplish specific SDGs by establishing supportive policies, encouraging innovation and consumer engagement. Using VPP's revolutionary potential in promoting the UN's sustainability agenda [113] requires advocating for and making contributions to their sustainable deployment and optimization.

#### Cybersecurity and data privacy

The protection of the grid's stability and dependability is one of the main justifications for prioritizing cybersecurity in VPP application. As crucial nodes in the grid, VPPs coordinate the functioning of DERs and provide a constant and reliable supply of electricity. A cyber-attack on a VPP has the potential to impair energy production, distribution, and grid management, resulting in power outages [114] and large financial losses.

The efficient operation of VPPs depends on data integrity [115]. For making decisions about the generation, distribution, and use of energy, VPPs depend on accurate data. Cybersecurity measures guard against data alteration or manipulation, ensuring that VPP operators have reliable data for maximizing energy resources and delivering crucial grid services. In order to increase consumer and prosumer confidence in VPP services, data privacy procedures on data collection and usage are essential [116].

VPPs are desirable targets for cybercriminals because of their crucial functions in grid management and their strength in the marketplace. VPPs are shielded by cybersecurity from a variety of dangers, such as malware and hacker attempts [117]. To address the cybersecurity issues, various approaches have been suggested and has been categorized by [118] as human and non-human approaches. Human approaches like updates and incremental patches installation aids in robust security posture, addressing vulnerabilities in software, but also require reboots causing downtime to regular operations. Engaging in customer interactions also creates awareness to recognize and respond to potential threats. However, allocating time and resources may be challenging for organizations with limited budgets and manpower.

Non-human approaches like the adoption of blockchain technology reduce the risk of single point failure as the technology operates on a decentralized network. This enhances resilience, making it more challenging for attackers to compromise the entire system. Another non-human approach is cloud computing which typically encrypts data during transmission and storage. This safeguards sensitive information from interception or unauthorized access.

Data privacy and cybersecurity are essential elements of VPP operations. They protect against cyberthreats, guarantee data integrity, enhance grid stability [119], promote consumer trust, enable regulatory compliance, and support the viability of VPPs financially. To ensure a secure, dependable, and sustainable energy future, cybersecurity and data privacy must be prioritized as VPPs continue to develop and broaden their role in contemporary energy systems [120].

#### Regulation and compliance

The operation of VPPs is greatly influenced by legislative or regulatory activities. This section will cover the regulatory structure that governs VPPs, emphasizing significant importance and their effects on the energy industry.

In the domain of grid integration standard and requirements, regulating bodies establish grid codes and integration standards that the VPP must adhere to when connecting to the electrical grid. The safe and dependable grid integration of DERs is ensured by these standards. The basis for secure VPP functioning is grid codes and standards. A manual for connecting DERs to the utility grid is provided by the IEC 62786. DER planning, operation, protection, and connectivity to distribution networks are the key applications. A global agreement on the use of DER in electrical power systems is being sought through the IEEE 1547 set of standards. This standard has received widespread acceptance on a global scale in outlining the requirements for the design, implementation, testing, and security of all sorts of DERs. Due to the increased penetration of DERs and the need to maintain system stability, the IEEE 1547 has recently been updated to IEEE 1547-2018 and IEEE 1547.1-2020 [121]. A crucial series of standards released to control the grid's interconnection and operability is the IEEE 2030. It is modified to implement cutting-edge communication and information technologies that provide interoperability solutions for the promotion of DER connectivity.

The European Committee for Electrotechnical Standardization (CENLEC), which is made up of 34 European Nations, oversees standardization efforts to increase commercial viability and foster technological growth. The CENLEC released the EN 50549-1 and EN 50549-2 DER integration standards with the goal of addressing all DER capabilities that are necessary for operation in tandem with distribution networks [121].

Also, there may be regional variations in regulations governing the integration of DERs with the grid [121]. For example, Canadian standards C22.3 No. 9 and C22.2 No. 257 offer technical advice for DER integration with the grid at medium and low voltage under 50 kV and low voltage systems under 0.6 kV, respectively. The British standard BS EN50438:2007 also offers technical advice for DER interconnection. The VDE-AR-N 4105 standard in Germany also offers technical recommendations for connecting DERs and low voltage systems. The JEAG.9701-2001 standard in Japan offers technical recommendations for distributed generating grid-connection. The standard permits DER owners to sell surplus energy to utility grids and mandates that power grids supply DER owners with backup power.

Various environmental and sustainability regulations may pertain to different jurisdictions [122], and they may provide incentives or requirements for VPPs to assist the integration of RERs and the reduction of emissions. In certain regions, these rules may have an impact on how VPPs function. The level of support for VPPs that use RERs may vary depending on the targets and incentives that jurisdictions set for renewable energy [123].

VPP operators and stakeholders must negotiate a complicated regulatory environment that is unique to their locations. It is essential for the implementation and operation of VPPs to comprehend and follow local legislations. Furthermore, as VPPs become more crucial to the world's energy landscape, regulators and industry participants must cooperate to unify rules and encourage uniformity in grid integration techniques across various jurisdictions.

#### Technical aspects of VPPs

The technical operations of a VPP involve a series of complex and coordinated processes to efficiently manage and optimize the aggregated DERs within the VPP. According to Ref. [124], the technical features of VPPs provide dynamic interaction for the integration of power distribution based on auxiliary services. These technical operations can vary depending on the specific architecture and goals of the respective VPP. This section of the paper delves into the technical intricacies of VPPs and explores their roles as key enablers in the transition toward a sustainable and resilient energy future. Some of these technical aspects of the VPPs are emphasized below:

- Resource optimization and scheduling: In a VPP, resource optimization and scheduling of various DERS are essential to achieve efficient and reliable energy management [28, 125]. It is also important to note that advanced algorithms and real-time data analytics [76] as summarized earlier in Table 2 are employed to forecast energy generation and demand profiles, ensuring dynamic resource optimization. The VPP intelligently dispatches DERs based on grid conditions and market signals, balancing supply and demand to enhance grid stability and maximize revenue generation [126]. By coordinating diverse DERs, VPPs optimize energy use, contribute to renewable integration, and support grid flexibility, making them crucial enablers in the transition to a sustainable resilient energy ecosystem.

  A summary of the relevant literature in accordance with resource optimization and scheduling is provided in Table 4.
- Load balancing and grid support/ancillary service: The load balancing and grid support functions of a VPP are very crucial [135]. The VPP dynamically modifies energy generation and consumption to fit grid demands by aggregating and optimizing vari-

**Table 4** Resource optimization and scheduling

| Refs. | Objective | Method | Practical implications | Limitations |
|---|---|---|---|---|
| [127] | Minimizing generation cost | Stochastic optimization, Markov-chain | Increase efficiency and utilization of RESs | Few RESs |
| [128] | Maximizing net profit | MILP | Provides a model for scheduling a VPP | Perfect assumption of uncertain parameters |
| [129] | Efficient utilization of energy | Fuzzy chance-constrained programming | Improve efficiency and sustainability of the power system | Data privacy |
| [130] | Optimal self-scheduling plan for VPPs | Robust optimization | grid stability and reliability of power system | Assumption of perfect wind power generation |
| [131] | Management and scheduling of MGs in VPPs to optimize the system efficiency | ANN | Grid decarbonization | Data privacy |
| [79] | Smart energy management | PLC, IoT | Dispatching energy optimally to achieve profit | Only validated through simulations |
| [132] | Optimal dispatch to minimize expected cost | MILP | Improved energy management | Computational complexity |
| [116] | Optimize residential users' energy scheduling for optimal energy management | Blockchain | For DER integration | Coordination and cooperation |
| [133] | Real-time smart energy management | Hybrid PSO | Energy management | Simulation only |
| [134] | Day-ahead energy management for aggregate prosumers | Column and constraint generation algorithm | Energy management | Real-world experiment |

*ANN* Artificial Neural Network, *IoT* Internet of Things, *MILP* Mixed Integer Linear Programming, *PSO* Particle Swarm Optimization, *PLC* Programmable Logic Controller

ous DERs. While storing excess energy during times of low demand, the VPP can supply additional power from DERs during times of peak demand to balance out high demand. This load-balancing ability makes VPPs essential for guaranteeing a dependable and resilient electricity supply since it improves grid stability, lowers grid stress, and adds to overall grid support.
In addition to its role of aggregating and optimizing DERs, a VPP offers a range of essential ancillary services. These services include frequency regulation. This is achieved by maintaining grid frequency within acceptable bounds through rapid power adjustment [136–139]. VPPs also provide voltage support by injecting or absorbing reactive power to stabilize voltage levels [80, 140, 141].

Moreover, VPPs contribute to peak regulation, managing demand during high load periods to alleviate grid stress [142–144]. The comprehensive suite of ancillary services offered by VPPs ensures grid stability, enhances reliability, and facilitates the integration of RESs, making them vital assets in modern power systems.

- Demand response and load management: A VPP inherent components of demand response and load control enable effective energy usage. By actively communicating with connected consumers to alter electricity consumption in response to grid circumstances and price signals, VPPs participate in demand response. In order to avoid peak demand times and lessen grid load, VPPs optimize the scheduling of operations and equipment that consume a lot of electricity [59, 81, 96]. This demand-side flexibility not only supports grid stability, but also empowers consumers to actively participate in energy conservation, contributing to a sustainable energy ecosystem [66, 145]. The VPP's ability to efficiently balance energy supply and demand through demand response and load management strategies makes it a pivotal stakeholder in modern power systems.

The technical aspects of VPPs represent a dynamic and transformative force in the energy sector. VPPs provide effective renewable energy integration, grid stability, and demand response capabilities by aggregating and optimizing various DERs.

### Market/economical aspect of VPP

VPPs provide an appealing scenario for the future of energy systems in terms of their commercial and financial prepositions. VPPs can completely alter the economics of electricity generation and consumption as they are dynamic aggregators of various DERs. VPPs maximize the use of DERs, optimize income generation, and improve participation in the energy market [11]. The VPP does this via real-time data analytics, complex forecasting algorithms, and clever energy trading methods. As a result of their capacity to offer a versatile and dispatchable portfolio of assets (DERs), VPPs are better equipped to meet swiftly to dynamic market conditions, such as energy pricing and demand patterns. VPPs deliver a strong economic case for sustainability, affordability, and resilience in the energy ecosystem by making it possible to efficiently deploy renewable sources of energy, support demand response programs, and provide ancillary services to the grid. VPPs technology's commercial implications hold significant promise for developing a more effective, competitive, and customer-focused energy landscape as it continues to advance.

Currently, the majority of jurisdictions have already started deregulation or liberalization and competition-opening process in their individual power markets [11]. In order to finance new infrastructure investments, increase the economic efficiency of power company operations, and particularly lower the ultimate prices of electricity delivery, deregulation or privatization has been advocated [146]. A vertical structure as stipulated by [146], where all activities were merged, was replaced with an organization where generation, transmission, distribution, and commerce work separately as a result of this reform in the energy sector.

Additionally, the large integration of renewables into the power grid that characterizes the contemporary energy landscape suggests a greater need for the system's balancing mechanism due to the random nature of the RESs generation schedule. One significant benefit of VPPs is that they boost their shared profit by selling energy on behalf of the DER owners to improve the balancing mechanism when they access the wholesale electricity markets. The participation of VPPs in various electricity markets is covered in this section.

- Day-ahead market: Day-ahead market refers to the buying and selling of electricity on the day before the actual production and delivery. VPPs actively participate in the day-ahead market by supplying their aggregated portfolio of DERs for electricity trading. VPPs forecast energy generation trends for the next day using advanced forecasting and data analytics. Based on these insights and market prices, VPPs strategically bid these aggregated resources to optimize revenue generation [84, 147–151].
- Ancillary service market: VPPs actively participate in the ancillary services market by providing critical assistance to the electric grid. The VPP does this by dynamically altering the output of their aggregated DERs. VPPs respond in real-time to grid signals to maintain stability, assure a continuous power supply, and improve grid reliability. With this, VPPs play an important role in supporting grid operations and optimizing grid performance. Several studies have incorporated the ability to engage in ancillary services markets into VPP modeling in order to enable regulation that ensures the security of electricity supply [26, 143, 150, 152–156].
- Reserve market: In the reserve market, VPPs actively participate by offering their combined output of DER as a reserve capacity to support the grid's reliability. VPPs reserve a portion of their generated power from the DERs, ready to be dispatched within short notice to address sudden changes in electricity demand and supply or even an outage of grid operator's outage of generators. By participating in the reserve market, VPPs offer a valuable and flexible solution for grid operators to maintain grid reliability. As VPP technology advances, their involvement in the reserve market will become ever more vital in contributing to the efficient and secure operation of the electric grid. Various strategies to make ideal or optimal reserve market decisions have been studied in several papers. According to the findings of these studies, the reserve market is more significant at times of peak demand since a contingency can have a higher impact [26, 127, 157–160].
- Intra-day/real-time market: The VPP actively participates in the intra-day market by precisely adjusting the energy traded in the day-ahead market. The VPP strategically optimizes its DER dispatch and offers flexible resources in response to dynamic market prices and grid needs [11].

Although intraday markets enable VPPs to adjust scheduled energy after the day-ahead market, an exchange power imbalance may still emerge as the dispatch time approaches. VPPs can thus participate in real-time balancing markets to avoid penalties. The goal of the real-time market is to reduce the imbalance errors and their associated cost. The various electricity markets in which the VPP participates are provided in Table 5 to outline the key characteristics. Figure 4 also gives a graphical analysis of the key characteristics of the electricity market that the VPP operates in.

#### Real-world implementation of VPPs

VPPs in the real world provide fascinating insights on their revolutionary impact on contemporary power systems. VPP implementations around the world demonstrate their adaptability in maximizing DERs. These examples elaborate on the value of VPPs in grid stability, renewable generation, and demand response. VPP projects are becoming more common, proving their

**Table 5** Electricity market characteristics

| Refs. | Electricity market | Characteristics |
|---|---|---|
| [84, 147, 150, 151, 155] | Day-ahead market | 24 h ahead energy market participation |
| [26, 143, 150, 153–156] | Ancillary market | Generation and demand balancing |
| [26, 157–161] | Reserve market | Responding to unexpected events such as generator loss |
| [43, 162–166] | Intra-day market | Modifying energy traded in day-ahead market |
| [147, 167–171] | Real-time market | Managing deviations in the day ahead and intraday markets |


**Fig. 4** Electricity markets characteristics

potential to revolutionize energy systems. The VPP market is expected to grow from $1.3billion in 2019 to $5.9billion in 2027, with a compound annual growth rate of 21.3% from 2020 to 2027 [25]. In Norway, Statkraf is the world's largest VPP with a capacity of 10GW from over 1000 aggregated assets. Recently, Tesla announced to scale up the south Australia VPP which connects assets from 4000 to 50,000 homes, which will make it the world's largest VPP [172]. Storing and distributing power from residential and commercial customers, Tesla's Powerpacks and Powerwall promote grid dependability and the integration of renewable energy. These real-world examples demonstrate how important VPPs are in creating a global energy ecosystem that is robust, efficient, and sustainable. Selected real-world applications [124, 172] are summarized in Table 6.

Applications of VPPs in the real world have offered an important lesson that will guide their development, deployment, and scalability. Key insights from these applications include the following but not limited to:

- Flexibility and scalability: The significance of developing flexible and scalable systems has been shown by the successful VPP deployments. VPPs support a variety of DERs and adjust to shifting market dynamics and grid conditions.
- Integration of DERs: For the VPP to operate at its best, several DERs must be integrated into a single, coordinated system. Advanced data analytics and control algorithms are essential for managing DERs efficiently and maximizing their contributions, as demonstrated by real-world applications.
- Interoperability and interconnection: VPPs generally operate in sophisticated energy ecosystems with a variety of stakeholders. Smooth VPP integration and operation require interoperability and seamless interconnection with grid operators, and other market participants.
- Market participation: The significance of active market participation has been emphasized by real-world VPP applications. Using effective energy trading

**Table 6** Summary of real-world VPP applications

| Name of VPP | DER type | Aggregated assets | Capacity | Geographical operation | Investments | Year of commencement |
|---|---|---|---|---|---|---|
| Nextkraftwerke | Biogas, CHP, PV, ESS, WT | 9000 | 7700 MW | Germany, Belgium, France, Austria, Italy, Netherlands | N/A | 2009 |
| Fenix Project | CHP, WT | 1000 + | 0.168 GW | UK, Spain, France | $17.4 m | 2005 |
| WEB 2 Energy | CHP, PV, WT, Biogas | 16 | 40.5 MW | Germany, Poland | N/A | 2009 |
| EDISON | EVs | 52 | 125 MW | Denmark, Germany | N/A | 2011 |
| ConEdison | PV, Battery storage | 1000 | 100–300 MW | USA | -N/A | 2016 |
| Zhangbei | PV, WT, ESS | About 500 | 49.5 MW | China | -N/A | |
| AGL VPP | Batteries, PV | 1000 | 5 MW | Australia | $19.5 m | 2017 |
| SA Tesla VPP | Solar panels, Batteries | 4000 | 250 MW | Australia | $66 m | 2018 |
| Statkraft | Wind turbines, Solar panels | 1000 | 10 GW | Norway | N/A | 2007 |
| OhmConnect | Solar panels | 1000+ | 550 MW | California | $20 m | 2014 |
| SunRun | Solar panels | About 8000 | 990 MW | California | $50 m | 2007 |

*CHP* combined heat and power, *ESS* energy storage system, *PV* photovoltaic, *WT* wind turbine

techniques and intelligent bidding in electricity markets. VPPs can maximize income production and assist the integration of RESs at a fair price.

The ongoing development and deployment of VPPs can be improved by taking lessons from these practical applications, ensuring that they continue to contribute to a sustainable, effective, and decentralized energy future.

However, despite the successes chalked up by these projects, there are still challenges that must be addressed. Cybersecurity threats, consumer engagement, data management and analytics, achieving a positive return on investment and profitability are some of the model challenges that these projects face. Collaboration between stakeholders is necessary to overcome these obstacles.

## Conclusions

VPPs have become transformative solutions revolutionizing the modern energy landscape. Applications in the real world have sounded their importance and have also demonstrated the adaptability and advantages of VPPs. VPPs have shown that they can promote the integration of renewable energy sources, aggregate and optimize a variety of DERs, and facilitate effective demand response.

Flexibility and scalability, which enable seamless adaptability to shifting grid conditions and market dynamics, have been shown to be essential for successful VPP adoption. VPPs have been able to improve cost-effective renewable energy integration and optimize revenue generation through active market participation and smart bidding tactics. Additionally, for VPPs including residential or commercial participants, consumer engagement and education are crucial for assuring buy-in and demand response programs.

Embracing the lessons learnt in the referenced literature, a VPP stands as a pivotal enabler in our journey towards a sustainable, decentralized, and resilient energy future. There can be an effective and customer-focused energy ecosystem that leads the path for a greener and more sustainable society by fully utilizing VPPs and maximizing their important contributions.

The ability of VPPs to maximize DERs, boost renewable energy integration, and improve grid stability makes them a crucial element in reaching a sustainable energy future. A VPP has the undisputed potential to change the energy landscape. The successful operation of VPPs in the modern era depends on a judicious blend of cutting-edge technology, supportive regulatory frameworks, and seamless connectivity with the existing electricity infrastructure. The aggregation and control of various DERs can be optimized by using real-time data analytics, artificial intelligence, and smart grid technologies. However, VPPs must overcome several obstacles, such as data security, grid interconnection, and scalability to realize their full potential. In a dynamic energy environment, taking care of these issues is essential to ensure the proper operation of VPPs.

Also, the development of flexible regulatory frameworks that support VPP implementation and market involvement is essential for the efficient operation of VPPs. The seamless integration of VPPs into current energy markets and the promotion of novel business models are made possible by clear regulations on market access, price structures, and grid services. Overall, an effective operation of VPPs in this era and beyond will depend on the following:

- Advanced technological integration such as data analytics, smart grid technologies which are vital real-time data processing, accurate forecasting, and efficient optimization.
- Regulatory support to encourage supportive and accommodative regulatory frameworks that will promote VPP deployment, and market participation.
- Implementation of robust data security measures to protect sensitive information, guarantee consumer privacy, and safeguard against potential cyberattacks.

Implementing these recommendations will help shape and harness the potential of VPPs to transform the energy industry. With correct planning, VPPs will significantly contribute to the modern era's goals of energy resource optimization, grid stability enhancement, and improved integration of RESs.

**Abbreviations**

| | |
|---|---|
| ANN | Artificial Neural Network |
| B/BP | Biogas/biomass power |
| BESS | Battery energy storage system |
| CHP | Combined heat and power |
| CNN | Convolutional Neural Network |
| CL | Controlled load |
| DERs | Distributed energy resources |
| DG | Distributed generation |
| DSO | Distribution system operator |
| ESS | Energy storage system |
| EU | European Union |
| EVs | Electric vehicles |
| FC | Fuel cell |
| GT | Gas turbine |
| HP | Hydropower |
| HPP | Heat pump power |
| HVAC | Heating, ventilation, and air conditioning |
| IoT | Internet of Things |
| LSTM | Long short-term memory |
| LU | Load units |
| MGs | Microgrids |
| MILP | Mixed Integer Linear Programming |
| MPC | Model predictive control |
| NP | Nuclear power |
| PHS | Pumped hydro storage |
| PLC | Programmable logic control |
| PSN | Power System Network |
| PSO | Particle Swarm Optimization |
| PV | Photovoltaic |
| RERs | Renewable energy resources |
| RESs | Renewable energy sources |
| SDGs | Sustainable Development Goals |
| TP | Thermal power |
| TSO | Transmission system operator |
| UN | United Nations |
| VPP | Virtual power plant |
| WT | Wind turbine |

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Not applicable.

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**Competing interests**
The authors declare no competing interests.

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