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Review Article

Comprehensive review of VPPs planning, operation and scheduling considering the uncertainties related to renewable energy sources

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Abstract: The penetration of renewable energies in the energy market has increased significantly over the last two decades due to environmental concerns and clean energy requirements. The principal advantage of renewable energy resources (RESs) over non-RESs is that it has no direct carbonisation impact on the environment and that it has none of the global warming effects which are caused by carbon emissions. Furthermore, the liberalisation of the energy market has led to the realisation of the virtual power plant (VPP) concept. A VPP is a unified platform for distributed energy resources that integrates the capacities of various renewable energies together for the purpose of improving power generation and management as well as catering for the buying and selling of energy in wholesale energy markets. This review study presents a comprehensive review of existing approaches to planning, operation and scheduling of the VPP system. The methodologies that were adopted, their advantages and disadvantages are assessed in detail in order to benefit new entrants in the power system and provide them with comprehensive knowledge, techniques and understanding of the VPP concept.

1 Introduction

The penetration of renewable distributed energy resources (DERs) and distributed generators (DGs) in the energy market has shown significant growth. Typically, this is due to the following factors: carbonisation of the environment, pollution and clean energy supply and demand requirements. These are the fundamental concerns that must be resolved considering the ongoing power supply and demand requirements [1–5]. The above-mentioned environmental concerns are stimulating, encouraging and intensifying the growth of DGs. Furthermore, the constant process of liberalisation of power markets, i.e. the gradual transformation of conventional markets into non-conventional ones, drawing large amounts of attention to institutions, scientists and researchers because the renewable energy resource (RES) are inexhaustible, environmentally friendly, pollution free and can be maintained locally [6–8].

The output of renewable DERs and DGs such as wind turbines (WTs) and photovoltaics (PVs) systems are heavily dependent on climate change, their output is variable and unpredictable as well as location constrained; therefore, the operational performance of the power system will be affected. This impact is closely associated with the DGs units (placement, size and types). Owing to unknown input parameters of DGs may add some grave complexities to the power system such as immense voltage fluctuation; hence, serious voltage quality problems. Therefore, the increase in voltage is a significant restriction on the rising share of sustainable energy resources in the electricity market, posing numerous challenges. To address these challenges, one way is the integration of DER units into virtual power plants (VPPs) [9–11].

A VPP is a modular designed entity based on software communication technologies which efficiently integrates, organises and manages decentralised generation, storage and consumption through a smart energy management system (EMS) [12, 13].

A VPP provides an aggregated platform for DER units. The EMS system of the VPP has the ability of risk aversion, is able to compensate the dropout of DER in real time and shows robustness to the variability of DER output. RESs play a key role in the power sector, but the challenge associated with RES is their intermittent nature [14]. The output of RES is variable and uncertain as it depends directly on the prevailing climate conditions; consequently, the amount of RES fed into the grid is difficult to predict. The stability of the grid requires a balance between power generation and consumption because electrical energy cannot be stored on a large scale.

A VPP supports the coordination of power generation and consumption more effectively. It provides a balanced system of supply and demand adjustment with a high degree of accuracy and facilitates the storage of energy, which creates the potential for the application of renewable energies application in the power sector [15, 16].

Hence, there is a huge opportunity for the VPP to connect the operational technologies with communication technology and also with external data assets, thereby collecting the forecasting data from dispersed units. Moreover then, a VPP will be able to have deep insights into the data, offer better and faster decision and real-time action for performance improvements.

Unlike VPP, a Microgrid tends to be inward looking and static then VPP. A VPP can only be created if there is a market to sell its power and services whereas MC can be created anywhere and is not as dependent on market structure. A microgrid can be disconnected from the main grid, while VPP cannot. However, once an MC starts to sell its services such as demand response then it becomes a VPP.

The key purposes of VPP are to provide the following opportunities to participating partners [17–21]:

(a) *Energy trading***:** They provide new ways and economically viable energy trading opportunities to DG owners in the competitive wholesale electricity markets.
(b) *Network services:* They provide system support facilitation services to transmission and distribution system operators.
(c) *Balancing services*: They balance production and consumption demand, utilising multiple markets simultaneously in real time. This results in economic, technical and environmental benefits for all participating partners.
(d) *Optimising:* Optimisation of production and consumption inside the VPP itself.

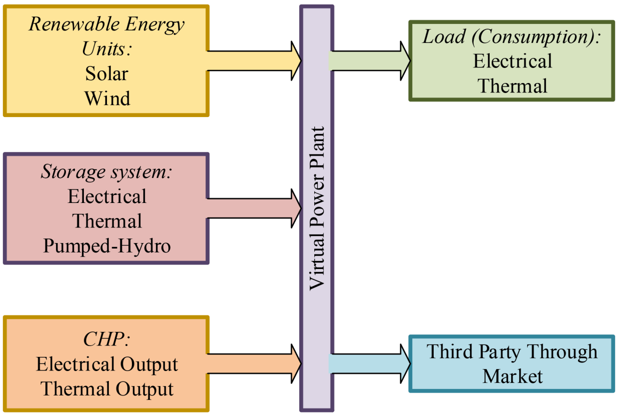

Fig. 1 *VPP structure*

1.1 Smart energy hubs

A smart energy hub is a multiple energy hosting systems which consists of many sources of energy conversion, energy storage or network technologies, and is controlled locally [22]. In comparison to a standard energy hub, a smart energy hub is more advanced as it is more sustainable in the features due to managing the energy sources more efficiently, it does this by combining both electricity and gas networks and outputting one source of energy by combining both networks. This is more efficient in comparison with a normal energy hub as that is unoptimised for storing multiple energy inputs [23], a fully automated system for smart energy hub is presented [24] and this system is based on a reinforced learning algorithm which helps encourage residential users to accept demand-side management (DSM) programmes in an effort to reduce their bills. In [25], in the energy hub formation, communication between the multi-energy carriers are thought of in providing the required load. The proper integration and selection of inputs and outputs advance toward a more optimised and efficient consumption rate. Smart energy hub frameworks are thought [26] to be more efficient and revolutionary because they maximise company profit while lowering customer bills as they allow customers to control and regulate their energy and gas data. A bi-level multi-energy system is suggested in [27]. On the basis of the energy retailers and consumers with load, in this energy system the retailer markets their price for multiple energy carriers to increase their expected profit. Users react to the marketed prices by managing their expenditure in the retail market to minimise their energy bill. The model results show a healthy reduction in the energy generation cost and the user's utility bill making it evident that both sides benefit from the system.

1.2 VPP definitions

The most contemporary concept of VPP has many different definitions in the literature. All of them agree on the fact that the concept of the VPP is a collection of dispersed heterogeneous DG units of various technologies that function as a unique power plant with the capability of controlling and coordinating the integrated units in order to maintain optimal power flow among these units and acquire better operational ability of the system [28].

According to Plancke *et al.* [29], a VPP is a set of aggregated DER units that can be managed and coordinated from a central entity, connected either to a distribution network or a transmission network, able to contribute and participate in the wholesale electricity market, providing ancillary services to distributed system operators (DSO's) and transmission system operators (TSOs). In accordance with Navigant Research, a VPP is a smart grid network that happens to link wholesale markets with retail markets. Achieving the greatest profit for DER asset owners is the primary goal of the VPP, linking with the primary goal the VPP also has to try and do so trying to maintain the balance of the electrical grid at the smallest environmental or economic cost [30]. According to Pudjianto *et al.* [18], a VPP is a distributed power plant which is cloud based; this power plant can aggregate the capacity of diverse DERs for the enhancement of power generation as well as the enhancement of its selling and buying powers on the electrical market. According to El Bakari and Kling [31] in the European Union, a VPP normally refers to an amalgamation of supply-side resources, most likely in a diverse pool of wholesale renewables. According to Abdelaziz *et al.* [32] in the USA, a VPP typically refers to demand response tap utility or peak critical pricing programmes itself as resources that when amalgamated can perform the essential features of conventional power plants unlocking the ability to deliver peak capacity, grid reliability services of regulation when requested by an independent or utility system operator. Fig. 1 represents the structure of a VPP.

1.3 VPP components

An ideal VPP system is composed of three components including DG units, energy storage components and information and communication technologies (ICTs). Their types, applications and advantages are explained in detail as follows [33]:

(a) *DGs:* In the recent past, the applications of DGs in the power sector have enormously increased. There are three reasons for this: they are small-scale power generation and storage units located close to the customer sites, the deployment of DGs reduces transmission network losses and they can improve the viability of grid and quality of power. The penetration of DGs and their significant contribution to the power sector are commonly acknowledged. It is acknowledged that the penetrations of DGs and its significant contribution in the power sector. DGs can be classified according to their applications. According to Pudjianto *et al.* [18], Plancke *et al.* [29] and Mashhour and Moghaddas-Tafreshi [34], the general types of DERs are combined heat and power (CHP), biomass, hydro-based energy generation, WTs and PVs.

(b) *Energy storage elements:* Energy storage elements play a vital role in the VPP functioning especially in case of RESs such as WT and PV systems because they depend on weather conditions and their output is greatly uncertain and variable. The energy storage system provides a smart way of energy storage that captures and stores solar and wind power and deliver it when it is needed most. In this way, it balances the supply and demand requirements. Energy storage system (ESS) can be classified according to their applications. According to El Bakari and Kling [31] and Ghavidel [33], the general storage elements are hydraulic pumped energy storage, compressed air energy storage, flywheel energy storage, battery energy storage and super capacitor energy storage.

(c) *ICTs:* ICTs are playing a decisive role in EMS. they manage all other elements of the VPP in bidirectional ways. ICTs are used to receive the data from dispersed RES, storage elements and consumption units. They ensure the coordination and smooth flow of energy among the VPP components. According to Abdelaziz *et al.* [32], the key systems of ICTs are an EMS, supervisory control and data acquisition and direct digital control.

1.3.1 Energy management system: The EMS is the technological core of the VPP. It is a key element of the VPP establishing a robust and sustainable energy data management system. EMS is capable of collecting, storing and analysing data from diverse remote monitoring devices in order to calculate the optimal operation schedules for electricity producers and consumers. Therefore, a VPP adopts the application of smart EMS system to coordinate, communicate and control all the activities taking place internally as well as externally [18, 34]. The key responsibilities of EMS are forecasting of the DER units' output power, forecasting of the controllable loads, power flow coordination among the VPP components, management of DG units and management of storage and consumption units. The purpose of EMS is to accomplish one of the following objectives [33]:

- To reduce energy production cost.
- To reduce power losses in distribution or transmission network.
- To reduce greenhouse effects.
- To increase the profit margin of energy.
- To enhance energy quality.

The pictorial representation of EMS of the VPP is presented in Fig. 2.

According to system support facilitations services and participation in a liberalised energy market; typically, a VPP architecture can be implemented in four steps:

(i) Forecasts for renewable energy generation and demand are made. Response units are generated.
(ii) Stochastic optimisation is run to determine market offers and bids.
(iii) On the basis of commitments and updated forecasts, unit commitment optimisation adjusts DER operation.
(iv) A controller is used to reach commitment target.

The remaining of this paper is outlined as follows. Section 2 describes the classifications and implementation challenges of the VPP. Section 3 describes various VPP projects. Section 4 presents planning, objectives and optimisation of the VPP. Section 5 describes uncertainties and uncertainty handling techniques including Monte Carlo method (MCS), auto-regressive moving average method (ARMA), point estimate method (PEM) and robust optimisation (RO). Section 6 explains the operational literature of the VPP, market participation and arbitrage strategy adopted by the VPP and the concluding remarks are made in Section 7.

1.3.2 Benefits of the VPP: The benefits originating from the concept of the VPP can be grouped among different stakeholders [28, 29]. In this section, the possible benefits associated with VPP will be arranged into the point of views of different entities interfacing with the power system. These benefits are more clearly and precisely illustrated in Fig. 3 [18, 30, 35]:

(a) VPP offers benefits to policy makers:

- Reduces global warming.
- Offers extra choices to consumers.
- Creates new business opportunities and employments.
- Improves wide deployment of DER units.
- Opens new windows for small-scale energy producers [28].

(b) VPP offers benefits to suppliers and aggregators:

- Minimises the economic risk of both the suppliers and aggregators.
- Creates new offers for both buyers and DERs.
- Reduces investment on distribution grids.
- Neutralises possible deviation in the prediction of energy supply and demand.
- Provides energy efficiency due to loss reduction on transmission network [29].

(c) VPP offers benefits to energy consumers:

- Enhances customer experience.
- Improves energy supply reliability to consumers during outages.
- Provides resiliency services to customers.
- Improves the quality of energy supply services.
- Integrates vehicle in the power systems.
- Reduces greenhouse gas emissions [34].

(d) VPP offers benefits to DSOs and TSOs:

- Provides ancillary services to system operators.
- Creates better coordination between DSO and TSO.
- Reduces grid investments.
- Reduces the operation of complex and inflexible distribution generation.
- Offers visibility to DER units in distribution or transmission network operation [1].

(e) VPP offers benefits to DER unit's owners:

- Cost reduction on energy market entry and operation.
- Real-time visuals of individual DER units in the energy market.
- Creation of space in the energy market for small-scale participants.
- Minimal financial risk of small producers through aggregation.
- Enhancement of assets' value of small producers in energy markets [31].

2 Classification of the VPP

For the purpose of specialisation, VPP functionalities can be grouped into two distinct entities, commercial VPP (CVPP) and technical VPP (TVPP). These two entities function in partnership to accomplish the optimal operation of the VPP [28, 29, 34]. The functionalities and responsibilities of both these entities are illustrated in Fig. 4.

TVPP: TVPP is accountable for the smooth and accurate functioning of DGs, energy storage units and controllable loads, regulating energy flow among VPP coalitions and ancillary services [18, 35]. TVPP collects data, transferred from CVPP about bilateral contracts of DG's and the consumption units. The received data must contain: (a) supply and demand prediction, (b) placement of DG units and consumption, (c) placement and size of energy storage units and (d) highest capacity of individual DG unit [29, 30]. TVPP ensures the correct and secure operation of the power system considering the physical constraints and system support facilitation services offered by the VPP. DSO's are responsible to maintain security and stability of distribution network, whereas TSO's are responsible for the bulk transmission of electric power on the main high-voltage electric networks [36]. The following functionalities are provided by TVPP [34]:

- It determines fault location.
- It provides maintenance facilitation services.
- It continuously monitors assets.
- It offers balancing services, management of local network and implementation of ancillary services.
- It offers visibility to DER units in energy markets.
- It ensures that the power system is operating in an optimal safe way.

CVPP: A CVPP deals with the amount of energy and its prices that it can supply to the electricity markets. A CVPP focuses on bilateral contracts between the DG units and the consumption units. The bilateral contract information should be sent to TVPP to take out the contracted power from the system [29, 32]. Small-scale energy producers were not able to participate individually in energy markets. Therefore, CVPP makes their participation possible in energy markets [30, 35, 37]. The functionalities of CVPP can be summarised as [34]:

- Trade dealing in the wholesale electricity markets.
- Selling DERs' power in the electricity markets.
- Power production and consumption forecast of the VPP.
- Preparation of DER bids and their submission to the electricity markets.
- Optimisation of daily schedule production.
- Balancing trading portfolios.
- Visualisation and participation of DER units in electricity markets.

To accomplish the aforementioned objectives, CVPP works together with the following entities:

- *DER:* The main target of DER is balancing supply and demand gaps. Its generation must be well-planned predicted and it must pass on that information to TVPP.
- *TSO:* The key responsibility of the TSO is to maintain supply and demand requirements and manage the transmission network without any interruptions.
- *TVPP:* It manages the data transferred from CVPP, optimising the information and operational reliability of the VPP and its interaction with the central grid.

2.1 Challenges to the implementation of the VPP

There are several implementation challenges faced by VPP. These can be listed into four main categories: (a) technical, (b) environmental, (c) regulatory and (d) commercial solving the above-mentioned challenges can facilitate an adequate utilisation and performance improvement of the VPP system [10, 38]. These challenges are presented and illustrated in Fig. 5:

Technical challenges: Technical challenges are related to voltage drop, unplanned outage, system capacity and transmission and distribution network operation. To achieve optimal results, the transmission and distribution network operators should deal optimally with the power network system. Improving power quality/profile, reducing transmission losses and enhancing distribution network capabilities may lead to reliable and stable operation of transmission network ensuring non-stop supply of power to active users without interruption [39].

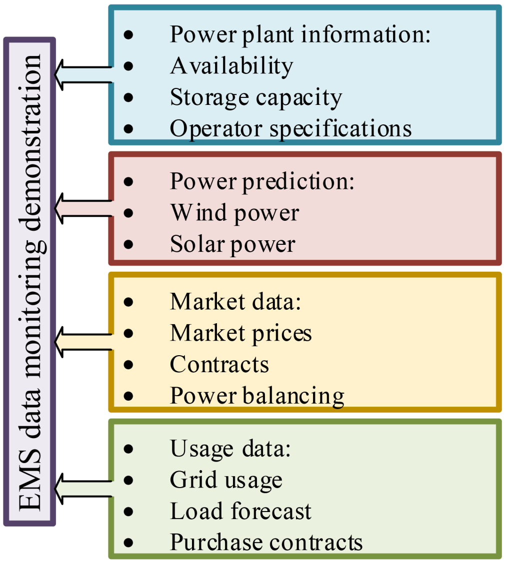

Fig. 2 *EMS*

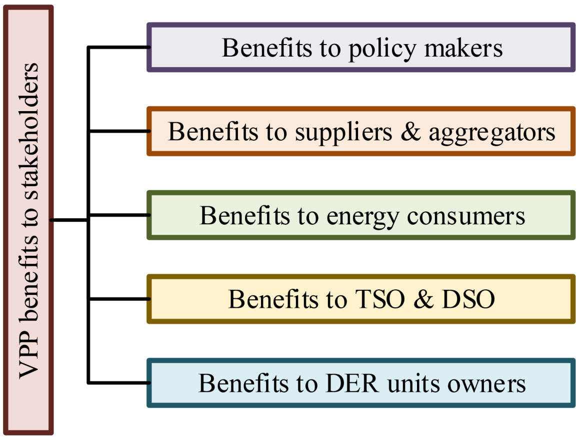

Fig. 3 *Benefits of the VPP*

Regulatory challenges: Owing to the lack of obvious governmental regulations, it is imperative to formulate and develop long-term fruitful governmental policies and appropriate regulations in order to support and facilitate small-scale participants in the liberal energy market [13].

Environmental: Environmental challenges faced by the VPP are related to dispatchable technologies such as WTs. When we integrate such kind of technologies run by fossil fuel also have a notable effect on the environment, these challenges are basically associated to fossil fuel technologies currently operating in power markets, which can have an adverse impact on the environment. They can also create a notable greenhouse effect, and hence damage the environment; therefore, it is essential to assess every operating technology implementation carefully [10, 40].

Commercial challenges: Commercial challenges are related to market structure, market forces and market prices. New commercial management methods need to be implemented to manage and support small-scale energy producers in the distribution network and minimise their cost associated with network maintenance and operation. Incentive strategies need to be implemented in order to reward renewable DG producers. Incentive strategies have recently been adopted in the USA. Currently, market structure and pricing strategies are based on a complex mechanism. Market accessibility mechanisms should be made simple, easy and affordable for maximum participation [41].

3 VPP projects

(a) *EU-project flexible electricity networks to integrate the expected energy evolution (FENIX)*: October 2005 was the month that started a four-year project called FENIX. This ‘14.7 million euro’ project had 20 partners involved all working together to create and design new control and communication devices to simulate the VPP approach, with the ultimate goal of solving system problems with the DER and making them an efficient and optimised solution to our current electrical supply system [42]. This was used as part of the VPP due to DER units being high in volume and low in size making them difficult to manage one by one; fortunately, the VPP counters this difficulty by collecting DER units together forming a cluster so that they can be managed much more easily. FENIX then began to further push their VPP concept to then allow mass scale aggregation of the DER units ultimately allowing the VPP to provide commercial as well as technical services [37, 43].

Demonstration: The operational performance and ability of the FENIX project were simulated in the EDF energy networks in the

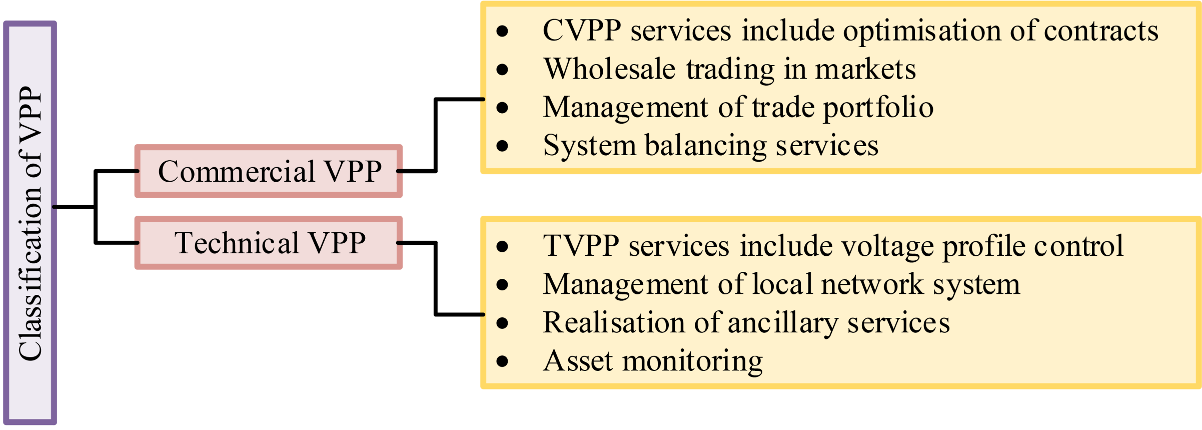

Fig. 4 *Classification of the VPP*

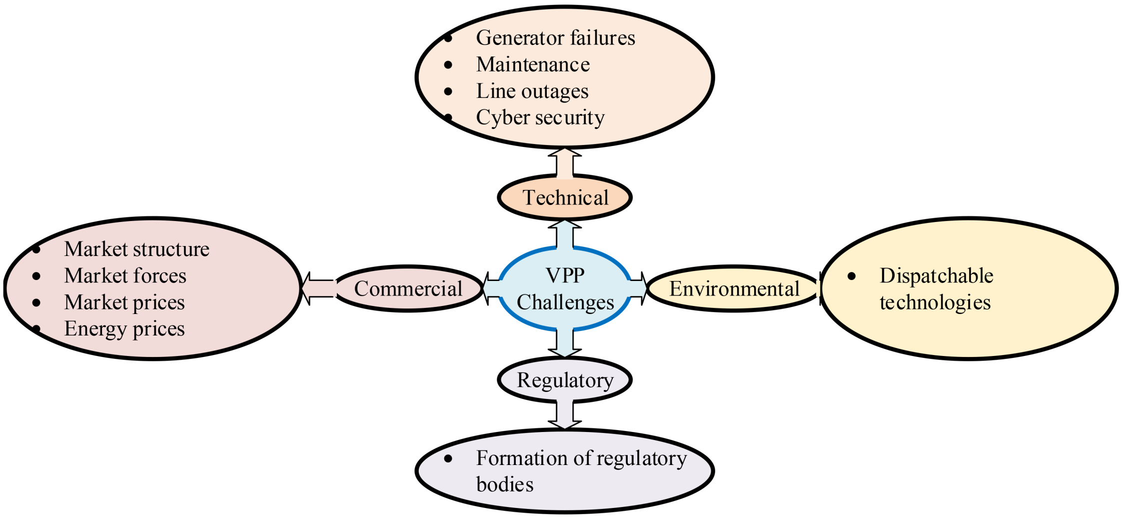

Fig. 5 *Challenges to the implementation of the VPP*

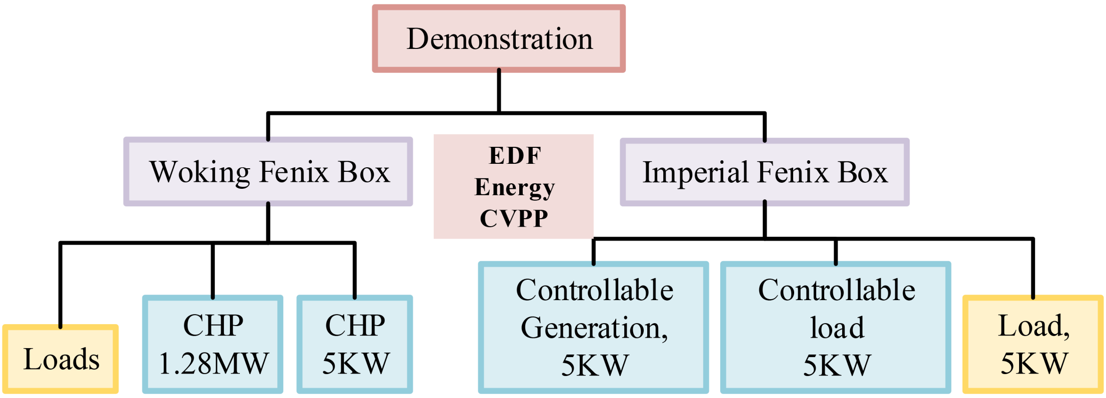

Fig. 6 *Arrangement of northern scenario*

UK (North Scenario); many demonstrations were performed on the components of the FENIX project to ultimately determine the effectiveness of the concept.

Northern scenario: The northern scenario indicates the value of market participation in the commercial sector of the VPP (CVPP) in regards to small-scale energy generation catering for low-voltage networks [43, 44]. The northern scenario simulation was also advanced by a number of FENIX partners (‘Areva, T&D, zuger industrielle verband, Electricite de France (EDF) Energy networks, National grid and Imperial College London working in collaboration with the Woking Borough Council’) to house the VPP in a number of controlled sites.

One of the tasks for the northern scenario was to simulate the FENIX concept in the present network environment (Fig. 6). Unification of a small number of generators chained to a low-voltage network was recognised in the private network of woking borough council (WBC). The WBC owns an entire generation project that supplies energy to its ‘civic centre, conference centre and other municipal facilities’. WBC's projects have mini-to-moderate-sized CHP units, fuel cells and PV plants with the ability to control loads for a short duration [42].

In the FINEX project demonstration, only four market participants are considered [41]:

- *National grid (TSO of the UK)*: Holds the responsibility for the systems’ security as well as the ability to balance the real-time market services.
- *EDF energy (electricity supplier of the UK)*: Is a part of the energy market, has the responsibility to reduce imbalances and assure the operational ability of the CVPP.
- *EDF energy networks (DSO of the UK)*: In charge of managing the network constraints, assuring operation of the TVPP as well as the distribution network in order to maximise operational capacity of the system.
- *Woking Borough Council (DER unit operator)*: Holds responsibility for the smooth operation of DER units as well as the maximisation of profits by the delivery service system through the CVPP.

The central value of the demonstrated project was to visualise the generation and demand as well as showing their flexibility with the FELIX VPP Project [42].

(b) *CVPP in Sauerland:* Two groups merged together (Siemens and RWE) in collaboration to create a CVPP in a rural area in Germany back in 2008. This VPP was equipped with nine hydropower facilities and was in full operation on April 2012. This VPP was also expected to increase its power output to 200 MW by 2015 [45]. The project takes in Siemens Distribution EMS; this technology is able to process the weather forecast as well as interpret energy prices and energy demand providing information to help in the process of making future decisions for the VPP [36].

(c) *China’s Zhangbei project*: This project is located in Zhangbei county, Hebei province, China and consists of the implementation and operation of 66 WTs each with a unit capacity of 750 kW. The total capacity of the project is 49.5 MW and the estimated annual electricity supplied to the grid is about 96.53 MWh at the full capacity. The emission reductions of the project are estimated to be ∼103,796 tons of carbon dioxide per year [46].

Social and sustainable benefits created by this project are reducing greenhouse gas emissions in china, helping to stimulate the growth of renewable energy development, create local employment opportunities, improving local livelihoods, infrastructures and benefiting the community and their local economy. [47]. China is hoping to become a reference for the world in global energy interconnection as well as to take full

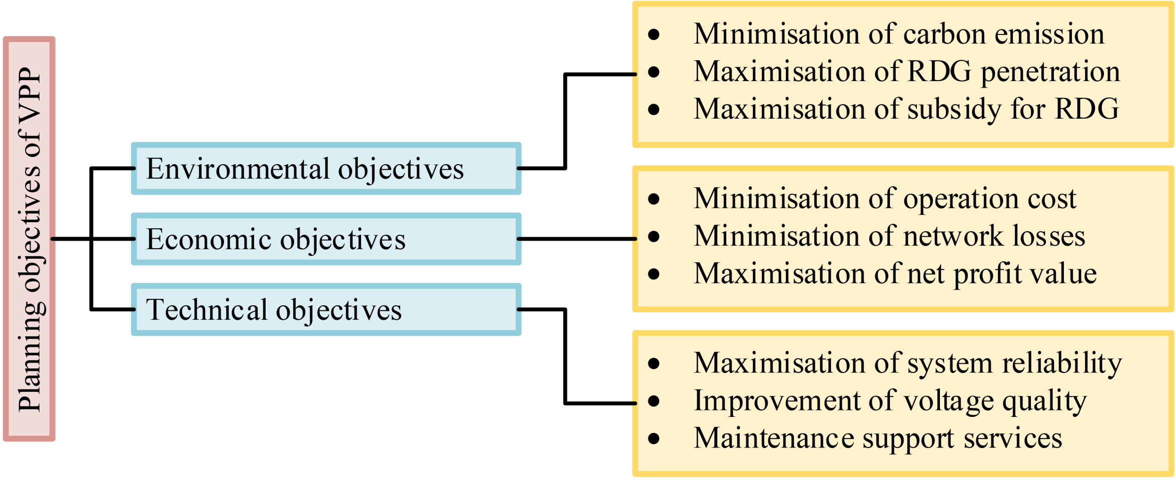

Fig. 7 *Planning objectives of the VPP*

advantage of the achievements in 'high-efficient utilisation' and 'green power utilisation of renewable energy' [48].

4 Planning of the VPP

Operational planning avoids unnecessary and unplanned power system interruption, network failure, losses and hence saves operational resources. Optimal operational planning and design of the VPP is a process of setting goals, guidelines and the strategies of serving and supplying cost-efficient power to active users [49, 50]. The aim of the VPP planning is to elaborate and assess technically and economically the viability of the plan to determine the least possible cost-plan with highest possible benefits of the VPP system [51–53]. Optimal planning of the VPP depends mainly on two aspects: technical aspects and maximisation of commercial objectives. Technical aspects include the capacity of equipment, line loading, losses and management of distribution network operation, power balancing, voltage profile and asset monitoring. The optimisation of commercial objectives refers to minimising the total operating cost of the system, maximising system stability, reliability and minimising transmission losses [54].

4.1 Planning objectives of the VPP

The planning objectives of VPP can be grouped into three main categories. Commercial/economic, technical and environmental objectives [55]. Planning objectives of VPP in the past literature are almost all economic objectives. About 95% of planning models concentrate on economic objectives, only 23% of planning models focus on environmental objectives. Although the share of technical objectives of the planning models is more than 50%, the efforts of all these models are transformed into economic benefits in the shape of economic variables such as cost reliability [56]. These objectives are more clearly explained and depicted in Fig. 7.

4.2 Optimisation of the VPP

To achieve the planning objectives of the VPP, illustrated in Fig. 7, various optimisation techniques can be implemented to optimise the cost of energy generation, balancing supply and demand requirements, production losses in case of fluctuating nature of RES units, reduction in transmission losses and the availability of power supply to electric vehicles [57]. The optimal operation of the VPP aims at maximising its operational functionalities and lowering the total cost of energy production. VPP optimisation can be listed into two categories: structural optimisation and operational optimisation of VPP [58].

4.2.1 Structural optimisation of the VPP: Structural optimisation is possible for a new VPP power system because it is possible to choose the capacity and suitable location of DER units, energy storage units and consumption units to be controlled using smart communication and control strategies. However, on the other hand, if the power system exists already, then the VPP structure optimisation is limited because of the pre-defined size and location of DG units, energy storage capacity and consumption units [58, 59].

4.2.2 Operational optimisation of the VPP: When the power system already exists with pre-defined sizing and siting of DG units, storage devices and consumption units, then the operational optimisation of the VPP could be possible by determining the production of DG units, energy storage system rate of charge and discharge and how much energy is purchased from the wholesale electricity market [60].

DGs are usually connected to the distribution network for a variety of purposes: optimising voltage profile, minimising power loss, improving the quality of power and also enhancing the reliability of the system. Optimal space benefits, in contrast, inefficient capacity or location and sizing of DGs, play a large role in capitalising and receiving the utmost DG units usually leads to negative effects [61].

4.2.3 DG calibration in regards to methodology: Sizing and placement for the VPP are fortunately very easy to achieve usually multiple optimisation methods are used to minimise power loss, costs and environmental emissions and maximise profits, the most efficient method could be analytical, numerical or heuristic [62]:

(a) *Analytical methods*: A method known by the name '2/3' was suggested in [63] for optimised installation of a DG at 2/3 the limit of the incoming generation and at 2/3 the 'length of the line'. This technique shows promise, but may not be as efficient for non-uniform distribution of loads; however, an upgraded method was provided in [64] in gathering four different classes of multiple distribution generators. This was for reducing the losses in primary distribution networks whilst also providing an advance for efficiently selecting the adequate DG factor of power.
(b) *Numerical methods*:

(i) A method is known by the name of 'linear programming' (LP). This method is utilised in optimising linear functions which are open to linear constraints [62]. This technique was used to improve linear systems to increase maximum DG penetration.
(ii) Another numerical method which contrasts to the one explained above non-LP (NLP). This technique was used for capturing the variations over time of numerous sites of renewable energy. This method also captured demands whilst also the 'effect of innovative control schemes' [63].
(iii) Dynamic programming is yet another method which is utilised to increase the maximum profitability of the distributed network operator by an enhanced selection of DG locational settings whilst taking into account the different levels of load conditions (medium, light and peak) [64].
(c) *Heuristic methods:*

(i) A method known as genetic algorithm (GA) was used to provide a solution for numerous distribution generators in their sizing and locational issues with security constraints in [65], where the enhancement process was solved by the merging of GA techniques with ways to determine the DGs impacts in system security, losses and their profile in voltage.
(ii) Another method is known as the 'firefly algorithm' provided a firefly-based enhancement process for the efficient sizing and location of DGs which are dispatchable. This was enhanced to reduce the impact of power losses [66].

5 Modelling of uncertainties in the planning, operation and scheduling of the VPPs

Uncertainty is a mathematical logic term which can be used in different ways and in different fields including engineering science, information technology and statistical analysis. This term differentiates between approximate values and the actual values including the variation in observation or computation. Uncertainty exists in stochastic environments due to lack of sufficient information. Numerous methods can be implemented to minimise the impact of uncertainty on the VPP operational functionalities. The main approaches are RO, MCSs, approximate methods and analytical methods [1, 67].

5.1 Uncertain parameters

The unknown parameters of the VPP can be classified into three types [68–70], illustrated in Fig. 8, and explained as follows:

Technical parameters: Technical parameters are related to transmission and distribution network operation. These include unplanned line outage, equipment failure, network losses, load demand and production.
Economical parameters: Economical parameters are related to aggregation of small-scale participants in energy retail markets, market structures, energy pricing, cost of energy generation and government economic policies.
Climatological parameters: Climatological parameters refer to RES outputs because their output is dependent on the weather conditions which are irregular, unpredictable and fluctuant; therefore, it is difficult to precisely predict the output of solar and wind power and hence this impacts the operational performance of the VPP.

5.2 Uncertainty modelling techniques

Very little work has been done specifically in the field of the VPP; therefore, a lot of work needs to be done in this research area to improve the economic perspectives of participants and transform the idea of the VPP into a successful and profitable part of the future energy market.

Very few uncertainties solving techniques have been developed and implemented to deal with the aforementioned VPP unknown input variables as depicted in Fig. 8. Fig. 9 summarises the application of different techniques proposed to model the unknown parameters. The key objective of these techniques is to explore and assess the impact of unknown input parameters on model outputs [69–71]. These techniques and their way of solving uncertainty problems are explained below in detail:

MCS: Monte Carlo simulation is one of the most common and precise stochastic methods. MCS is acknowledged to be a system-sized-independent approach. MCS is employed when the system is highly irregular, intermittent and has several uncertain parameters. According to [69], Aien *et al.* assessed the uncertainties associated with PV and wind power output. Furthermore, energy prices in the energy market are comprehensively studied by employing MCS. To lower the impact of uncertain parameters on VPP operational functionalities, the suggested model is satisfactorily applied to the unknown variables in the process. The findings of the model showed encouraging outcomes and were supported by simulations.

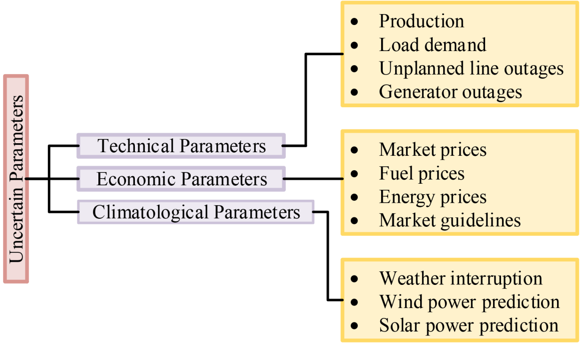

Fig. 8 *VPP uncertainty parameters*

According to [72], Degeilh and Gross suggested MCS because this technique thoroughly samples the uncertainties of the load demand side, the fluctuating nature of RES and the intraday market operation of the VPP. The authors also suggested the application of MCS in [73]. It solves the uncertainties of a VPP associated with load values and market pricing. Zio in [74] proposed MCS application in order to deal with the uncertainties of wind speed and PV irradiation forecast. The MCS technique is able to support all kinds of probability density functions and it is inherently uncomplicated to implement. The MCS can be further classified into sequential and non-sequential Monte Carlo simulation and probabilistic uncertainty analysis.
Normal distribution method (NDM): Shafie-khah *et al.* in [75] evaluated the uncertainties associated with the estimation of uncertain variables (selling and buying of energy cost calculation) are which elaborated in detail by employing the NDM in order to efficiently minimise the risk of estimation of uncertain parameters of the VPP. The results obtained from the model are evidenced, the improvement of the VPP revenue as well as customers and also market efficiency. Dragičević *et al.* in [76] proposed a model for uncertainties associated with RES weather conditions, demand and production in order to maximise the VPP production and profit. The findings of the model are viable.
Weibull distribution method: According to Yang *et al.* [77], the author's employed Weibull distribution modelling to study the uncertainties related with solar power, wind power and load demand in order to lower the uncertainty impact on the VPP operation. The proposed model is successfully implemented and the results showed an encouraging impact on VPP operation income. Hawkes and Leach in [78] evaluated the uncertainties related with the VPP wind power supply and forecasted prices of energy and reserve market by implementing the Weibull distribution modelling with intention of lowering the influence of unknown parameters on the VPP profit. The findings of the model showed a positive impact on the VPP profit.
ARMA method: ARMA model was developed and implemented for the first time by Jenkins and Box in 1970. This model was developed to accurately and precisely predict future energy consumption. Sowa *et al.* in [79] assessed and analysed the impact of uncertainties related with the wind power and flexible load on the VPP operation by suggesting an ARMA model in order to lower the uncertainty impact of wind supply on the VPP operational capability. In this model, the flexible load is incorporated to wind supply as a storage component to store energy during off peak time and then release the stored energy during peak time to cover the intermittent nature of wind power. The findings of the proposed model showed a notable and positive impact on the VPP's optimal operation. Expectations are supported by simulations.
PEM: PEM is a simple, non-iterative and efficient technique that can be implemented easily. In [80], uncertainties associated with the fluctuating nature of RES, power demand and energy prices in the market are evaluated and analysed in depth by the authors whilst implementing a PEM in order to effectively cut down the impact of input uncertain parameters on the VPP scheduling procedure. The results demonstrated that the VPP reserve can balance the reasonable insufficiency of the VPP energy to the

market by virtue of uncertainties. In [81], Qiao *et al.* modelled the uncertainty in wind power and in the market prices in order to facilitate the VPP with optimal bidding in the electricity market. The proposed model also solved the scheduling problem of DER in the deregulated energy sector. In [82], the uncertainties related to the energy prices in market and DER's are thoroughly analysed by the authors with the intention of lowering the uncertainty impact on the VPP owner's profit. The robustness and effectiveness of the proposed model are evidenced by the results of the simulations. In [83], Zamani *et al.* evaluated and analysed the energy and reserve in the VPP. Peik-Herfeh *et al.*in [84] suggested a probabilistic-based approach PEM. In this method, the variability of DER is compensated by additional reserve and also an industrialised economic dispatch algorithm is implemented to investigate fully the large-scale unification of DERs.

Two-PEM method: About 2 m PEM method is the extension and/or an improved version of PEM. Typically, this method has been implemented in a power system investigation. This method explores the uncertainties associated with market prices, DSM and the output power of WT and PV units. In [80], 2 m PEM method is suggested by the authors to model the variabilities related to electricity prices, DSM and WT speed. In [81], Qiao *et al.* proposed a novel probabilistic scheme based on 2 m PEM method; in this scheme, it is suggested to consider the unknown input parameters for the utmost achievement of energy management in microgrid and in the VPP along with dissimilar sources of renewable energies.

RO: The term RO was first implemented by Soyseter in 1973. It is a novel approach to solve the optimisation problem influenced by input uncertain parameters. Particularly when there is no obvious data on the nature of variability [85]. In [86], the uncertainties related to the output of wind power and the imbalance of penalty price are comprehensively evaluated by implementing an RO approach to reduce the uncertainty impact on the VPP bidding strategy while participating in the electricity market. Findings of the RO approach show optimality of VPP bidding strategy and increase in VPP profit. In [10], the RO technique is applied by the authors to manage the uncertainties associated with electricity prices in the energy market. The influence of uncertainty on the VPP losses’ minimisation has been improved to a considerable level. The conclusion is illustrated by simulations.

Scenario tree method: In [72], the effect of uncertainties associated to electricity and fuel prices variation is explored and considered by proposing a scenario tree method for the optimal scheduling process of a VPP. Improved scheduling strategy would be able to enhance the profit of DG owners with due consideration of all possible tree scenarios. Results showed encouraging information regarding the VPP scheduling process and sustained by simulation. In [87], a VPP prototype-based firm capacity provision is presented, in which the intermittency nature of RES is accommodated. In this work, the decision trees method is practised while optimising the stochastic problem taking into account the short- and long-term firm capacity supply periods. This prototype vitalises the viability of the VPP in order to make the availability of reserve capacity and also effectively contribute to electricity markets.

6 Operation of the VPP

The operational application of the least possible cost-plan of the VPP into practical realisation is known as the implementation phase. Successful operational utilisation of the VPP incorporates and takes into account all external as well as internal conditions and factors associated with stability, reliability, the security of power system and cost competitiveness. The improved and customised aggregated strategy of the VPP for diverse economic objectives in the power market is made up of the spot energy market, the intraday energy market and balancing the energy market via trading connections [88]. Application of the VPP system assists the power sector in various ways, for example, energy trading services, supply and demand balancing services and system network support facilitation services for the optimisation of operational cost and maximising profit [16].

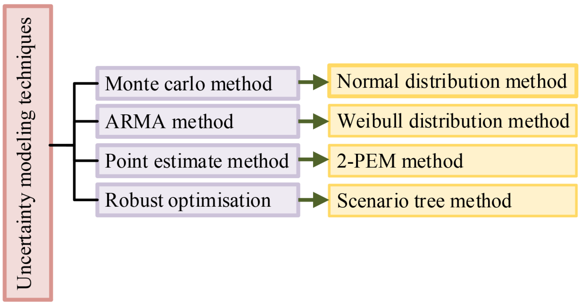

Fig. 9 *Uncertainty modelling approaches*

The implementation of the VPP is made resourcefully in the power market to control widespread power generators, supplying real-time data on power production in the process and online energy optimisation. The EMS system constantly forecasts data and adjusts the predicted information according to market demands in seconds [72]. This service is made through the application of smart communication systems. The WTs and solar power could be integrated into one large power plant, employing the concept of the VPP, delivering bit-by-bit power reserve for a common purpose of lowering cost and profit maximisation.

6.1 Market participation of the VPP

Multiple trading platforms can be simultaneously utilised by the VPP through trading connections including the spot, intraday and balancing the energy markets. Current day-ahead and intraday prices, as well as the trading results attained on the different markets, can be continuously and immediately transferred to the VPP for action. Current energy consumption of consumer's flows into the load prediction in the VPP and the demand of controllable consumers can be continuously adjusted through constant optimised load management [16]. A key objective of the VPP market participation is to optimise active user's electricity remittance and maximise its capital; therefore, the customer's inclination is more toward price-based strategies in order to locally manage the supply and demand requirements [21].

Morais *et al.* [89] suggested a valuable conventional configuration for the operational application of the VPP in the electricity market. In this framework, the DER units present their energy trade plan to the VPP operators. The VPP operators prepare an energy price plan to be discussed in the energy market or directly with consumers, once the energy price plan strategy is established. VPP starts negotiation with the market, regarding the DER unit's sales proposal. After a detailed and comprehensive discussion of the VPP with the power market, the market operators formulate the sale trade agreement. The market outputs must be confirmed by the system operators when the technical curtailments of sale agreement are breached, then it is essential to release the censorious points of the sale agreement to both parties, the energy generator and consumers, in order to authorise them to arbitrage the supply to a different energy generator. It is necessary to note that in case of energy supply violation by the VPP, the requirements could be different from those of individual generators. The reason is that a VPP can alter the schedule of energy injection to the system in order to overcome the technical problem. This is a very important feature of the VPP. If there are no technical issues, then the system operator will transmit it to the market operator for the realisation of the transaction. The next day, the VPP must take full control of energy submitted to the network by an individual producer in order to correct the imbalance created by renewable technologies. Generated energy and the climate conditions should be applied to streamline the EMS database in order to forecast more effectively the energy that they will be capable of supplying to the VPP.

6.2 Bidding strategies of the VPP

The bidding strategies suggested for a VPP are classified into different categories in order to accomplish various goals, e.g. in [90], a VPP is confronted the bidding problem with two distinct goals, participation in the day-ahead markets and contributing to spinning reserve facilitations services. The model presented here for the bidding strategy is a non-equilibrium which is based on a deterministic price-based unit commitment. This bidding strategy is considered the balance in supply and demand constraints as well as security constraints. The aims of [91] are to increase self-supply and market profit of the CHP-based VPP as well as the system operators. Mashhour and Moghaddas-Tafreshi [92] propose a strategy based on an evolutionary optimisation algorithm, with the aim of decreasing the operational cost of a VPP while managing the DER network. The objective of [71] is to balance a two-stage VPP operational planning for the short term. In this work, a stochastic-based bidding model is proposed in order to maximise the VPP profit in the electricity market. It also suggests a mechanism to achieve the highest-bidding planning strategy for the VPP, incorporating a CHP and DERs system for the highest benefit. Zapata *et al.* [93] suggest an utmost bidding strategy for a CVPP, comprising DER units, storage devices and consumption units. The suggested bidding strategy is used in order to lower consumption and maximise the profit in real time. Kardakos *et al.* [94] suggest a model for a TVPP in order to lower its cost. The suggested model is based on NLP with due attention to DG and demand response constraints. The emission reduction of a VPP system should be considered as a high priority. Strantzali and Aravossis [95] proposed a multi-agent system which is used to regulate the emission of aggregated generators. In this work, the simulations obtained from the operational system are cross-matched with an experimental system. Emission of the VPP must be close to the reference value. Fanzeres *et al.* [85] suggested a model of the EMS for a VPP to explore and assess the cost and emission effect of the VPP.

6.3 Arbitrage strategy of the VPP

The term arbitrage refers to buying energy when the cost of electricity is low and selling the same energy when the cost of electricity is high. This method can be adopted by VPP using energy storage systems. Moreover, a VPP can also fulfil bilateral contracts, either by buying energy from power markets or from regional producers. The arbitrage trading between regional producers and power market is more cost-effective as compared with acquiring power alone from the market. Consequently, a VPP can satisfy active and reactive power supplies either by regional producers or by market purchase. Furthermore, a VPP can make more profit through the application of arbitrage trading rather than sole energy trading as an entity [86].

7 Conclusion

VPP is a comparatively new, wide-ranging and interesting concept of energy generation and management, which needs to be further researched and explored to make its implementation simpler, valuable and more profitable. The concept of the VPP provides a unified platform and opportunities to each DER owners to participate in the power market. The greatest commercial advantage of the VPP is to maximise the profit of the DER owners in the electricity market and minimise their financial risk. This review paper evaluates and assesses the recently published papers as a detailed literature review. The subject matter of this paper is the operation, planning and scheduling of the VPP taking into consideration its uncertainties.

Every researcher or engineer investigating this topic has its own observation and perception of VPP, but the primary objective of VPP is to achieve the largest possible profit for its asset owners. The vision is clear; however, progressing toward achieving it is challenging, but there are signs that the VPP market is maturing. New businesses are creating more efficient technology to help creatively manage distributed energy sources.

This work presents a detailed insight into the VPP explanations, definitions, elements and the relationship between these elements. Furthermore, the EMS system, benefits and classifications of the VPP are explained and the applicability and usefulness of TVPP and CVPP are thoroughly reviewed with the intention to effectively understand the concept of the VPP. Additionally, the structural and operational optimisations of the VPP, uncertain parameters and uncertainty modelling techniques are reviewed systematically. Moreover, the bidding and arbitrage strategies of the VPP in a liberalised electricity market are also highlighted.

This review paper will help the academia and new researchers to better understand the concept of the VPP, its planning, operation and scheduling considering the uncertainties related to RESs.

Further work is needed to reconcile the economic efficiency and technical feasibility of electricity transactions in the smart distribution energy systems considering the cooperation between CVPP and TVPP. Furthermore, the cooperation between VPPs and load aggregators would be worthy of investigation. Moreover, modelling the risk of DER asset owners due to unplanned eventualities such as unit failures or forecast errors would be worthwhile.

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