

# Virtual Power Plant Solution for Future Smart Energy Communities

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## Chapter 5

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A Comprehensive Smart Energy  
Management Strategy for TVPP, CVPP,  
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# 5 A Comprehensive Smart Energy Management Strategy for TVPP, CVPP, and Energy Communities

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## CONTENTS

5.1	Introduction .....	105
5.2	Objective .....	105
5.3	Mathematical Model of Optimization Engine in Different Operation Modes.....	105
5.3.1	TVPP Model .....	105
5.3.2	CVPP Model .....	109
5.3.3	Energy Community Model .....	109
5.4	Mathematical Model of Components Within the VPP.....	111
5.4.1	DG Units .....	111
5.4.2	ES Units .....	111
5.4.3	Flexible Loads .....	112
5.5	Numerical Analysis and Discussions.....	112
	Acknowledgement .....	116
	References .....	117

## NOMENCLATURES

### INDICES

<i>b, b'</i>	system buses
<i>i</i>	conventional diesel units
<i>es</i>	energy storage units
<i>pv</i>	PV generation sites
<i>Sb</i>	source buses
<i>fl</i>	flexible loads

$wf$	wind farms
$t$	time slots
$w$	scenarios
$m$	linear partitions in load flow linearization

## PARAMETERS

$\lambda_{w,t}^{DA}$	day-ahead market price scenarios (\$/kWh)
$\lambda_t^{Grid}$	upstream market price (\$/kWh)
$C_i^{DG}$	generation cost of DG units (\$/kWh)
$SUC_i^{DG}$	start-up cost of DG units (\$)
$INC_{fl}$	incentive payment for load curtailment (\$/kWh)
$P_{pv,w,t}^{PV}$	PV site generation scenarios (kW)
$P_{wf,w,t}^{Wind}$	wind farm generation scenarios (kW)
$P_{b,w,t}^D$	active power consumption scenarios (kW)
$R_{b,b'}/X_{b,b'}/Z_{b,b'}$	impedance elements of branches (Ohm)
$Q_{b,w,t}^D$	reactive power consumption scenarios (kVar)
$P_i^{DG,max}$	maximum DG capacity limit for active power (kW)
$P_i^{DG,min}$	minimum DG capacity limit for active power (kW)
$P_{es}^{DchES,max}/P_{es}^{ChES,max}$	maximum discharging/charging power of ES (kW)
$\alpha_{fl}^{flex}$	percentage of flexible load at each load point (%)
$V_b^{min}/V_b^{max}$	minimum/maximum allowable voltage magnitude of buses (kV)
$RU_i^{DG}/RD_i^{DG}$	ramp-up/down capability of DG units (kW/h)
$MUT_i/MDT_i$	minimum up/down time of DG units (h)
$LR_{fl}^{pickup}$	pickup rate of flexible loads (kW/h)
$LR_{fl}^{drop}$	drop-off rate of flexible loads (kW/h)
$\eta_{Ch}^{ES}/\eta_{Dch}^{ES}$	charging/discharging efficiency of ESs
$SOE_{es}^{ES,min}/SOE_{es}^{ES,max}$	minimum/maximum energy limit of ESs (kWh)
$\rho_w$	occurrence probability of scenarios

## VARIABLES

$P_{Sb,t}^{DA}$	the amount of selling or purchasing power in DA energy market (kW)
$P_t^{Grid}$	the amount of selling or purchasing power from upstream grid (kW)
$P_{i,w,t}^{DG}$	scheduled active output power of DG units (kWh)
$P_{fl,w,t}^{flex}$	curtailed active amount of flexible load (kWh)
$P_{es,w,t}^{ChES}/P_{es,w,t}^{DchES}$	scheduled charge/discharge power of ESs (kW)
$ V_{b,w,t} $	voltage magnitude of network buses (kV)
$I_{b,b',w,t}$	current of network branches (A)
$Q_{i,w,t}^{DG}$	scheduled reactive output power of DG units (kVarh)
$Q_{fl,w,t}^{flex}$	curtailed reactive amount of flexible load (kVarh)
$P_{b,b',w,t}^+/P_{b,b',w,t}^-$	auxiliary variables for active power flow (kW)
$Q_{b,b',w,t}^+/Q_{b,b',w,t}^-$	auxiliary variables for reactive power flow (kVar)

$U_{i,t}^{DG}$	binary variable indicates on/off situation of DG units
$U_{es,t}^{ES-Ch}$	binary variable indicates charge/discharge situation of ES units
$SOE_{es,w,t}^{ES}$	state of the energy level of ESs (kWh)

## 5.1 INTRODUCTION

In the context of future smart grids, the distributed and small-scale energy resources will play a more remarkable role in comparison with their present situation. One of the main technical and commercial challenges for integration of distributed energy resources (DERs) into the grid is their invisibility from system operator's viewpoint. Virtual power plant (VPP) concept seems an appropriate solution to tackle such a problem. In fact, a VPP is composed of small DERs (traditional and renewables), controllable loads, and energy storage (ES) devices and can coordinate them in order to provide several local and system services through participation in different electricity markets with the aim of maximizing its profits.

## 5.2 OBJECTIVE

As mentioned before, the VPP aggregates and manages not only distributed generations such as diesel generators (DGs), photovoltaic (PVs), and wind turbines (WTs) but also ESs as well as flexible loads (FLs) through an integrated optimization framework so that there is a maximization of its revenues in various electricity markets. In other words, a VPP is a flexible representation of a portfolio of DERs that can be used to make contracts in the wholesale market and offer services to the system operator. On this basis, the objective of this deliverable is to develop a centralized optimization engine for a VPP that can be operated in different modes, including technical VPP (TVPP) mode, commercial VPP (CVPP) mode, and also energy community (EC) mode according to the user preferences.

## 5.3 MATHEMATICAL MODEL OF OPTIMIZATION ENGINE IN DIFFERENT OPERATION MODES

### 5.3.1 TVPP MODEL

A TVPP is a type of VPP that consists of DERs from the same geographic location. The TVPP encompasses the real-time impacts of the local network on the aggregated profile of DERs as well as representing the cost and operating constraints of the portfolio. The TVPP can participate in day-ahead and intraday energy markets for purchasing or selling power on behalf of the existing resources under its umbrella. The operator of a TVPP, so-called VPP aggregator, requires detailed information of the local network as well as the existing resources [1]. In fact, in this case, the optimization engine must be considered the network structure and run an optimal power flow in order to avoid either feeder's congestion or voltage magnitude violation.

To model the stochastic nature of renewable resources as well as taking into account the electricity market price’s volatility, the proposed methodology makes use of a two-stage stochastic programming framework and considers a network-constrained market participation procedure from a TVPP point of view. The structuring of the stochastic programming problem into two stages is justified by the fact that the TVPP aggregator must submit its offers into different electricity markets, while facing a number of uncertainties such as volatility in market prices, load consumption, and generation of renewable resources. The proposed model has a hierarchical structure so that it encompasses both day-ahead and intraday time frames as can be observed in Figure 5.1.

In fact, the optimal strategy of VPP for participation in day-ahead energy market is determined at the first stage, while the second stage is assigned for intraday market decisions which are based on the updated information obtained between the closure of the day-ahead and the intraday energy markets.

The objective function of the TVPP is formulated in Eq. (5.1). The objective function is the total expected cost during the scheduling horizon, which contains three terms, including cost/revenue in day-ahead energy market, cost of DG power production, and incentive payment to FL, respectively. It is notable that the objective function that must be optimized for the second stage is completely similar to Eq. (5.1) with the difference that the power traded in day-ahead market is an input parameter since the day-ahead market has been cleared. In fact, the first term in the objective function must be substituted by the revenue or cost term for selling or purchasing power in intraday market.

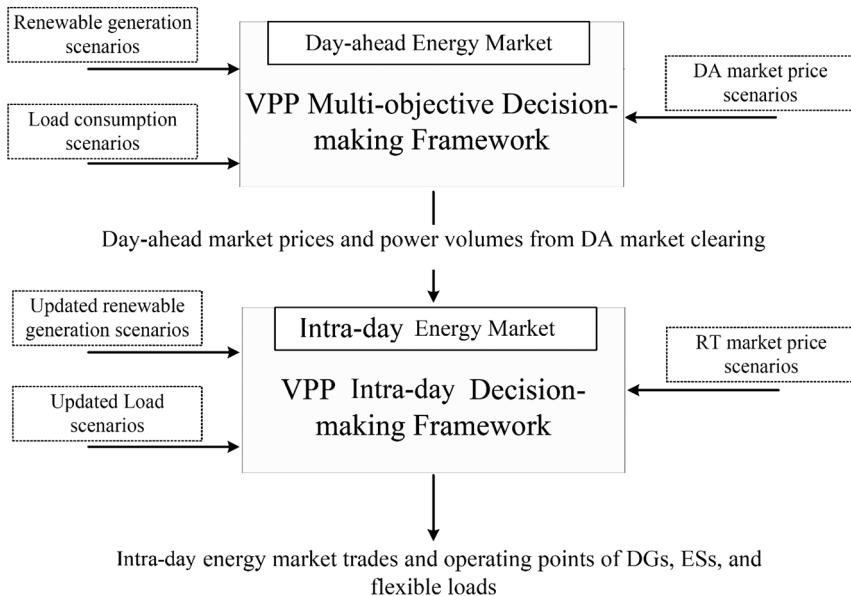


FIGURE 5.1 Schematic of the proposed hierarchical optimization model.

$$\begin{aligned}
Min \quad OF &= \sum_{w=1}^{NW} \rho_w (F_w^1 + F_w^2 + F_w^3) \\
F_w^1 &= \sum_{Sb=1}^{NSb} \sum_{t=1}^{NT} \lambda_{w,t}^{DA} P_{Sb,t}^{DA} \\
F_w^2 &= \sum_{t=1}^{NT} \sum_{i=1}^{NDG} [C_i^{DG} (P_{i,t}^{DG} + \Delta P_{i,w,t}^{DG}) + C_{\_Startup} p_{i,t}] \\
F_w^3 &= \sum_{t=1}^{NT} \sum_{fl=1}^{NFL} INC_{fl} P_{fl,w,t}^{flex}
\end{aligned} \tag{5.1}$$

The active and reactive power balance constraints have been formulated in Eqs. (5.2) and (5.3), respectively. Note that the first term in Eq. (5.2) is associated with power transactions with the upstream grid and just must be taken into account for the source bus.

$$\begin{aligned}
&\sum_{Sb \in b} P_{Sb,t}^{DA} + \sum_{i \in b} P_{i,w,t}^{DG} + \sum_{pv \in b} P_{pv,w,t}^{PV} + \sum_{wf \in b} P_{wf,w,t}^{Wind} + \sum_{es \in b} (P_{es,w,t}^{Dch} - P_{es,w,t}^{Ch}) \\
&+ \sum_{fl \in b} P_{fl,w,t}^{flex} + \sum_{b'} (P_{b',b,w,t}^{+} - P_{b',b,w,t}^{-}) \\
&- \sum_{b'} [(P_{b,b',w,t}^{+} - P_{b,b',w,t}^{-}) + R_{b,b'} I_{2b,b',w,t}] = P_{b,w,t}^D
\end{aligned} \tag{5.2}$$

$$\begin{aligned}
&\sum_{Sb \in b} Q_{Sb,t}^{DA} + \sum_{i \in b} Q_{i,w,t}^{DG} + \sum_{fl \in b} Q_{fl,w,t}^{flex} \\
&+ \sum_{b'} (Q_{b',b,w,t}^{+} - Q_{b',b,w,t}^{-}) \\
&- \sum_{b'} [(Q_{b,b',w,t}^{+} - Q_{b,b',w,t}^{-}) + X_{b,b'} I_{2b,b',w,t}] = Q_{b,w,t}^D
\end{aligned} \tag{5.3}$$

The active and reactive power relations are considered according to the power factor concept as can be observed in the following equation.

$$\begin{aligned}
Q_{b,w,t}^D &= PF \times P_{b,w,t}^D \\
Q_{Sb,t}^{DA} &= PF \times P_{Sb,t}^{DA} \\
Q_{fl,w,t}^{flex} &= PF \times P_{fl,w,t}^{flex}
\end{aligned} \tag{5.4}$$

The TVPP must consider the power flow restrictions within its optimization model. On this basis, the linear form of load flow equations has been formulated in Eqs. (5.5)–(5.15) [2].

$$V2_{b,w,t} - 2R_{b,b'}(P_{b,b',w,t}^+ - P_{b,b',w,t}^-) + X_{b,b'}(Q_{b,b',w,t}^+ - Q_{b,b',w,t}^-) - Z2_{b,b'} I2_{b,b',w,t} - V2_{b',w,t} = 0 \quad (5.5)$$

$$V2_{b,w,t}^{Rated} I2_{b,b',w,t} = \sum_{m=1}^{NM} [(2m-1)\Delta S_{b,b',w,t} \Delta P_{b,b',m,w,t}] + \sum_{m=1}^{NM} [(2m-1)\Delta S_{b,b',w,t} \Delta Q_{b,b',m,w,t}] \quad (5.6)$$

$$P_{b,b',w,t}^+ + P_{b,b',w,t}^- = \sum_{m=1}^{NM} \Delta P_{b,b',m,w,t} \quad (5.7)$$

$$Q_{b,b',w,t}^+ + Q_{b,b',w,t}^- = \sum_{m=1}^{NM} \Delta Q_{b,b',m,w,t} \quad (5.8)$$

$$0 \leq \Delta P_{b,b',m,w,t} \leq \Delta S_{b,b',w,t} \quad (5.9)$$

$$0 \leq \Delta Q_{b,b',m,w,t} \leq \Delta S_{b,b',w,t} \quad (5.10)$$

$$\Delta S_{b,b',w,t} = (V^{Rated} I_{b,b'}^{\max}) / NM \quad (5.11)$$

$$0 \leq I2_{b,b',w,t} \leq |I_{b,b'}^{\max}|^2 \quad (5.12)$$

$$0 \leq P_{b,b',w,t}^+ + P_{b,b',w,t}^- \leq V^{Rated} I_{b,b'}^{\max} \quad (5.13)$$

$$0 \leq Q_{b,b',w,t}^+ + Q_{b,b',w,t}^- \leq V^{Rated} I_{b,b'}^{\max} \quad (5.14)$$

$$|V_b^{\min}|^2 \leq V2_{b,w,t} \leq |V_b^{\max}|^2 \quad (5.15)$$

Equation (5.5) is considered with the aim of balancing voltage between two nodes. It is notable that  $V2$  in Eq. (5.5) is an auxiliary variable that shows the linear form of squared voltage relation. Also, linearization of active and reactive power flows that appear in the apparent power is formulated in Eq. (5.6). Equations (5.7)–(5.11) have been formulated for piecewise linearization. The number of blocks needed to linearize the quadratic curve is considered to be five based on [3], which maintains

the right balance between accuracy and computational requirements. Further descriptions and justifications of the network model used can be found in [4, 5]. The maximum allowable current flow of branches is taken into account in Eq. (5.12). Note that  $I2$  refers to an auxiliary variable that demonstrates linear form of the squared current flow  $I^2$  in a given branch. Moreover, at most one of these two positive auxiliary variables, i.e.,  $P_{b,b',w,t}$  and  $Q_{b,b',w,t}$ , can be nonzero in a time. This condition is again implicitly enforced by optimality. Equations (5.13) and (5.14) restrict these variables through the maximum apparent power for completeness. Finally, Eq. (5.15) represents the allowable voltage magnitude at each node. The remaining constraints are associated with the existing resources within the TVPP, which are presented in the following.

### 5.3.2 CVPP MODEL

CVPP performs commercial aggregation and does not take into account any network operation aspects that active distribution networks have to consider for stable operation [6]. The aggregated DER units are not necessarily constrained by location but can be distributed throughout different distribution grids. Hence, a single distribution network region may have more than one CVPP-aggregating DER units in its region. The objective function of CVPP is completely similar to Eq. (5.1); however, the active power balance constraint is different due to non-consideration of network. Also, there is no need to consider reactive power in the case of CVPP due to the same reason. The active power balance constraint for CVPP is modelled in Eq. (5.16).

$$P_t^{DA} + \sum_i P_{i,w,t}^{DG} + \sum_{pv} P_{pv,w,t}^{PV} + \sum_{wf} P_{wf,w,t}^{Wind} + \sum_{es} (P_{es,w,t}^{Dch} - P_{es,w,t}^{Ch}) + \sum_{fl} P_{fl,w,t}^{flex} = P_{w,t}^D \quad (5.16)$$

The remaining constraints are assigned to the existing resources within the CVPP, which are presented in the following.

### 5.3.3 ENERGY COMMUNITY MODEL

EC is an innovative concept that has been developed to facilitate grid integration of small-scale renewable energy resources, optimize the consumption pattern of customers, and alleviate the loading of the grid through using available flexibility of active prosumers. In the following, a general model of an EC consisting of several small-scale resources is given. It is notable that these resources are spatially very close to each other and connected to the same distribution network. Also, it is assumed that there is a non-profit community coordinator who dispatches the existing resources within the community and manages the transactions with upstream utility as well as other ECs in order to supply the load with minimum cost. The conceptual schematic of the considered model is presented in Figure 5.2.

As it can be observed in Figure 5.2, the EC coordinator runs the local market in order to find an optimal dispatch for the components within the EC, including PV generation, FLs, DGs, and ES units. In this regard, the ECs can also have transactions with other ECs in order to share their available flexibility with each other.



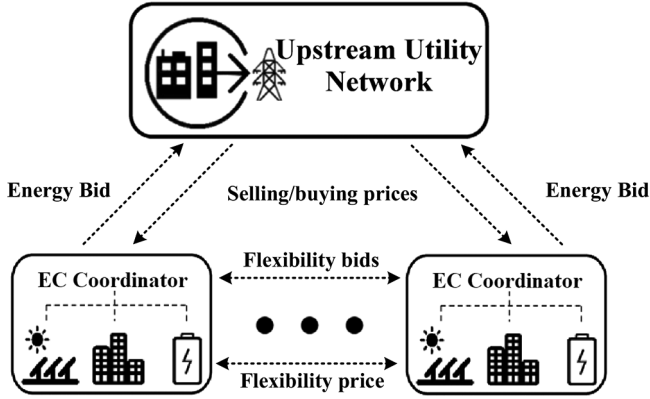


FIGURE 5.2 Conceptual schematic of energy community model.

Moreover, the ECs can buy or sell power to the upstream utility with the aim of ensuring power balance within the community. The mathematical formulation of EC is presented later.

The objective function is a cost minimization problem that has been formulated in Eq. (5.17). The first and second terms in the first line of the objective function represent the costs/revenues as a result of transactions with the upstream utility. The first term in the second line of Eq. (5.17) associates with the cost of DG’s power generation containing their start-up cost. Finally, the last term of objective function is assigned to incentive payments for load curtailment through FLs.

$$\begin{aligned}
 \text{Min } OF = & \Delta \times \sum_{t=1}^{NT} \lambda_t^{Grid} P_t^{Grid} \\
 & + \sum_{t=1}^{NT} \sum_{w=1}^{NW} \rho_w \left\{ \sum_{i=1}^{NDG} \left[ \Delta \times C_i^{DG} P_{i,w,t}^{DG} + C_{-Startup_{i,t}} \right] \right. \\
 & \left. + \Delta \times \sum_{fl=1}^{NFL} INC_{fl} P_{fl,w,t}^{flex} \right\} \quad (5.17)
 \end{aligned}$$

The  $\Delta$  in the previous equation represents the time step coefficient and can be defined as  $\Delta = Time\_step/60$ . The  $Time\_step$  in fact indicates the resolution of optimization time slots in minutes. The previous objective function should be minimized while satisfying a number of constraints for different devices. The EC power balance constraint has been modelled in Eq. (5.18).

$$P_t^{Grid} + \sum_{pv=1}^{NPV} P_{pv,w,t}^{PV} + \sum_{i=1}^{NDG} P_{i,w,t}^{DG} + \sum_{fl=1}^{NFL} P_{fl,w,t}^{flex} + \sum_{es=1}^{NES} (P_{es,w,t}^{DchES} - P_{es,w,t}^{ChES}) = P_{w,t}^D \quad (5.18)$$

## 5.4 MATHEMATICAL MODEL OF COMPONENTS WITHIN THE VPP

This section is assigned to the model of existing resources within the VPP and is similar for all operation modes, i.e., TVPP, CVPP, or EC. The considered components are DGs, ESs, and FLs that are modelled in this section. Note that the renewable generations such as PV and WT have been taken into account. According to the priority of renewable resources in dispatch, these resources are modelled to such a negative demand. In fact, the whole production of these resources is integrated into the VPP power scheduling. Moreover, the operation costs of the mentioned resources assume to be zero that is a logical assumption.

### 5.4.1 DG UNITS

The constraints in Eqs. (5.19)–(5.25) are related to technical restrictions of DGs. The minimum and maximum ranges of output power of DGs are shown in Eq. (5.19). The ramp-up and ramp-down capabilities of conventional DGs are formulated in Eqs. (5.20) and (5.21), separately. Equation (5.22) is assigned to start-up cost of DGs. Moreover, Eqs. (5.23) and (5.24) indicate minimum up and down time limitations of DGs, respectively.

$$P_i^{DG,\min} U_{i,t}^{DG} \leq P_{i,w,t}^{DG} \leq P_i^{DG,\max} U_{i,t}^{DG} \quad (5.19)$$

$$P_{i,w,t+1}^{DG} - P_{i,w,t}^{DG} \leq \Delta \times RU_i^{DG} \quad (5.20)$$

$$P_{i,w,t}^{DG} - P_{i,w,t+1}^{DG} \leq \Delta \times RD_i^{DG} \quad (5.21)$$

$$\begin{aligned} C\_Startup_{i,t} &\geq SUC_i \times (U_{i,t}^{DG} - U_{i,t-1}^{DG}) \quad \text{for } t > 1 \quad \text{and} \\ C\_Startup_{i,t} &\geq SUC_i \times U_{i,t}^{DG} \quad \text{for } t = 1 \\ C\_Startup_{i,t} &\geq 0 \end{aligned} \quad (5.22)$$

$$\sum_{t'=t}^{t+MUT_i-1} (1 - U_{i,t'}^{DG}) + MUT_i (U_{i,t}^{DG} - U_{i,t-1}^{DG}) \leq MUT_i \quad (5.23)$$

$$\sum_{t'=t}^{t+MDT_i-1} U_{i,t'}^{DG} + MDT_i (U_{i,t-1}^{DG} - U_{i,t}^{DG}) \leq MDT_i \quad (5.24)$$

### 5.4.2 ES UNITS

The constraints of ESs that should be satisfied are formulated in Eqs. (5.25)–(5.30). Limitations on charging and discharging power of ESs are modelled in Eqs. (5.25) and (5.26). The state of energy (SOE) level and its limits are also given in Eqs. (5.27)

and (5.28), separately. Furthermore, it is presumed that the SOE level at the end of scheduling period must be greater or equal to the amount of SOE at the beginning of scheduling period as formulated in Eq. (5.29). This is due to the fact that the ES units must have sufficient energy for the next day.

$$0 \leq P_{es,w,t}^{ChES} \leq \Delta \times P_{es}^{ChES,max} \times U_{es,t}^{ES-Ch} \quad (5.25)$$

$$0 \leq P_{es,w,t}^{DchES} \leq \Delta \times P_{es}^{DchES,max} \times (1 - U_{es,t}^{ES-Ch}) \quad (5.26)$$

$$SOE_{es,w,t}^{ES} = SOE_{es,w,t-1}^{ES} + \eta_{Ch}^{ES} P_{es,w,t}^{ChES} - P_{es,w,t}^{DchES} / \eta_{Dch}^{ES} \quad (5.27)$$

$$SOE_{es}^{ES,min} \leq SOE_{es,w,t}^{ES} \leq SOE_{es}^{ES,max} \quad (5.28)$$

$$SOE_{es,w,t}^{ES} \Big|_{t=NT} \geq SOE_{es}^{ES,ini} \quad (5.29)$$

### 5.4.3 FLEXIBLE LOADS

The other set of constraints is associated with FLs as shown in Eqs. (5.30)–(5.32). Equation (5.30) restricts the amount of FL due to the fact that just a portion of the load is flexible. Also, the maximum load-pickup and load-drop rates for flexible demand are stated in Eqs. (5.31) and (5.32), respectively.

$$0 \leq P_{fl,w,t}^{flex} \leq \alpha_{fl}^{flex} P_{w,t}^D \quad (5.30)$$

$$P_{fl,w,t}^{flex} - P_{fl,w,t-1}^{flex} \leq \Delta \times LR_{fl}^{pickup} \quad (5.31)$$

$$P_{fl,w,t-1}^{flex} - P_{fl,w,t}^{flex} \leq \Delta \times LR_{fl}^{drop} \quad (5.32)$$

## 5.5 NUMERICAL ANALYSIS AND DISCUSSIONS

In order to show the effectiveness of the proposed model, some numerical analyses have been reported in this section. To this end, a CVPP is considered with the following assets. There is a 500-kW wind farm and a 200-kW PV site so that each of the wind farm and PV site generation is modelled considering three independent scenarios, including as forecast, high, and low, with probabilities 0.6, 0.2, and 0.2, respectively. Also, there is one ES unit with the energy capacity of 200 kWh and maximum charging/discharging rates of 100 kW/h. The charge and discharge efficiencies of ES are assumed to be 85%. In addition, it is assumed that the maximum

**TABLE 5.1**  
**DGs Technical and Cost Data**

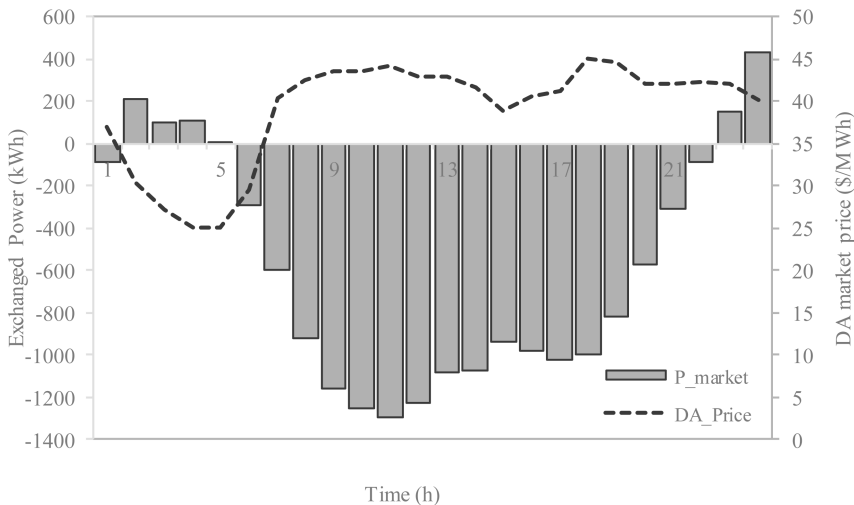
	$P_i^{max}$ (kW)	$P_i^{min}$ (kW)	$RU_i$ (kW/h)	$RD_i$ (kW/h)	$SUC_i$ (\$)	$C_i$ (\$/kWh)
DG 1	600	100	105	120	20	0.040
DG 2	950	200	175	200	30	0.035

and minimum SOE of the ES are equal to 90% and 10% of its energy capacity due to life-time considerations. The initial SOE of ES is 50% of its energy capacity.

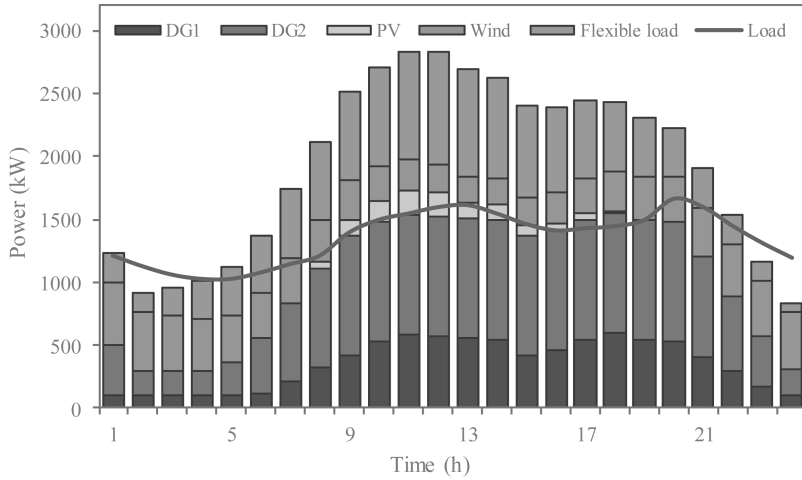
It is assumed that only there are three FLs so that they can curtail 20% of their initial consumption in each hour in response to 0.035 \$/kWh as an incentive payment. The load-pickup and load-drop rates are considered to be 25 kW/h. Furthermore, two conventional DGs are available with technical characteristics as well as cost terms reported in Table 5.1.

Figure 5.3 represents the trading power of CVPP in the day-ahead market. In this figure, the positive values are assigned to purchased power, while the negative values represent the sold power in the day-ahead market. According to this figure, it is obvious that the CVPP purchases power in time periods with low market prices (early morning and end of the night), whereas it sells power to the market during the day when the market price is relatively high.

The obtained results for the optimal dispatch of various components belonging to CVPP have been reported in Figure 5.4. According to Figure 5.4, when the aggregated generation is more than consumption, the CVPP sells the extra power to the market and vice versa. It is obvious that both DGs are generating so that their generation in the early morning and end of the day is set to minimum, and during the day,



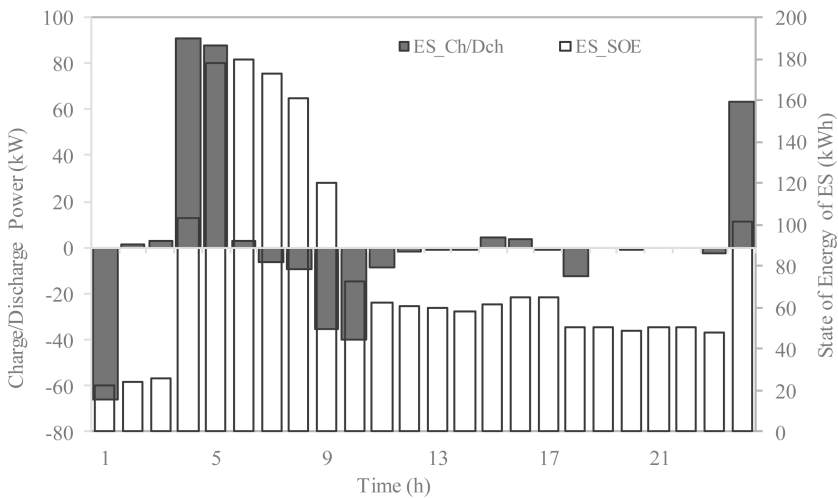
**FIGURE 5.3** CVPP trading power vs. expected day-ahead market prices.



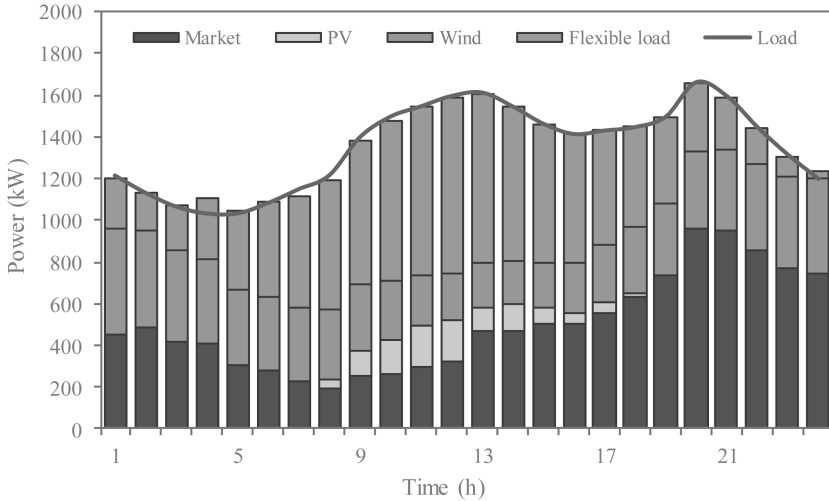
**FIGURE 5.4** Power dispatch of components belongs to CVPP.

these DGs generate with full capacity due to the fact that their generation costs are lower than market prices. Moreover, it can be seen that the CVPP utilizes the FLs at all the periods.

The charging and discharging plan of ES during the scheduling horizon has been illustrated in Figure 5.5. As it can be seen, the ES unit charges during the early morning period, particularly at hours 4:00 and 5:00, and injects its power to the grid during the day, specifically between 7:00 and 11:00. The charging and discharging plan of ES unit is completely based on the day-ahead market variations. In fact, in



**FIGURE 5.5** Charging power, discharging power, and state of energy of ES.



**FIGURE 5.6** Power dispatch of components belongs to CVPP with emission cost consideration.

addition to ES role in facilitating the integration of renewable generations such as PV and WT, it uses the energy price arbitrage and makes more profit for CVPP.

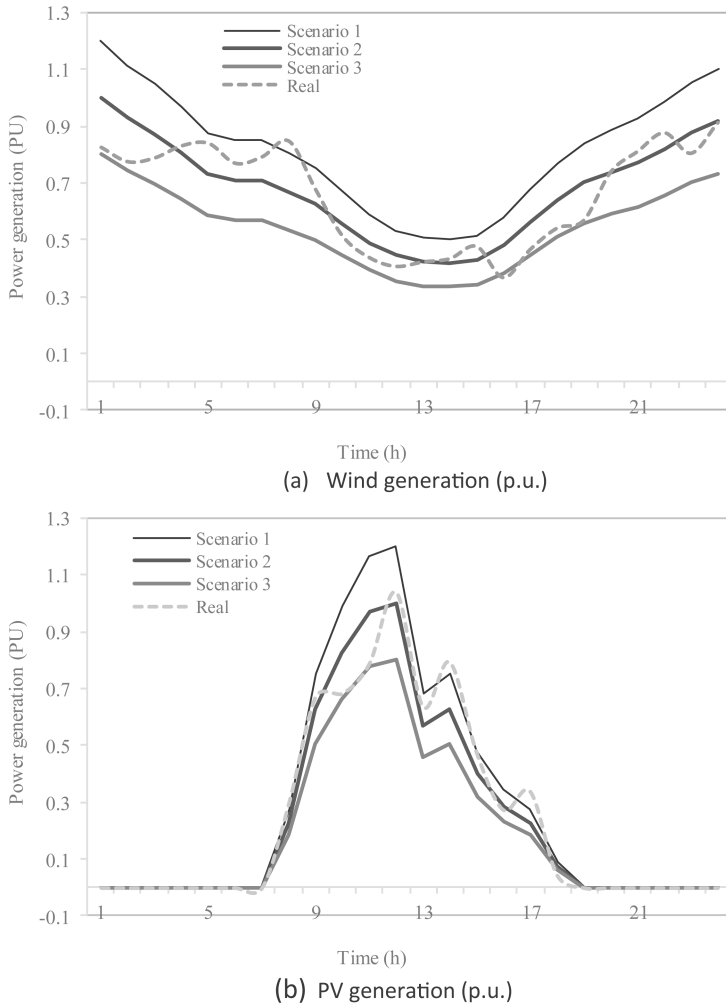
The other important points that can affect the CVPP strategy is consideration of pollutant emission cost for DGs due to the fact that the DG’s technology is mainly based on diesel burning. In this case, it is assumed that the costs of DGs are multiplied by 1.3. On this basis, both of the DGs never generate and the CVPP is forced to purchase power from market at all time. The power dispatch in this case is shown in Figure 5.6.

As mentioned in the modelling part, the stochastic programming approach has been used here in order to take into account the uncertainties of renewables, load, and market price. In order to evaluate the impacts of forecasted parameters on the power dispatch of various resources, the obtained results for the real case are compared with outputs of the stochastic model. The forecasted scenarios for PV and WT have been compared with the real generation in Figure 5.7.

In such a situation, the obtained results for the cost terms of objective function have been compared in Table 5.2.

**TABLE 5.2**  
**Comparison of Cost Terms in Objective Function**

Case	Market Transaction		Flexible Load	
	Cost (\$)	DG Cost (\$)	Cost (\$)	Total Cost (\$)
Scenario-based	-586.5	965.6	420.7	799.8
Real data	-588.9	973.1	414.0	798.2

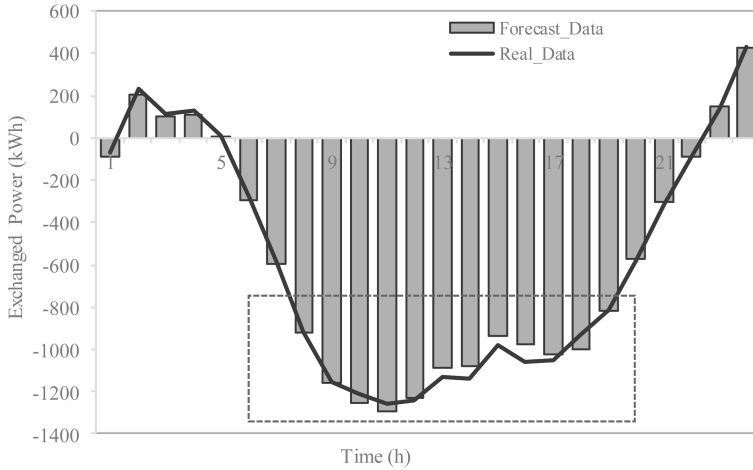


**FIGURE 5.7** Scenarios and real data of renewable generation: (a) Wind generation (p.u.) and (b) PV generation (p.u.)

The obtained results for market transactions of the CVPP in two mentioned cases (real and forecasted data) have been compared in Figure 5.8. As observed, the proposed model is relatively robust in the face of forecast tool’s error. However, there are some deviations in the number of time slots (red box).

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**FIGURE 5.8** CVPP trading power comparison in two defined cases.

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