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Research Article

Operational Planning and Design of Market-Based Virtual Power Plant with High Penetration of Renewable Energy Sources

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Abstract. Renewable energy sources (RESs) are becoming more prevalent as a source of clean energy, and their integration into the power market is speeding up. The fundamental reason for this is the growing global concern about climate change. However, their weather-dependent and uncertain nature raise questions about grid reliability particularly, when photovoltaics (PVs) and wind turbines (WTs) technologies are used. As a result, rationally managing Energy Storage Systems (ESSs) under the virtual power plant (VPP) setting is being encouraged as a way of minimizing the impact of the uncertain nature of renewable energies. A VPP is comparatively a new concept that aggregates the capacities of dispatchable and non-dispatchable energy sources, electrical loads, and energy storage systems for the purpose of improving energy supply and demand imbalance. It enables individual consumers and producers to participate in the power markets. In this study, a new market-based (MB)-VPP operational planning model is designed and developed with the aim to evaluate the optimal active power dispatched by (WT, PV, and ESS) operating in the day-ahead power market to maximize the social welfare (SW) of the market. SW can be described as the maximization of the consumer's benefit function minus the cost of energy generation. The optimization process was carried out by using a scenario-based approach to model the uncertainties of renewable energy sources (i.e, WTs & PVs) and load demand. The proposed model and method performance is validated by simulation studies on a 16-bus UK generic distribution system (UKGDS). The simulation results reveal that the proposed approach maximizes overall system social welfare. The capacity of total active power dispatched by (WT, PV, and ESS) has a positive impact on the VPP profit maximization. This empirical study could be used as a reference baseline model for other energy services providers interested in conducting similar research in the future.

Keywords: Climate change, Renewable energy sources, Distributed generators, Electricity market, Economic mechanism, Uncertainty modeling, Virtual power plant

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1. Introduction

Day by day, the energy demand is increasing, necessitating increased penetration of distributed generators and more efficient power grid operation (Hirsh & Koomey, 2015; Oladipupo *et al.* 2022). The Increase in population, better living standards, economic growth, a deteriorating environment, and a decline in the output of traditional energy sources such as (fossil fuels) are the main factors contributing to the current situation. Fossil fuels have numerous negative impacts on our environment including gases emission that contribute to global warming and pollution (Ullah *et al.* 2019; Ugwu *et al.* 2022). The Climate Change Act 2008, along with reforms to the electricity market firmly established the United Kingdom (UK) position as a global leader in renewable energy, especially wind power (Baseer *et al.* 2019; Cordero *et al.* 2020). To achieve these goals, the UK government has implemented five-yearly carbon budgets that are now in effect until 2032. The UK Government has set a limit on how much greenhouse gas could be lawfully released over the next five years (Rogelj *et al.* 2016).

However, renewable energy sources generation is variable and uncertain, which Poses severe risks to the operational performance, reliability, and security of the grid, as it widens the supply-demand gap (Jordehi, 2022). Coupling renewable energy sources with other technologies like traditional generators, controllable load, electric vehicles, and energy storage systems could be a way forward to solve these challenges. It is possible under the VPP setup. A VPP is a modularly built entity that pools up the capacity of renewable energy sources (RESs) with the aim to promote and develop clean energy generation, distribution, and as well as generating revenue by selling or buying power in the electricity markets. The VPP elements are interconnected together using cutting-edge control, smart distributed controllers (SDC), smart metering, and advanced internet communication technologies (ICTs). The VPP operators determine the optimal operational planning and bidding strategy in the

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electricity market while taking into account the operational constraints of the VPP components, therefore, boosting the distribution grid efficiency at the local level.

VPP functionality can be classified into two categories: commercial VPP (CVPP) and technical VPP (TVPP). These two entities work in collaboration to ensure that the VPP operates optimally (Koza & Öztürk, 2021; Zhang, 2022). A CVPP is concerned with the quantity of energy it can deliver to the electricity markets, as well as the prices associated with that energy, in order to maximize its profitability. A CVPP mainly concentrates on bilateral contracts between distributed generation and electrical loads. Bilateral contracts information should be transmitted to TVPP so that the contracted electricity can be withdrawn from the system (Rouzbahani *et al.* 2021). Small-scale energy producers have historically been unable to participate in energy markets on an individual basis. Thus, CVPP enables them to participate in energy markets (Mao *et al.* 2020). Some of the functions provided by a CVPP are as follows: **(1)** trade-in the wholesale electricity market, **(2)** balancing trading portfolios, **(3)** participation of DER units in electricity markets, and **(4)** Optimisation of daily schedule production (Ullah *et al.* 2019). TVPP is in charge of the efficient and reliable operation of distributed generations, dispatchable loads, and energy storage systems, as well as regulating energy flow between VPP coalitions members and auxiliary services providers (Naval & Yusta, 2021). TVPP imports information from CVPP about bilateral contracts between DGs and load demand. This data must contain the following information: (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 units (Wang *et al.* 2019). TVPP assures that the power system operates correctly and securely while taking into account the physical limitations and system support facilitation services provided by the VPP. The following are some of the functions delivered by the TVPP: (1) Determines fault location, (2) provides maintenance facilitation services, and (3) ensures that the power system is operating in an optimal safe way (Badar *et al.* 2022).

A VPP is a unified platform that lets distributed energy resources, energy storage systems, and demand response programs play an active role in grid operations and deliver grid services. This makes the grid more stable by offering utilities with additional operating reserves at the local distribution level. As a result, VPP adoption is expected to have far-reaching beneficial repercussions on grid operations and provide a secure way to significant penetration of distributed energy resources in power systems. The prior research work on VPP's operational planning is very limited, with just a few publications devoted to modeling the VPP operational planning. Most of them seem to be only concentrated on the uncertainties related to wind generation, disregarding other sources of uncertainties that come with photovoltaics and electrical loads. This restricted focus may mislead power system operators in charge of system operational security and control performance. All uncertainties related to WTs, PVs, and load demand are considered in this study when estimating the required generation performance over the planning horizon.

2. Literature Review

The following are some of the relevant and closely related studies proposed and highlighted in the literature review. Ntanos *et al.* (2022) examined the role of school personnel and students in encouraging the use of environmentally friendly renewable energy education in schools, as well as energy upgrades, and school-based energy-saving programs. School principals are key participants in implementing school-based energy-saving programs. They should be well trained and informed about Renewable energy technologies. Drosos *et al.* (2021) emphasized the significance of environmental education while focusing on energy-saving measures in the educational environment. The need to develop educational awareness programs in schools in regard to renewable energy sources. This will result in increased environmental recognition between teachers and students, as well as greater active participation in efforts to "greenify" the school environment. The authors of (Guo *et al.* 2021) have proposed a new operational technique for sophisticated VPP that considers market transaction mechanisms and integrates CHP units, wind energy, gas boiler, and electrical loads. The authors of (Sadeghi *et al.* 2021) have investigated a VPP's optimal bidding strategy in the day-ahead energy markets. They employed a deep learning approach for the uncertainty analysis. The authors of (Vahedipour *et al.* 2020) have proposed an optimal bidding mechanism for a VPP that competes in the day-ahead energy markets to lower end-user costs. The Bayesian Network Classifier was found to be the most effective method for predicting willingness to invest in renewable energy by Anagnostopoulos *et al.* (2020), with a classification accuracy of 0.7942. Ullah & Mirjat. (2021) have assessed a VPP energy trading model, made up of conventional and non-conventional sources of energy, energy storage systems, and electrical loads with the aim of maximizing SW while disregarding the uncertainties associated with renewable energy sources. The authors of Ullah & Mirjat. (2021) have analyzed VPP interactive characteristics in the distribution systems providing energy flexibility support services in the distribution system without considering the uncertainty of photovoltaics. Ntanos *et al.* (2018) have examined the correlation between renewable energy usage and economic growth in different countries. According to the proposed model, the correlation between RES and high GDP countries is high, while non-RESs consumption is more common in countries with lower GDP. Liu *et al.* (2017) have proposed a technique for multi-stage market transactions that featured VPP involvement and evaluated the significance of VPP collaboration, but they did not account for DGs uncertainties. The estimated generation of the VPP may deviate from the actual generation due to the uncertainties. Consequently, the VPP's actual profit falls short of its target profit. Therefore, it is necessary to consider DG uncertainties. Arabatzis *et al.* (2017) used a multivariate cluster analysis statistical approach. The focus of this research was to construct a typology of Greece's regional units (NUTS III) based on the number and installed power of renewable energy plants for electricity generation. Baseer *et al.* (2019) have analyzed the operational planning of hybrid AC-DC microgrids considering the uncertainties of wind turbines, photovoltaics, and electrical loads. The aim was to maximize social welfare. However, in the case of renewable energy generation, the impact of storage systems was neglected. The uncertainty problem is characterized as a multi-objective optimization problem by the authors of (Salkuti, 2019) using the NSGA-II method.

Table 1
Comparison of the proposed method with existing literature

Social welfare Maximization	Power Market	Uncertainty Modeling	ESS Model	RES Management	References
No	No	No	No	Yes	Ntanos *et al.,* (2022)
No	No	No	No	Yes	Drosos *et al.,* (2021)
No	Yes	No	No	Yes	Guo *et al.,* (2021)
No	Yes	Yes	Yes	Yes	Sadeghi *et al.,* (2021)
No	Yes	Yes	Yes	Yes	Vahedipour *et al.,* (2020)
No	No	No	No	Yes	Anagnostopoulos *et al.,* (2020)
Yes	Yes	No	Yes	Yes	Ullah *et al.,* (2021)
No	Yes	No	Yes	Yes	Ullah *et al.,* (2021)
No	No	No	No	Yes	Ntanos *et al.* (2018)
No	Yes	Yes	Yes	Yes	Liu *et al.* (2017)
No	No	No	No	Yes	Arabatzis *et al.,* (2017)
Yes	Yes	Yes	No	Yes	Baseer *et al.,* (2019)
No	Yes	Yes	Yes	Yes	Salkuti, (2019)
Yes	**Yes**	**Yes**	**Yes**	**Yes**	**This Paper**

However, in the case of renewable energy generation, the influence of the energy storage systems has been neglected. Existing studies lack a systematic investigation of market-based virtual power plants operating under uncertainty associated with WT, PV, and load demand to maximize SW. This study provides a novel approach for the VPP operational planning in the context of the power market to maximize SW. A scenario-based approach is used to evaluate the impact of WT and PV energy penetration on the SW. A comprehensive comparison of the proposed method with existing research is presented in Table 1.

The following are the key contributions of this work regarding the literature reviewed.

a) To design a market-based operational planning strategy for a VPP that trades in the day-ahead energy market.
b) To develop a market-based computationally efficient model for a VPP that operates in the day-ahead market.
c) Scenario-tree method is used to address the uncertainties associated with wind speed, solar irradiation, and load demand.
d) Perform a case study to demonstrate the effectiveness of the proposed strategy by thoroughly assessing the simulation results.

3. Proposed Method

The VPP increases the operational performance and security of the power networks by aggregating various distributed generation technologies in the power market. The VPP market strategy performance is analyzed in the day-ahead power market as seen in Figure 2. The hourly dynamic pricings of the electrical load, utility grid, WT, and PV generation are forecasted. The participants submit their hourly power offers along with prices for the following day. The offer and bid prices have been agreed upon, and the competitors have made commitments. The VPP's DA market operation is based on a set of assumptions. The VPP supplies power to the electrical load in order to optimize its participant's profit which is determined by hourly dynamic pricing. In this model, we assumed to exercise centralized control over all trading activities occurring within the VPP structure. The day-ahead market is a mechanism of selling and buying electric energy one day in advance of the scheduled delivery day. Offers are made to the market operators by sellers and buyers. The VPP owner who participates in the DAM submits their energy biddings (sells/buys) and manages its aggregated components in such a way as to maximize SW. It determines the amount of energy that can be sold or bought in the electricity market. Figure 3 shows the VPP's grid-optimized dispatch approach and how it interacts with the power market. The VPP model is made-up of wind farms, photovoltaics, electrical loads, and energy storage systems. It reflects the power trading with the grid and the electricity market. Operators of the VPP solve the operational planning problem based on the available data. A direct control mechanism is applied in this study for the optimal DER coordination and market representation as a single entity. Individual VPP units will submit requests to the VPP control center which will be based on the owner's constraints and preferences. The output of the VPP is determined by the intensity of wind speed and solar irradiation, both of which are impacted by environmental variables. These uncertainties make energy distribution problematic. thus, uncertainty is essential. Modeling the uncertainties associated with wind speed, solar irradiation, and load demand is done using the scenario-based method. This method assesses the WTs, PVs', and ESS active power generation and delivery capacity to load over the planning horizon to maximize SW.

4. Uncertainty Modeling

A scenarios-based approach is used to model the uncertainties associated with wind speed, solar irradiation, and load demand, where a scenario is described as a possible realization of an uncertain parameter (Zubo & Mokryani, 2019). The probability density function (PDF) is used for each wind speed, solar irradiation, and load demand to generate 24 scenarios.

4.1 Wind Speed Modeling

Weibull PDF (Reddy *et al.* 2012; Ahmed & Mohammed, 2012; Mokryani, 2017; Zubo *et al.* 2018) is used to model the wind speed variation in a given area. The PDF function that describes the relationship between the wind speed and the WT power generation is stated by (Baringo & Rahimiyan, 2020) as follows:

$$PDF(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (1)$$

where υ refers to the speed of the wind, the Weibull PDF scale index of the wind speed is represented by *c*, and the shape index is represented by *k*. The power curve of the WTs can be used to analyze the power generated as stated by (Reddy *et al.* 2013; Baseer *et al.* 2019; Lu & Cheng, 2021).

The speed of the wind (**υ**) and the power generated by the WTs (P_w) can be correlated by using operational parameters. Where P_{rated} indicates the rated power, $\boldsymbol{\upsilon_r}$ indicates the WTs' rated speed, υ_{ci} indicates the cut-in speed, and $\boldsymbol{\upsilon_{co}}$ indicates the cut-off speed.

$$P_{wt}(v) = \begin{cases} 0, & 0 \le v \le v_{ci} \\ P_{rated,} \times \dfrac{v - v_{ci}}{v_r - v_{ci}}, & v_{ci} \le v \le v_r \\ P_{rated,} & v_r \le v \le v_{co} \\ 0, & v_{co} \le v \end{cases} \quad (2)$$

The power curve of the wind speed P_w is illustrated in Fig1. The power generated by the WT at bus *i* and scenario *w* is described as follows:

$$0 \le P^{wt}_{i,w} \le \gamma^{wt}_{i,w} \times P^{wt}_{i.rated} \quad (3)$$

Where $\gamma^{wt}_{i,w}$ is the percentage of active power generated by the WT at bus *i* and scenario *w*.

4.2 Modeling of Solar Irradiance

The modeling of solar irradiance is done with Beta PDF, which is explained below:

$$PDF(S) = \begin{cases} \dfrac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)+\Gamma(\beta)} \times s^{\alpha-1} \times (1-s)^{\beta-1}, & 0 \le s \le 1, 0 \le \alpha, \beta \\ 0 & else \end{cases} \quad (4)$$

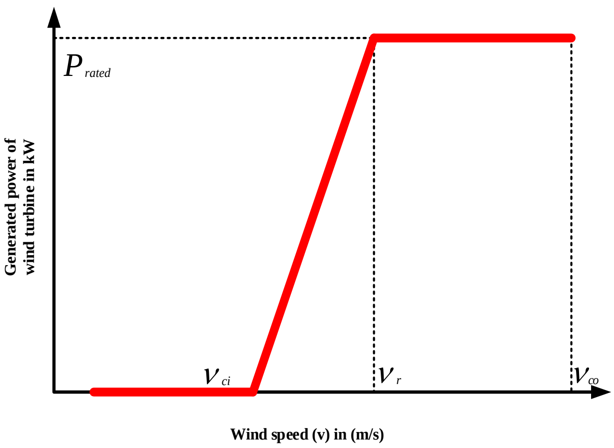

Fig. 1 WTs speed power curve.

The solar irradiation (kW/m^2) is expressed by *s*. α and β are the two parameters of Beta PDF, and they can be obtained in the following manner.

$$\beta = (1-\mu) \times \left(\frac{\mu \times (1-\mu)}{\sigma^2} - 1\right) \quad (5)$$

$$\alpha = \frac{\mu \times \beta}{1-\mu} \quad (6)$$

Where σ represents the standard deviation of the random variable and μ represents the mean value. According to (Montoya *et al.* 2016; Baseer *et al.* 2019; Kabbani & Honnurvali, 2021), The PV output power is determined by using Eqs. (7) & (8) depending on solar irradiation and cell temperature.

$$P_{PV} = P_{STC}\left\{\frac{G}{100}\left[1 + \delta\left(T_{cell} - 25\right)\right]\right\} \quad (7)$$

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20}{800}\right) G \quad (8)$$

The PV power generation in kilowatts is represented by P_{PV}. P_{STC} is the power in megawatts under standard test conditions. The power-temperature coefficient is represented by δ in (%/^0C). The cell temperature is represented by T_{cell} in ^oC. The ambient temperature is represented by T_{amb} in ^{o}C. The national operating cell temperature conditions are represented by NOCT in ^{0}C, and the solar irradiation is represented by G in (W/m^2) (Fatch *et al.* 2022).

4.3 Load Demand Uncertainty Modeling

The load demand of each bus is modeled using the standard PDF function. The PDF of the normal distribution for uncertain load *l* is given by (Reddy *et al.* 2013; Reddy *et al.* 2013) as follows:

$$PDF(l) = \frac{1}{\sigma_l\sqrt{2\pi}} \times \exp\left[-\left(\frac{(l-\mu_l)^2}{2\sigma_l^2}\right)\right] \quad (9)$$

where σl is the standard deviation and μl is the mean value.

The Genetic algorithm (GA)-based load forecasting method uses point forecasts, that do not approximate the entire range of possible future values, whereas the probabilistic forecasts approach provides an approximation of the entire distribution of possible future values and quantifies their uncertainty. DG system reliability can be analyzed using analytical state enumeration and Monte Carlo simulation approaches. Prior studies, suggested that all uncertainties associated with DGs can be defined as random variables X, which are characterized in terms of PDF, f(x) (Li & Zio, 2012; Baseer *et al.* 2019; Zubo & Mokryani, 2019).

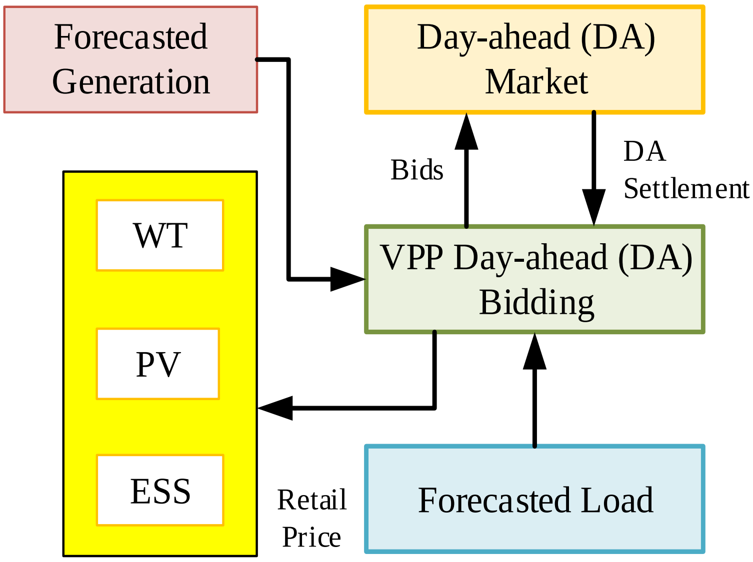

Fig. 2 The VPP's day-ahead market strategy

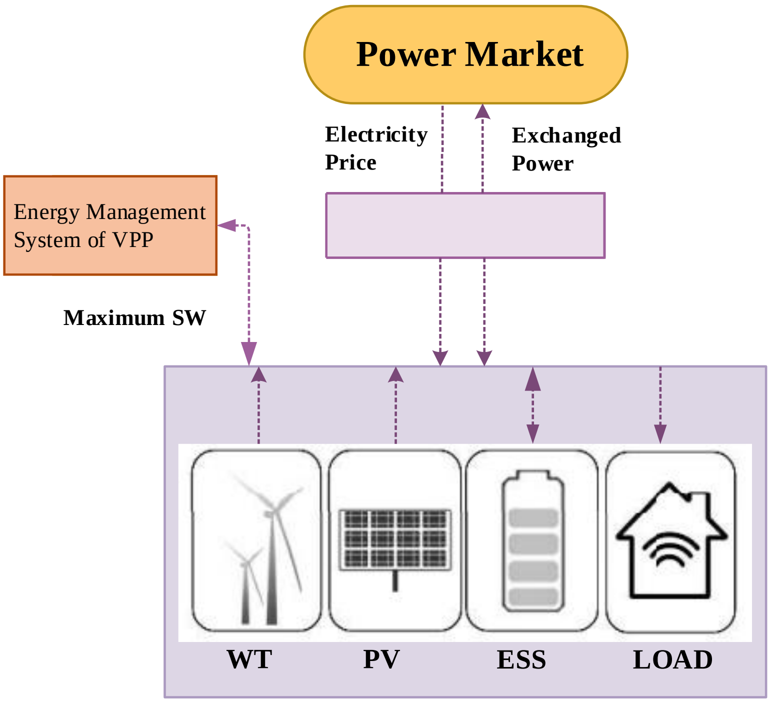

Fig. 3 Proposed VPP electricity market structure

5. Objective Function

The market-based VPP operational planning problem's objective is to maximize social welfare in (10). It maximizes end-user benefits while minimizing the cost of energy generation over the planning horizon is expressed as follows:

$$Maximise\ SW=\left[\begin{array}{l}\sum_{i}\sum_{t}\sum_{w}P_{i,t,w}^{Demand}*C_{i,t,w}^{Demand}+\sum_{t}\sum_{w}P_{t,w}^{Grid}*C_{t,w}^{Grid}\\-\sum_{i}\sum_{t}\sum_{w}P_{i,t,w}^{WIND}*C_{i,t,w}^{WIND}-\sum_{i}\sum_{t}\sum_{w}P_{i,t,w}^{PV}*C_{i,t,w}^{PV}\\+\left(\left(P_{ess,t,w}^{DIS}-P_{ess,t,w}^{CH}\right)\cdot C_{ess,t,w}^{CH,DIS}\right)\end{array}\right] \quad (10)$$

Where $P_{i,t,w}^{Demand}$ represents the active power load demand at bus *i*, time *t*, and scenario *w*, respectively. $C_{i,t,w}^{Demand}$ represents the bid price for load demands at bus *i*, time *t*, and scenario *w*, respectively. $P_{t,w}^{Grid}$ is the quantity of power traded with the grid at time *t* and scenario *w*. $C_{t,w}^{Grid}$ is the price of power that can be traded with the grid at time *t* and scenario *w*. The sum of the amount of energy generated by $P_{i,t,w}^{WIND}/P_{i,t,w}^{PV}$ at bus *i*, time *t*, and scenario *w* multiplied by the price of its production cost $C_{i,t,w}^{WIND}/C_{i,t,w}^{PV}$ at bus *i*, time *t*, and scenario *w* equal the production cost of DGs. $P_{ess,t,w}^{CH}/P_{ess,t,w}^{DIS}$ indicates the energy storage system charging/discharging at time *t* and scenario w times cost $C_{ess,t,w}^{CH} / C_{ess,t,w}^{DIS}$ of energy storage unit charging/discharging at time t and scenario w respectively.

Constraints

Wind turbines installed capacity: The power generated by wind turbines is limited by their installed capacity, as stated in eq. (11). It indicates the maximum and minimum limits of WT power generation at each candidate bus.

$$0 \le P_{i,t,w}^{WIND} \le P_{i,t,w}^{WIND\,MAX} \tag{11}$$

Photovoltaics installed capacity: The amount of active power generated by PVs is limited by their installed capacity as shown in eq. (12). It indicates PV's maximum and minimum power generation limits at each candidate bus.

$$0 \le P_{i,t,w}^{PV} \le P_{i,t,w}^{PV\,MAX} \tag{12}$$

Maximum installed capacity: The combined capacity of WTs and PVs installed is equivalent to the total power produced as shown in eq. (13). It shows the maximum power generation capacity of both (WT & PV) generators.

$$P_{i,t,w}^{MAX} = \sum_{a=1}^{NG} P_{i,t,w}^{WIND} + P_{i,t,w}^{PV} \tag{13}$$

Equation (14) expresses the maximum and minimum limits on the quantity of power that can be traded with the grid. It shows the limitations on power exchange capacity between the VPP and the upstream grid.

$$0 \le P_{t,w}^{Grid} \le P_{t,w}^{Grid\,Max} \tag{14}$$

Voltage limits: The minimum and maximum voltage at each bus is expressed by eq. (15).

$$V_i^{MIN} \le V_i \le V_i^{MAX} \tag{15}$$

Energy storage system operation: The energy storage system operation is presented from eq. (16) to (22). This paper explains the utilization of ESS, to store surplus power capacity of RESs or bought from the DA market during periods of low electricity prices. The energy stored will either be used to meet VPP's peak load demand or resell it to DA markets at a profit during periods of high electricity prices.

$$0 \le P_{ess,t,w}^{CH} \le P_{ess,t}^{CH\,MAX} \cdot U_t^{CH} \tag{16}$$

$$0 \le P_{ess,t,w}^{DIS} \le P_{ess,t}^{DIS\,MAX} \cdot U_t^{DIS} \tag{17}$$

$$E_{ess}^{MIN} \le SOC_{ess} \le E_{ess}^{MAX} \tag{18}$$

$$SOC^{(t=0)} = E_{ess}^{INTIAL} \tag{19}$$

$$SOC^{(t=24)} = E_{ess}^{FINAL} \tag{20}$$

$$U_{ess}^{CH} + U_{ess}^{DIS} \le 1 \tag{21}$$

$$SOC^{(t)} = SOC^{(t-1)} + \eta_{CH} \cdot P_t^{CH} - \frac{P_t^{DIS}}{\eta_{DIS}} \tag{22}$$

Where $P_{ess,t,w}^{CH}$ and $P_{ess,t,w}^{DIS}$ represent the ESS charging and discharging of power at time t, $P_{ess,t}^{MAX\,CH} / P_{ess,t}^{MAX\,DIS}$ represents the ESS's maximum charging /discharging of powers, the binary variables U_{ess}^{CH} and U_{ess}^{DIS} represent the ESS charging/discharging status at time t, the maximum and minimum amount of energy stored in ESS is denoted by E_{ess}^{MAX} / E_{ess}^{MIN} respectively, the ESS has two energy levels represented by $E_{ess}^{INITIAL} / E_{ess}^{FINAL}$, the ESS charging and discharging efficiencies are represented by η_{CH} and η_{DIS} respectively. ESS's state of charge at time t is represented by $SOC^{(t)}$.

$$\sum_{a=1}^{NG} P_{i,t,w}^{WIND} + \sum_{a=1}^{NG} P_{i,t,w}^{PV} + P_{t,w}^{Grid} + P_{ess,t,w}^{DIS} - P_{ess,t,w}^{CH} \ge P_{i,t,w}^{Demand} \tag{23}$$

Power balance: The power balancing equation, represented by eq (23), must be satisfied for each bus. It means that the required generation and requested quantity of power in the VPP setup should be fulfilled.

6. Case Study

6.1 Parameters Setting

A case study has been presented to demonstrate the effectiveness of the proposed approach and to verify the results. The simulation study is performed on a 33-kV UK generic 16-bus distribution system (UKGDS). Figure 4 shows a single-line diagram of a 16-bus UKGDS. The VPP is wired into the main grid during normal operation. To maximize SW, optimal power flow is applied to determine the maximum potential of WTs, PVs, and energy storage systems over the planning horizon. In this study, we supposed that the distribution network has four WTs and three PVs units. WTs candidate buses are located in the distribution network at 3, 6, 9, and 11, with nominal generations of 660kW, respectively, and PVs candidate buses with the nominal generation of 440kW are located in the distribution network at 12, 14, and 16, respectively (Zubo *et al.* 2018). The energy storage system, with a capacity of 200kW, is installed at their designated candidate bus at 15. The minimum and maximum voltage limits are considered to be Vmin = 0.94 p.u. and Vmax = 1.06 p.u (Ullah & Mirjat, 2021).

All the essential data reported in (Baseer *et al.* 2019; Ullah & Mirjat, 2021) has been used with some adjustments to fit into our proposed model. This study considered the operational planning problem of a VPP within the electricity market. A new approach for the operational planning of a VPP in the energy environment is presented, optimizing SW while accounting for wind, photovoltaic, and electrical loads uncertainties. The number of scenarios in the GAMS environment has been limited to 24 for the sake of improving the speed and accuracy of addressing the problem. GAMS software package is used to formulate the problem as mixed-integer linear programming (MILP) (Fourer *et al.* 1990; Soroudi, 2017; Baringo & Rahimiyan, 2020), and the CPLEX solver yielded the optimal results

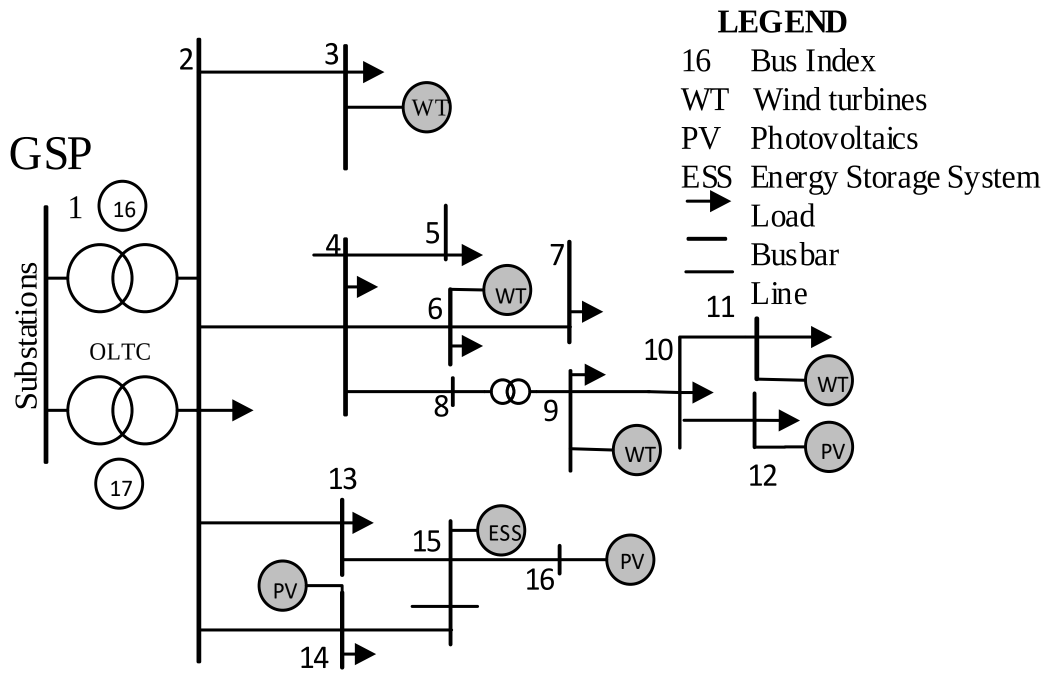

Fig. 4 Single-line diagram of 16-bus UKGDS

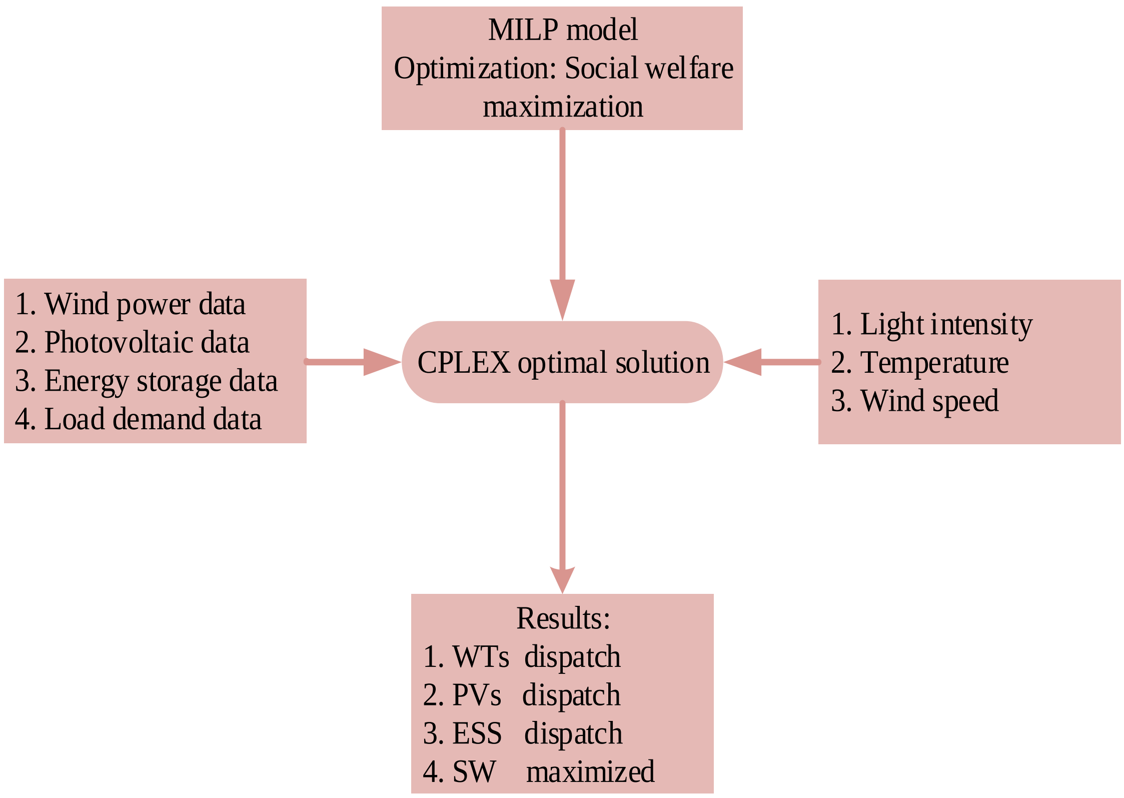

Fig. 5 The flowchart of the problem-solving process

6.2 Simulation Results and Discussion

The total quantity of power dispatched by WT units at candidate buses 2, 6, 9, and 11 in all scenarios is shown in Figure 6. Buses 2 and 6 have the least and the most quantities of power dispatched, in comparison to buses 9 and 11. This is due to the fact that the quantity of power dispatched by WT generators at each bus is working at their maximum and minimum power generation level, as well as the bid price of the demand loads (consumers) and the offer price of the WT generators at each bus.

Figure 7 shows the total amount of power dispatched by PV units at candidate buses 12,14, and 16 in all scenarios. Bus 12 and bus 16 have the lowest and the highest quantity of power dispatched in comparison to bus 14. This is due to the fact that the quantity of power dispatched by PV units at each bus is operating at their maximum and minimum power generation level, as well as the offer price of the PV units and bid price of the demand loads (consumers) at each candidate bus.

The energy storage system has two modes of operation: When the energy price is low, it operates as a load and stores energy and when the energy price is high, it operates as a producer of energy and sells it on the market at a profit. According to Figure 8, the ESS is scheduled to charge in 1-6 and 12-17 hours. During these hours, the ESS is charged with a total of 49.3 kW of power. While according to figure 9, the ESS is scheduled to discharge between 7-11 and 18-24 hours. The ESS has discharged a total of 49.2 kW of power. The ESS delivered the stored energy to meet the internal demand load of VPP. The ESS has performed well in terms of flattening the load curve. This mitigates the dependency of VPP on the utility grid while also lowering its overall energy cost.

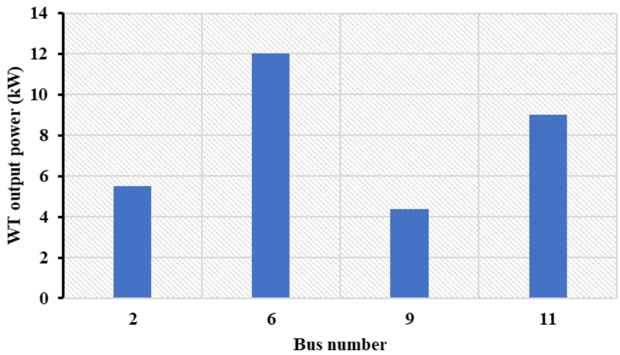

Fig. 6 Total active power dispatched by (WTs) in all scenarios at candidate buses

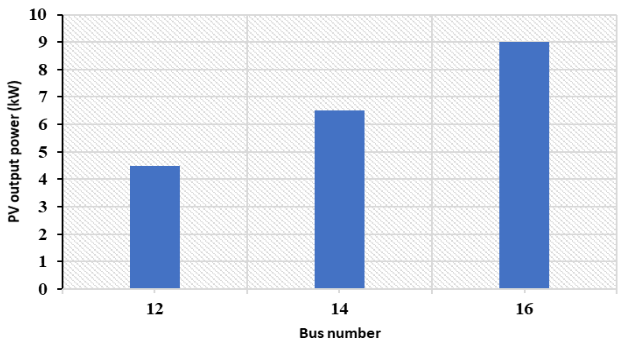

Fig. 7 Total active power dispatched by (PVs) in all scenarios at candidate buses

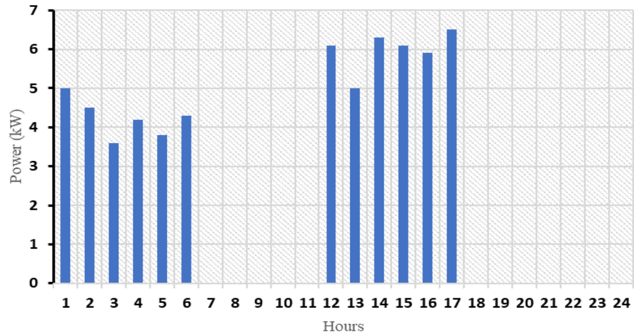

Fig. 8 Energy storage unit charging

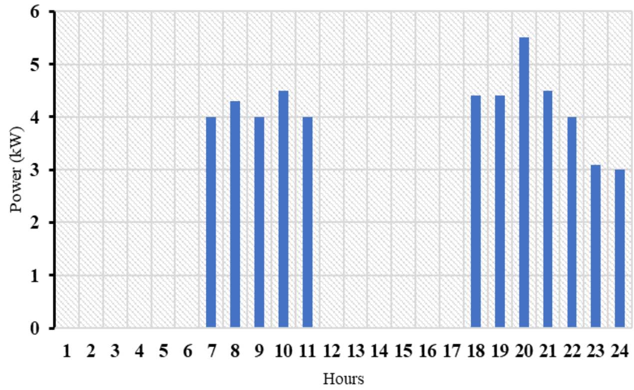

Fig. 9 Energy storage unit discharging

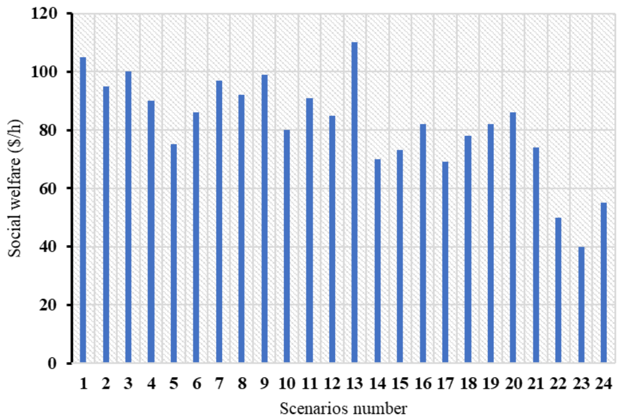

Fig 10 Social welfare in each scenario

Figure 10 shows the social welfare in each scenario over the planning horizon. In scenario 13, SW has the highest value, which is around (110 $/h). This is due to the fact that this scenario has the highest probability compared to others scenarios. While scenario 23 has the lowest value of SW (40 $/h). It is due to the fact that this scenario has the lowest probability compared to other scenarios.

Wind and solar energy, being clean technologies, significantly reduce pollution and have low operating costs. Therefore, these are compelling reasons to invest in renewable energy development and transition to cleaner energy solutions. The data from Figs 6 & 7 demonstrated that both WT and PV dispatched active power in the day-ahead market, relieving the peak load burden on the VPP by supplying to the VPP's internal demand load, as a result, it contributes to the curve of load demand becoming flattened. Moreover, it also brings economic value to the DGs' owners. It can be observed from the data in Figs 8 & 9 that ESS facilitated a greater usage of renewable energy generation. It provides security as well as a more sustainable system that is less vulnerable to interruptions. The electrical ESS increases the economic viability of wind turbines and photovoltaic energy and bolsters their competitiveness in the clean energy market. Moreover, the ESS provides a significant contribution by its rapid response to supply and demand imbalances.

In terms of social welfare maximization (i.e. maximum consumer's benefit minus cost of energy generation), this strategy could notably promote the participation of distributed generating units, particularly those with intermittent output, in the day-ahead market, considering system constraints and reliability. The performance and effectiveness of the proposed method have been validated using a 16-bus UKGDS. In comparison to passive networks, more wind energy could be incorporated into the grid. The findings of simulation studies revealed that the viability of VPPs in competitive power markets would be very susceptible to market price volatility, the determination of an appropriate reserve, as well as considering the volatility of these generation units. In addition, the proposed strategy has the potential to considerably relieve the load on distribution systems while simultaneously providing empirical recommendations for distribution system planning, development, and management. As a result, the system's overall benefits demonstrate the proposed method's optimal performance.

7. Conclusions and Future Research

In this study, a new MB-VPP's model has been designed and developed operating in the day-ahead power market. Scenario based approach is used to model the uncertainties associated with WTs, PVs, and load demand. This method evaluates WTs, PVs', and ESS total active power dispatch capacity to load. The proposed method is tested on a 16-bus UKGDS with WTs, PVs, ESS, and load demand. GAMS, an optimization tool is used to solve the problem as a MILP problem using a CPLEX solver. A case study is used to understand the usefulness and efficiency of the proposed model.

The simulation results have revealed that the VPP requires the minimum amount of electricity from the utility grid when all of its internal generators are in a state of operation supplying loads. The proposed strategy benefits VPP owners in making successful electricity market decisions. The energy storage system is permitted to charge when there is less demand (off-peak hours) and discharge when demand (peak-hours) is high. The ESS has performed well in terms of flattening the load curve and improving grid stability. Furthermore, the ESS is collaborating with the DGs aggregated in the VPPs to maximize resource utilization by exploiting their inherent charging and discharging characteristics.

The proposed model helps in the optimal delivery of power supply to the VPP customers. If the power generated by renewable energy sources is scheduled properly, the VPP can satisfy the day-ahead market's load demand while minimizing grid power imports, encouraging participants to increase their benefits by delivering more power to the grid on a price-based dispatch. In the above-mentioned case study, the renewable energy sources optimally dispatched the active power to meet the load demand. Further research that includes environmental goals can be incorporated in the VPP configuration in addition to pure economic optimization as well as integrating demand response (DR) programs and multi-energy systems in a market-based virtual power plant environment.

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