Chapter 6
Offering Strategy of Thermal-Photovoltaic-Storage Based Generation Company in Day-Ahead Market

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6.1 Introduction

Sustainability and environmentally friendly as well as diminishing fossil fuel consumption are among the main benefits of turning to clean energy sources. However, these sources of energy are not free from defects, high investment costs, the intermittent output power of some of these resources (e.g., wind and solar units), and dependence on climate can be enumerated as the disadvantages of renewable energy sources. Nevertheless, the advantages of renewable energy sources preponderate over its disadvantages. In 2016, 52.4% of the electricity

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consumed by Danish consumers was supplied by renewable energy sources, which 37.6 and 2% were the shares of wind and photovoltaic units, respectively [1]. It should be mentioned that in 2017 43.7 % of Denmark's electricity demand was supplied through wind power share, which until now was the highest percentage of wind power contribution in Denmark's electricity industry [2].

Renewable energy sources with a large capacity or a group of renewable energy sources owned by a generation company (GenCo) must design appropriate offering strategies to achieve the maximum profit by participating in various electricity markets. Different attitudes and approaches in this problem, along with the representation of various mathematical models in accordance with the real technical specifications of generation units, are among the unique aspects of these studies in the literature of offering strategy problem. The offering strategy of a pumped-storage power plant in energy and ancillary services market is studied in [3, 4]. Contrary to [3], authors in [4] considered the risk associated with price forecasting errors of target markets using the covariance matrix in the process of maximizing profits. In [5], a risk-based offering strategy for a sample GenCo is proposed. Modeling the uncertainty associated with rival's behavior with the Monte Carlo technique and optimizing the whole proposed problem via SPSO-TVAC (self-organizing particle swarm optimization time-varying acceleration coefficients) is the main contribution of this work. In [6], an optimal offering strategy model for an emission-constrained GenCo is proposed. The authors modeled the electricity market price uncertainty through a set of scenarios while several emission allowances are considered to evaluate the impact of this parameter on GenCo's expected profit.

Another challenge faced by researchers in the optimal offering strategy problem is how to deal with the unspecified nature of parameters playing key roles in the optimization process. To this end, various approaches have been proposed by researchers of this field to deal with the uncertainties of the bidding strategy problem. Uncertainty management through a set of scenarios in the form of stochastic programming has been considered in [7]. That paper focuses on the offering strategy of a wind-hydro-pumped storage system, while water inflows for the reservoirs, markets prices, and wind power output are the considered uncertainties in this work. A stochastic bi-level self-scheduling framework for a GenCo in coordination with an electric vehicle load aggregator is suggested in [8], while the uncertainties related to wind power production and driving pattern of electric vehicle owners are modeled using appropriate scenario generation techniques. Also, authors in [9] have proposed a coordinated offering strategy for combined heat and power (CHP) units and renewable energy sources through the concept of the virtual power plant while the uncertain sources are taken into account with numerous scenarios. Robust optimization is another common approach in engineering and economic studies that assists the decision-maker in designing a suitable strategy for the worst realization of the uncertain parameters [10]. Kabiri Renani et al. [10] developed the SS problem for a transmission-constrained GenCo with incomplete market information while the robust optimization is used to deal with locational market prices (LMPs) and wind power production. In [11], the authors have developed a novel method for optimal participating of the wind power producers (WPP) in the day-ahead (DA) electricity market while the uncertainty associated with wind power and electricity prices are considered via stochastic scenarios. The authors benefit from kernel density estimation for modeling wind power uncertainty. In [12], short-term offering strategy for a price maker wind power producer has been introduced. The considered WPP in that paper is treated as a price-taker agent in the day-ahead market while its treatment in the balancing market is like a price-maker agent. Information gap decision theory (IGDT) [13], interval optimization [14], and hybrid probabilistic–possibilistic techniques [15, 16] are other approaches that have been repeatedly investigated by diverse researchers to cope with uncertainties in electricity market issues.

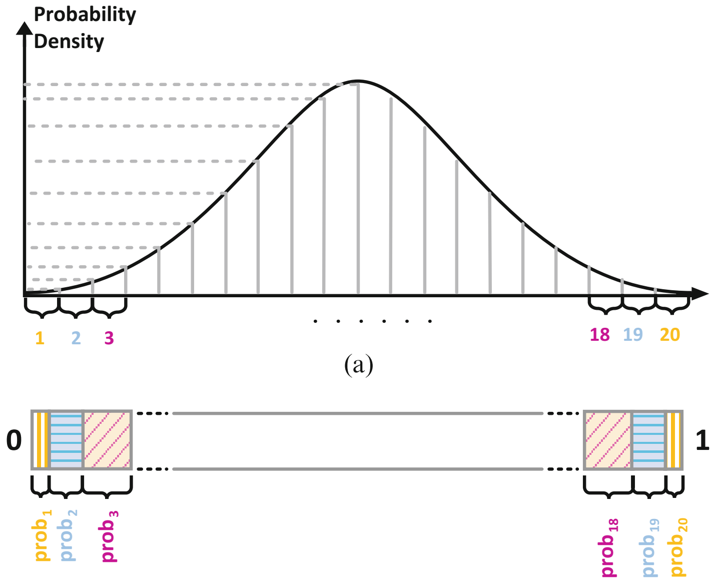
This chapter provides a risk-constrained offering strategy for a thermal-photovoltaic-battery storage (TPVBS) GenCo in the DA market. The uncertainty that stems from the DA and imbalance prices as well as photovoltaic (PV) production are taken into consideration via a set of scenarios. The offering strategy problem is formulated as a multi-stage stochastic programming problem while the emission limitations concerning the thermal units are incorporated in the offering process and the associated risk is modeled through conditional value at risk (CVaR) technique. The optimal offering strategy of the TPVBS system is examined in various risk levels, especially in both emission-constrained and emission-free conditions, and finally, appropriate offering curves will be obtained.

In the next section, the uncertainty modeling of input parameters, including electricity market prices and output power of the PV system, are described. Then the precise formulation of the proposed problem is presented. In the next section, numerical studies are conducted, and the simulation results are discussed. Eventually, the research findings are explained.

6.2 Uncertainty Modeling

In this chapter, uncertain sources are split into two categories: electricity prices and renewable production. The price of electricity in various markets is the most substantial factor affecting the offering strategy problem, which is entirely faced with many uncertainties. On the other hand, the output of the PV site is proportional to the solar irradiance, which is an uncertain parameter. Despite the almost zero irradiance during night-long, it is not even possible to consider a specified value for this parameter throughout the daylight. A variety of factors, including season and climatic conditions have the potential to affect the solar irradiance. For example, during certain hours of the daylight, solar radiation may be at the highest level, but due to specific weather conditions, such as cloudy weather, this potential can be significantly reduced. In the present chapter, normal and beta distributions are utilized to characterize the market prices and solar irradiance, respectively [17].

After modeling the probabilistic behavior of uncertain parameters with proper distribution functions, the roulette wheel technique (RWT) will be applied for scenario generation [18]. To this end, first, the continuous probability density



(a)

(b)

Fig. 6.1 A typical PDF and its relevant roulette wheel technique. (**a**) PDF of electricity prices. (**b**) Roulette wheel technique

functions (PDF) of each parameter are divided into 20 levels with their relevant normalized probabilities as depicted in Fig. 6.1a for the normal PDF. It is noteworthy to say that the number of levels for each parameter is selected in such a way that it does not reduce the precision of the proposed method and not raise the intricacy of the problem [18]. Next, as shown in Fig. 6.1, the interval [0, 1] is occupied by the different levels of discretized probability density function concerning their normalized probabilities. Then, a random number in the range of [0, 1] pertaining to each uncertain parameter is generated. This random number will be allocated to a specified level of the roulette wheel, which will represent the corresponding realization of the uncertain parameter in each scenario. This procedure will be reiterated till the required number of scenarios is attained. It is undeniable that considering a large number of scenarios will lead to an intractable problem. To this end, fast forward reduction technique is employed to reduce the initially generated scenarios [19]. Consequently, by applying this method, the initial scenarios pertaining to the electricity market prices (DA and imbalance prices) and solar irradiance are reduced to ten scenarios for each separate parameter. Eventually, the final set of scenarios for the proposed offering strategy problem will contain 1000 scenarios (10^3). It is worth highlighting that the current chapter does not cope with the correlation between electricity prices and renewable power production. A survey on the correlation between all uncertain parameters entails a new topic which is outside the scope of this chapter.

6.3 Problem Formulation

The offering strategy problem from the perspective of GenCos is an issue to maximize total profit in the intended scheduling horizon. In this problem, a suitable strategy for the participation of TPVBS system in the DA market is provided. The scheduling period is 24 h, and the uncertainty that originates from market prices (DA and imbalance prices) and production power of the PV site are characterized via appropriate scenarios. The proposed decision framework in the offering strategy problem is divided into three stages, which the classification of these decisions is presented in Table 6.1.

In the following subsections, at first, the objective function of the coordinated operation of all three sources, i.e., thermal units, PV site, and BSS, is presented, and then, the relevant constraints of the offering strategy problem will be entirely described.

6.3.1 *Objective Function*

The CVaR-based objective function of the suggested offering strategy for a sample TPVBS system shown in Fig. 6.2 with the aim of profit maximization is developed as a mixed integer programming (MIP) problem as follows:

$$\begin{aligned}
\text{Max}\quad PF^{TPVBS} = \sum_{s=1}^{S} prob_s \times \Bigg[\sum_{t=1}^{T} \Bigg\{ & \left(\vartheta_{t,s}^{DA}\chi_{t,s}^{DA,th}\right) + \left(\vartheta_{t,s}^{DA}\chi_{t,s}^{DA,PV}\right) \\
& + \left(\vartheta_{t,s}^{DA}\chi_{t,s}^{DA,BS,dis}\right) - \left(\vartheta_{t,s}^{DA}\chi_{t}^{DA,BS,ch}\right) \\
& + \left(\vartheta_{t,s}^{DA}\rho_{t,s}^{+}\delta_{t,s}^{+}\right) - \left(\vartheta_{t,s}^{DA}\rho_{t,s}^{-}\delta_{t,s}^{-}\right)
\end{aligned}$$

Table 6.1 Classification of decisions in the proposed three-stage stochastic programming framework

First stage decisions	Charging power of BSS and operation status of BSS and thermal units
Second stage decisions	Offering curves of the TPVBS system in the DA market
Third stage decisions	Imbalance costs/incomes in the balancing market due to energy deviations in this market

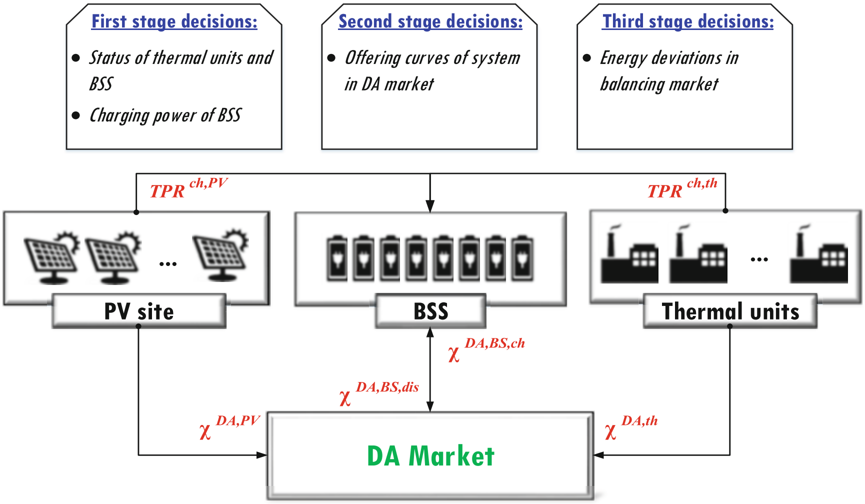


Fig. 6.2 Schematic of the proposed GenCo

$$-\sum_{g=1}^{G} CF_{g,t,s}\left(PR_{g,t,s}^{DA,th}+PR_{g,t}^{ch}\right)\Big\}\Big] - \sum_{t=1}^{T}\sum_{g=1}^{G}\left(U_{g,t}+D_{g,t}\right)$$

$$+\beta\left(\gamma-\frac{1}{1-\alpha}\sum_{s=1}^{S} prob_s\eta_s\right) \tag{6.1}$$

where the first two parentheses are related to the participation of thermal units and PV site in the DA market, respectively. The next two parentheses represent the income and expense terms of BSS for selling/buying energy in/from the DA market. The third row refers to income and expense of TPVBS system in the balancing market, while the fourth row calculates the costs arising from thermal units for the energy production as well as their start-up and shut-down. Finally, the last row represents the risk modeling term, namely CVaR.

6.3.2 Emission Constraint

In this chapter, it assumed that our TPVBS system is an emission-constrained power producer, which in certain circumstances, it cannot exceed the specified level of emission during the scheduling period. Equation (6.2) calculates the total expected emission of thermal units while the emission limitation of TPVBS system is imposed by (6.3).

$$EM^{TPVBS} = \sum_{s=1}^{S} prob_s \times \left[\sum_{\kappa}^{\mathrm{SO_2,\,NO_X}} \sum_{g=1}^{G} E_{\kappa,g} \times \left(PR_{g,t,s}^{DA,th} + PR_{g,t}^{ch} \right) \right] \tag{6.2}$$

$$EM^{TPVBS} \leq E_{\max} \tag{6.3}$$

6.3.3 CVaR Constraints

The constraints related to the applied risk index, i.e., CVaR, are expressed by the following equations:

$$\begin{aligned} & \left[\sum_{t=1}^{T} \left\{ -\left(\vartheta_{t,s}^{DA} \chi_{t,s}^{DA,th} \right) - \left(\vartheta_{t,s}^{DA} \chi_{t,s}^{DA,PV} \right) - \left(\vartheta_{t,s}^{DA} \chi_{t,s}^{DA,BS,dis} \right) \right. \right. \\ & \quad + \left(\vartheta_{t,s}^{DA} \chi_{t}^{DA,BS,ch} \right) - \left(\vartheta_{t,s}^{DA} \rho_{t,s}^{+} \delta_{t,s}^{+} \right) \\ & \quad \left. \left. + \left(\vartheta_{t,s}^{DA} \rho_{t,s}^{-} \delta_{t,s}^{-} \right) + \sum_{g=1}^{G} CF_{g,t,s} \left(PR_{g,t,s}^{DA,th} + PR_{g,t}^{ch} \right) \right\} \right] \\ & \quad + \sum_{t=1}^{T} \sum_{g=1}^{N_G} \left(U_{g,t} + D_{g,t} \right) + \gamma - \eta_s \leq 0, \quad \forall s \end{aligned} \tag{6.4}$$

$$\eta_s \geq 0, \quad \forall s \tag{6.5}$$

6.3.4 Imbalance Constraints

Constraints (6.6)–(6.8) are utilized to address the imbalances in the offering strategy of TPVBS system. Constraints (6.6) and (6.7) are fulfilled to, respectively, limit the negative and positive energy deviations of TPVBS system in the balancing market while Eq. (6.8) calculates the total energy deviations in the aforementioned market.

$$0 \leq \delta_{t,s}^{-} \leq CAP^{PV} + \sum_{g=1}^{G} CAP_g^{th} u_{g,t} + CAP^{dis} v_t^{dis}, \quad \forall t, \forall s \tag{6.6}$$

$$0 \leq \delta_{t,s}^{+} \leq \chi_{t,s}^{DA,th} + \chi_{t,s}^{DA,BS,dis} + RP_{t,s}^{PV} - TPR_t^{ch,PV}, \quad \forall t, \forall s \tag{6.7}$$

$$\begin{aligned}\delta^{+}_{t,s}-\delta^{-}_{t,s}&=\left(\chi^{DA,th}_{t,s}+\chi^{DA,BS,dis}_{t,s}+RP^{PV}_{t,s}-TPR^{ch,PV}_{t}\right)\\&\quad-\left(\chi^{DA,th}_{t,s}+\chi^{DA,BS,dis}_{t,s}+\chi^{DA,PV}_{t,s}\right),\quad\forall t,\forall s\end{aligned}\tag{6.8}$$

6.3.5 BSS Constraints

The operational constraints of the BSS are introduced in this subsection. The total provided energy by all thermal units for charging the BSS is represented in (6.9). Constraints (6.10) and (6.11) enforce the limitations pertaining to the maximum charging and discharging capacities of BSS. Constraint (6.12) prevents concurrent discharging and charging of BSS. The energy level of BSS will be updated according to (6.13) while the boundaries of this energy level are imposed in (6.14).

$$\sum_{g=1}^{G}PR^{ch}_{g,t}=TPR^{ch,th}_{t},\quad\forall t\tag{6.9}$$

$$0\le\chi^{DA,BS,dis}_{t,s}\le CAP^{dis}v^{dis}_{t},\quad\forall t,\forall s\tag{6.10}$$

$$0\le\chi^{DA,BS,ch}_{t}+TPR^{ch,th}_{t}+TPR^{ch,PV}_{t}\le CAP^{ch}v^{ch}_{t},\quad\forall t,\forall s\tag{6.11}$$

$$v^{dis}_{t}+v^{ch}_{t}\le 1,\quad\forall t\tag{6.12}$$

$$\begin{aligned}EL^{BS}_{t,s}&=EL^{BS}_{t-1,s}-\left(\frac{1}{\Upsilon^{BS,dis}}\right)\left(\chi^{DA,BS,dis}_{t,s}\right)\\&\quad+\Upsilon^{BS,ch}\left(\chi^{DA,BS,ch}_{t}+TPR^{ch,th}_{t}+TPR^{ch,PV}_{t}\right),\quad\forall t,\forall s\end{aligned}\tag{6.13}$$

$$0\le EL^{BS}_{t,s}\le EL^{BS,\mathrm{Max}},\quad\forall t,\forall s\tag{6.14}$$

6.3.6 Thermal Units Constraints

Thermal units are subject to several technical limitations which each of them will be individually presented in the following. Equation (6.15) computes the aggregate amount of units' offer in the DA market, while constraint (6.16) ensures that the offered energy by each thermal unit should be bound within its allowable production limit. Constraint (6.17) limits the provided power by each thermal unit for charging the BSS. Constraints (6.18) and (6.19) are utilized to model the start-up and shut-down costs of thermal units. Finally, the technical limitations pertaining to minimum up/down times as well as ramp-up/-down rates of each thermal unit are imposed by (6.20)–(6.25).

$$\sum_{g=1}^{G} PR_{g,t,s}^{DA,th} = \chi_{t,s}^{DA,th}, \quad \forall t, \forall s \tag{6.15}$$

$$\mathrm{MIN}_{g}^{th} u_{g,t} \leq PR_{g,t,s}^{DA,th} + PR_{g,t}^{ch} \leq CAP_{g}^{th} u_{g,t}, \quad \forall g, \forall t, \forall s \tag{6.16}$$

$$0 \leq PR_{g,t}^{ch} \leq CAP^{ch} u_{g,t}, \quad \forall g, \forall t \tag{6.17}$$

$$0 \leq U_{g,t} \geq UC_{g} x_{g,t}, \quad \forall g, \forall t \tag{6.18}$$

$$0 \leq D_{g,t} \geq DC_{g} y_{g,t}, \quad \forall g, \forall t \tag{6.19}$$

$$\sum_{n=t-UT_g+1}^{t} x_{g,t} \leq u_{g,t}, \quad \forall g, \forall t \tag{6.20}$$

$$\left(\sum_{n=t-DT_g+1}^{t} y_{g,t} \right) + u_{g,t} \leq 1, \quad \forall g, \forall t \tag{6.21}$$

$$y_{g,t-1} - u_{g,t} + x_{g,t} - y_{g,t} = 0, \quad \forall g, \forall t \tag{6.22}$$

$$PR_{g,t,s}^{DA,th} + PR_{g,t}^{ch} = PR_{g,t,s}^{tot,th}, \quad \forall g, \forall t, \forall s \tag{6.23}$$

$$PR_{g,t,s}^{tot,th} \leq PR_{g,t-1,s}^{tot,th} + RU_{g} u_{g,t-1} + SRU_{g} x_{g,t}, \quad \forall g, \forall t, \forall s \tag{6.24}$$

$$PR_{g,t-1,s}^{tot,th} \leq PR_{g,t,s}^{tot,th} + RD_{g} u_{g,t} + SRD_{g} y_{g,t}, \quad \forall g, \forall t, \forall s \tag{6.25}$$

6.3.7 PV System Constraints

Equations (6.26)–(6.29) are applied to bound the DA offer of the PV system, the charging power provided by the PV system for BSS, and the aggregate amount of DA power and the charging power within the maximum capacity of PV site.

$$0 \leq \chi_{t,s}^{DA,PV} \leq CAP^{PV}, \quad \forall t, \forall s \tag{6.26}$$

$$0 \leq TPR_t^{ch,PV} \leq CAP^{PV}, \quad \forall t \tag{6.27}$$

$$0 \leq TPR_t^{ch,PV} \leq CAP^{ch}, \quad \forall t \tag{6.28}$$

$$0 \leq TPR_t^{ch,PV} + \chi_{t,s}^{DA,PV} \leq CAP^{PV}, \quad \forall t, \forall s \tag{6.29}$$

6.3.8 Offering Curves Constraints

In many electricity markets, the power producer will be asked to submit non-decreasing energy offers in the electricity markets. Consider two different scenarios s and $\widetilde{s}$ that $\vartheta_{t,s}^{DA}$ is greater than $\vartheta_{t,\widetilde{s}}^{DA}$. The non-decreasing constraints will enforce that the offering quantity for a specific hour t in scenario s should be greater than or equal to the bidding quantity in the scenario $\widetilde{s}$. In fact, these constraints prevent the submit of inconsequent offers by the power producer in the electricity markets. The non-decreasing energy offer in the DA market is modeled according to the following Eq. (6.30):

$$\chi_{t,s}^{DA,\Gamma} \leq \chi_{t,\widetilde{s}}^{DA,\Gamma}, \quad \forall s, \widetilde{s} : \left[\vartheta_{t,s}^{DA} \leq \vartheta_{t,\widetilde{s}}^{DA} \right], \quad \forall t \quad \& \quad \Gamma = th/PV/BS, dis \tag{6.30}$$

$$\chi_{t,s}^{DA,\Gamma} = \chi_{t,\widetilde{s}}^{DA,\Gamma}, \quad \forall s, \widetilde{s} : \left[\vartheta_{t,s}^{DA} = \vartheta_{t,\widetilde{s}}^{DA} \right], \quad \forall t \quad \& \quad \Gamma = th/PV/BS, dis \tag{6.31}$$

where Eq. (6.31) is used to ensure that energy offers in two distinct scenarios with the same realization of electricity prices must be identical. This limitation is called non-anticipativity constraint.

6.4 Numerical Results

6.4.1 Input Data

In this section, the simulation results related to the offering strategy of a TPVBS system are presented. The considered GenCo in this chapter comprises a PV site, a BSS, and a thermal power plant with the nominal capacities of 150 MW, 50 MW, and 794 MW, respectively. The technical specifications of the BSS have been shown in Table 6.2. The nominal capacity of BSS has been assumed 50 MW while its discharging and charging efficiencies are equal to 0.95 and 0.8, respectively. Data on the characteristics of every thermal unit has been provided in Tables 6.3 and 6.4. As can be seen from this table, the considered power plant includes fourteen units, in which their quadratic cost function has been linearized with four blocks [20]. The historical data of the first half of 2018 has been utilized for the uncertainty modeling of electricity prices [21], and solar irradiance [22] has been given in Fig. 6.3. The value of α is set to 0.95. The intended problem has been formulated as a MIP problem which CPLEX under general algebraic modeling system (GAMS) has been employed to solve the suggested offering strategy problem.

6.4.2 Simulation Results

First, the simulation results of the offering strategy of TPVBS system in the DA market will be presented, and accordingly, the effect of imposing emission limitations on the offering strategy problem will be investigated. In other words, in the first study, the system maximizes its expected profit by ignoring constraint (6.3), whereas in the second study, the results of the offering strategy problem are examined under various emission limits.

Table 6.2 Information on BSS

Parameter	Value	Unit
$\Upsilon^{BS,dis}$	95	%
$\Upsilon^{BS,ch}$	80	%
CAP^{dis}	50	MW
CAP^{ch}	50	MW
EL^{BS}	250	MWh

Table 6.3 Data on the cost curve and the emission rate of each thermal unit

Generation units	Piece wise linearization parameters (MW)				Cost pertaining to each block (€/MW)				Emission ratios (lbs/MWh)	
	MIN	$P(1)$	$P(2)$	CAP	$C(1)$	$C(2)$	$C(3)$	$C(4)$	$E_{NO_X,g}$	$E_{SO_2,g}$
G1–G5	2.4	6	9.6	12	48.41	48.78	51.84	55.4	2.513	1.005
G6–G9	15.8	16	19.8	20	54.58	55.42	67.82	68.28	1.834	0.734
G10–G13	15.2	38	60.8	76	36.46	36.96	38.89	40.97	6.889	2.755
G14	140	227.5	280	350	35.08	35.66	36.09	36.72	18.371	7.348

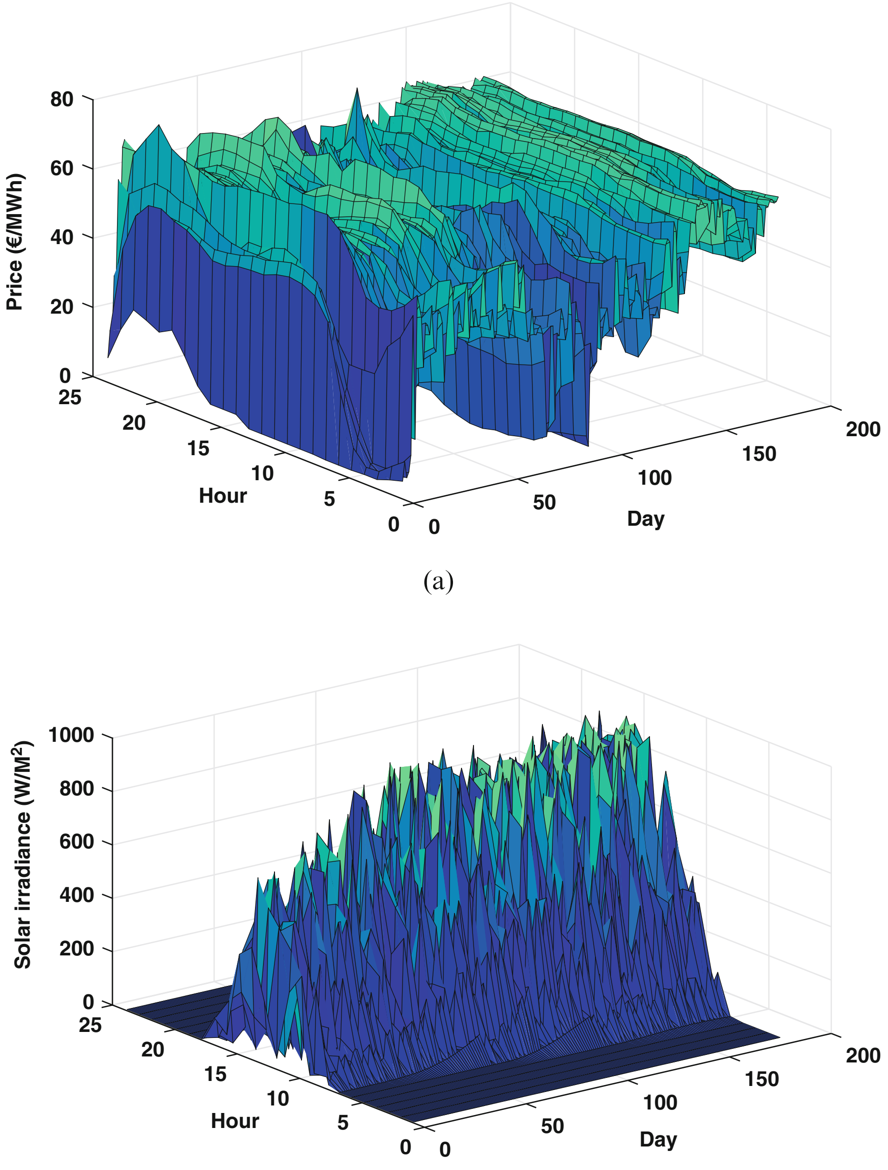
Table 6.4 Technical data of each thermal unit

Generation units	RU_g and RD_g SRU_g and SRD_g (MW/hr)	UC_g (€)	DC_g (€)	UT_g (hr)	DT_g (hr)
G1–G5	12	87.4	8.74	4	2
G6–G9	20	15	1.5	1	1
G10–G13	35	715.2	71.52	8	4
G14	180	2298	229.8	4	4

The results of risk-based offering strategy for a TPVBS system have been reported in Table 6.5. According to this table, in the risk-neutral scheduling, i.e., $\beta = 0$, the expected profit, CVaR, and expected emission of TPVBS system are, respectively, equal to €244,454.898, €177,110.864, and 270,586.518 lbs. By changing the system's attitude towards a more conservative approach, i.e., increasing the value of β, the system's expected profit will lessen, and on the other side, the amount of CVaR will significantly grow. For example, by comparing two situations $\beta = 0$ and $\beta = 0.5$, it can be seen that the CVaR gain will be 3.8% while the expected profit will only reduce 0.07%.

Figure 6.4 illustrates the optimal participation of thermal units and PV site in the DA market for two separate scheduling approaches, i.e., $\beta = 0$ and $\beta = 4$. Overall, the participation level of these sources in the DA market by increasing parameter β will decrease. It stems from the fact that the system tends to lessen its participation in the market in the hope of diminishing its risk. The optimal behavior of BSS in the suggested offering model in two different modes of operation, namely risk-neutral and risk aversion, has been depicted in Fig. 6.5. By altering the operation mode of the system from a risk-neutral case to a risk aversion situation, it can be seen from these figures:

1. The charging period of BSS through thermal units will entirely change, except hour 1.
2. In the risk-neutral condition, the BSS does not benefit from the DA market for charging, while in the risk aversion situation, it purchases energy from the DA market at hours 7 and 16.
3. The stored energy level of the BSS system will considerably change. In the risk aversion case, it only includes one peak with the value of 155 MWh, while in the risk aversion state, it experiences two peaks of 110 MWh.



(a)

(b)

Fig. 6.3 Data on DA market price and solar irradiance. (**a**) DA market. (**b**) Solar irradiance

The offering curves of TPVBS system in the DA market for time interval $t = 14$ in two different values of β, i.e., $\beta = 0$ and $\beta = 4$ have been demonstrated in Fig. 6.6. It can be observed from these figures that:

Table 6.5 Results of the suggested offering strategy problem

β	Expected profit (€)	CVaR (€)	Expected emission (lbs)
0	244,454.898	177,110.864	270,586.518
0.5	244,278.972	183,839.477	270,843.719
1	243,485.075	185,033.449	270,909.745
2	242,642.108	185,668.329	270,556.397
4	242,421.594	185,737.515	270,556.397
6	242,313.791	185,783.973	270,556.397

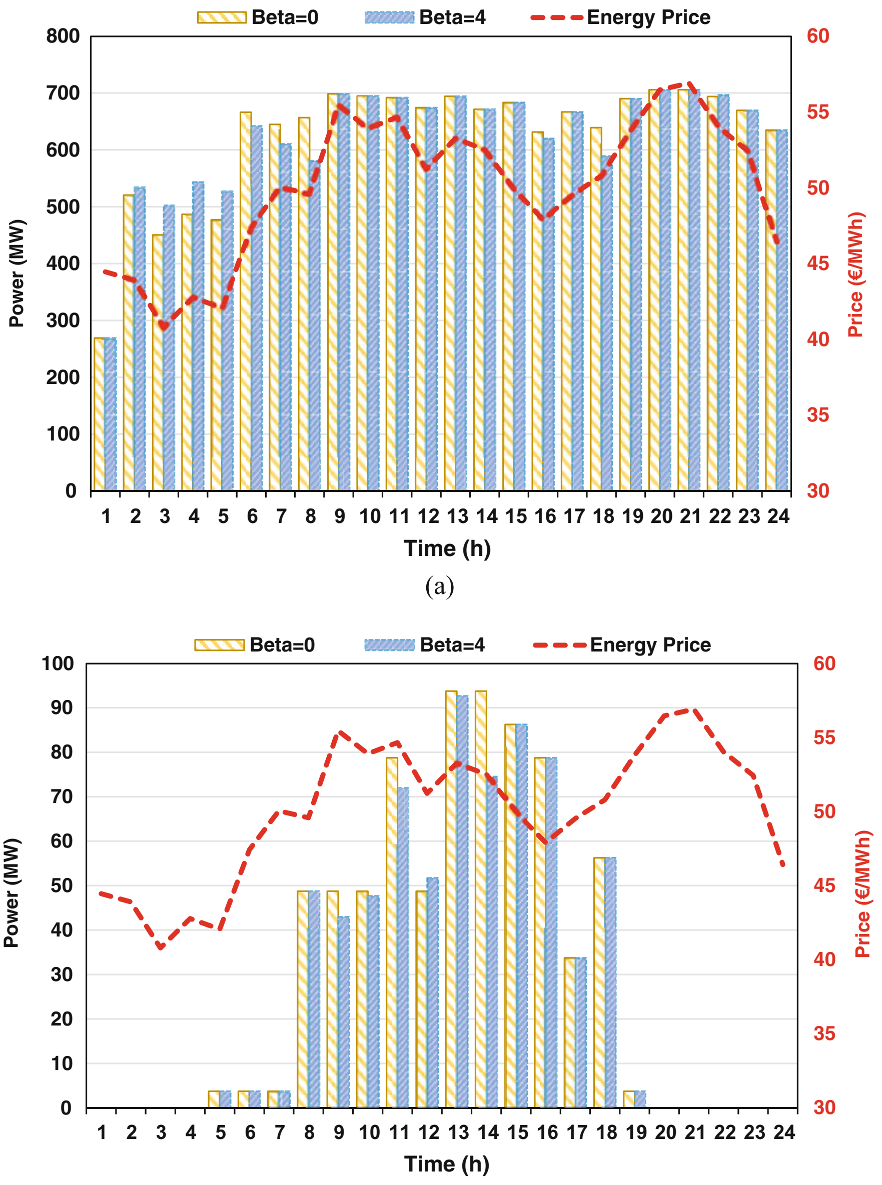
1. The thermal units' strategy at this hour will not change by varying parameter β.
2. In the risk-neutral case, the participation of the PV system will be the same in a risk-free mode will be the same for all values of DA market price, while in $\beta = 4$, it reduces its offering quantity for prices lower than 68 €/MWh.
3. In $\beta = 0$, the BSS will offer 50 MWh for DA prices higher than 56 €/MWh, while in the risk aversion case, it will offer 50 MWh for prices higher than 68 €/MWh.

In the previous studies, the authors simulate the offering strategy problem for a TPVBS system without any emission limitation. The results of the suggested offering strategy problem for an emission-constrained TPVBS system have been shown in Fig. 6.7. It should be noted that, contrary to the previous study, Eqs. (6.2) and (6.3) are also considered in the optimization process, and the results are reported for three values of $E_{\max}$, i.e., $E_{\max}$= 200,000, 175,000, and 150,000 lbs.

The presented results show that for all values of β, emission limit $E_{\max}$= 200,000 lbs contains the highest values of expected profit, while the presented results show that for all values of β, emission limit $E_{\max} = 200{,}000$ lbs contains the highest values of expected profit, while $E_{\max} = 150{,}000$ lbs has the lowest profit. It can also be seen that by changing the $\beta = 0$ to $\beta = 0.5$, the system will experience the most increment in CVaR.

6.5 Conclusion

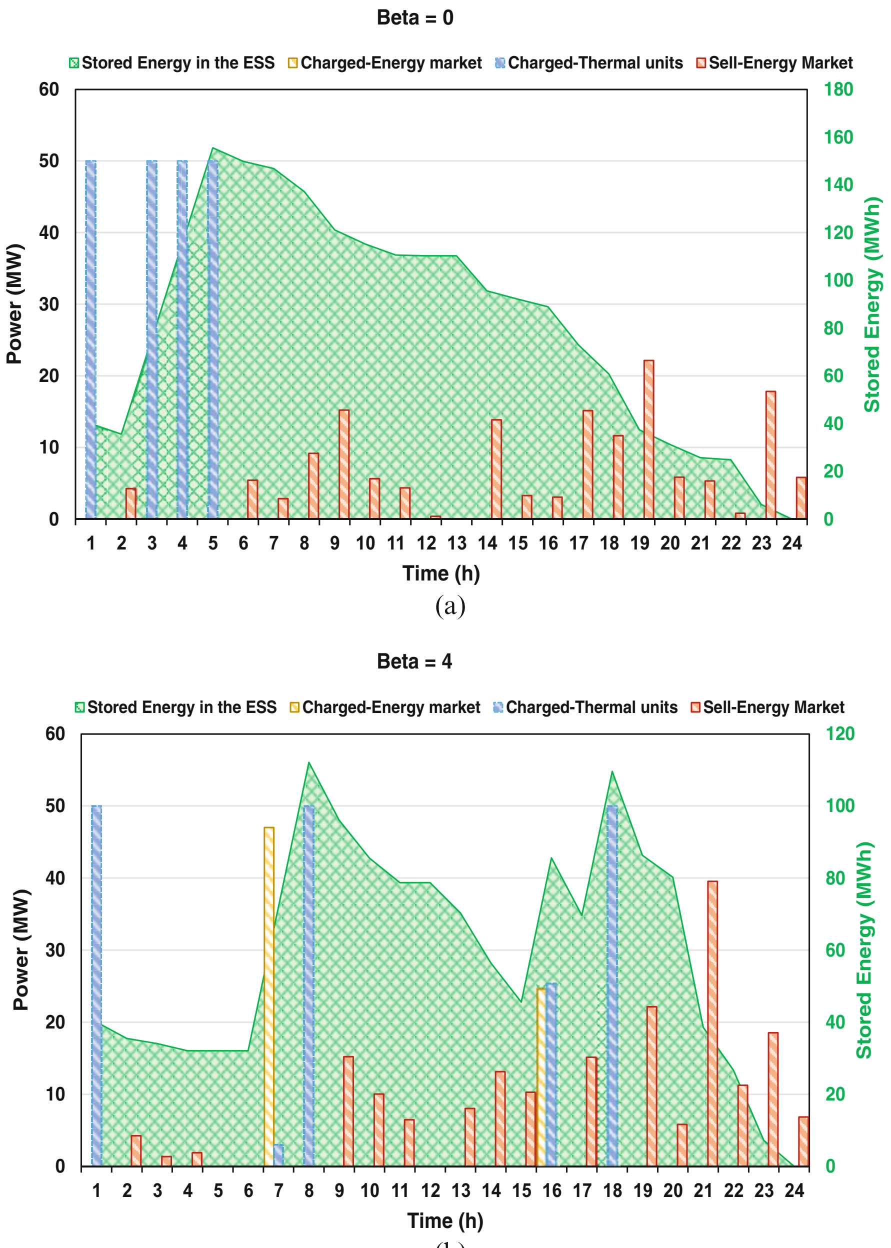
In the present chapter, a risk-constrained offering strategy for a GenCo comprising thermal units, PV system, and BSS system was proposed. The DA electricity market was considered as the target market. Decision-making in an uncertain environment, i.e., electricity market, requires addressing significant sources of uncertainty by an appropriate approach. To this end, all problem uncertainties, namely DA market price, imbalance price, and PV production, were characterized by a set of scenarios. Roulette wheel technique was employed to generate the desired number of scenarios, and finally, in order to prevent computational burden in the optimization stage, the fast forward reduction method was applied to reduce the initially generated scenarios. In the proposed methodology, an applicable risk measure, namely CVaR



(a)

(b)

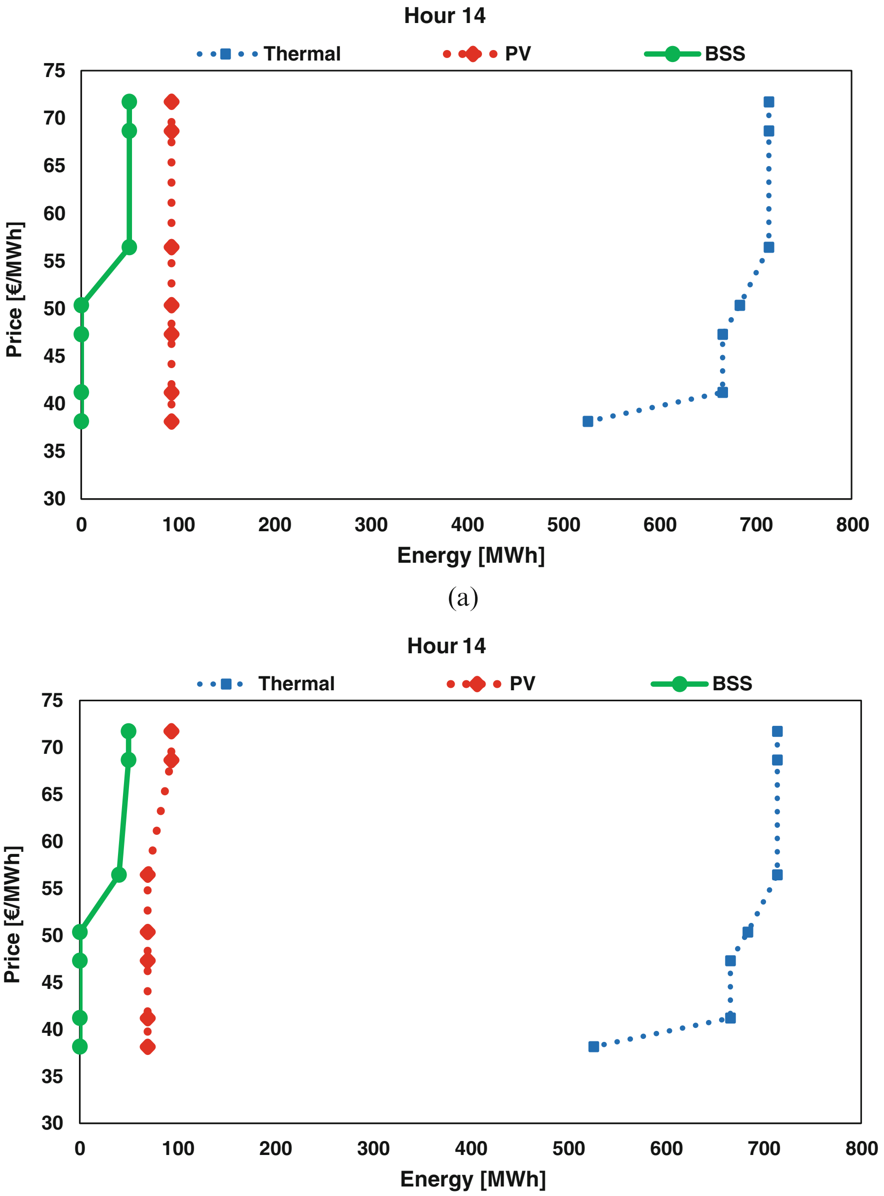
Fig. 6.4 Participation of thermal units and PV site in the DA market. (**a**) Thermal units. (**b**) PV site



(a)

(b)

Fig. 6.5 Optimal behavior of BSS in the DA market. (**a**) Risk-neutral operation. (**b**) Risk aversion operation



(a)

(b)

Fig. 6.6 Offering curves of TPVBS system in the DA market. (**a**) Risk-neutral case ($\beta = 0$). (**b**) Risk aversion case ($\beta = 4$)

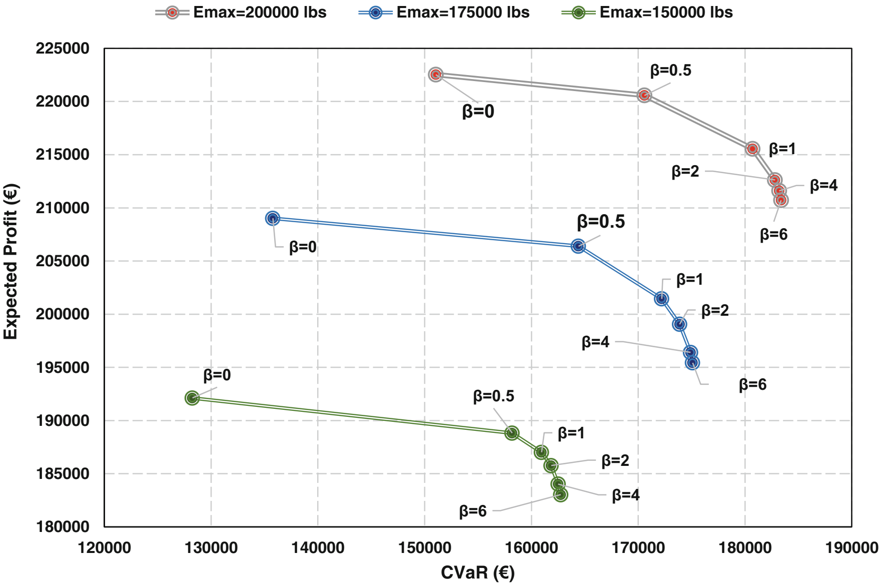


Fig. 6.7 Results of offering strategy problem for the emission-constraint system

metric, was incorporated. The presented results have revealed that a very slight decrement in the GenCo's expected profit can be used for a considerable decrease in the risk of experiencing low profits which accordingly, the system can design its offering strategy with more safety margin. The suggested offering model was also able to take into account the emission limitation that would probably be imposed by the independent system operator.

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Nomenclature

Indices

t	Index indicating period
g	Index indicating each thermal unit
s	Index indicating scenario
k	Index indicating emission type

Constants

$prob_s$	Probability of a scenario incidence
CAP^{PV}	Nominal capacity of the PV site, MW
UC_g/DC_g	Cost appertaining to start-up/shut-down of thermal units, €
DT_g/UT_g	Minimum down/up times of thermal units, hr
RU_g/RD_g	Rates appertaining to ramp up/down of thermal units, MW/hr
E_{max}	Emission limitation of the system, lbs
$CAP_g^{th}/\mathrm{MIN}_g^{th}$	Upper/lower bound of permitted production of thermal units, MW
$P^{dis,\mathrm{Max}}/P^{ch,\mathrm{Max}}$	Maximum allowed charging/discharging power for ESS, MW
$PS_g^{th,S,\mathrm{Max}}$	Maximum allowable power of every thermal unit for taking part in spinning reserve market, MW.
$E_{k,g}$	Rate of emission appertaining to each emission type and each thermal unit, lbs/MWhr
SRU_g/SRD_g	Ramp limits appertaining to start-up/shut-down of thermal units, MW/hr
$C(L)$	Cost appertaining to segment of L in linearized cost curve of thermal units, €/MWh
$\Upsilon^{BS,dis}/\Upsilon^{BS,ch}$	BSS efficiencies appertaining to discharging/charging mode.
$EL^{BS,\mathrm{Max}}$	BSS maximum allowable stored energy, MWh

Variables

$\vartheta_{t,s}^{DA}$	Price appertaining to DA market, €/MW
$\chi_{t,s}^{DA,th}/\chi_{t,s}^{DA,PV}$	Offering quantity from thermal units/PV system in the DA market, MW markets, MW
$\chi_{t,s}^{DA,BS,dis}/\chi_{t,s}^{DA,BS,ch}$	Selling/purchasing quantity of BSS in the DA market, MW
$RP_{t,s}^{PV}$	Actual power of PV system, MW.
$PR_{g,t,s}^{tot,th}$	Final generated power of each thermal unit, MW
$\delta_{t,s}^{+}/\delta_{t,s}^{-}$	Upward/downward imbalance, MW
$U_{g,t}/D_{g,t}$	Cost appertaining to start-up/shut-down of thermal units, €
$CF_{g,t,s}()$	Cost function of thermal units
$PR_{g,t,s}^{DA,th}$	Offering quantity from each thermal unit in the DA market, MW
$PR_{g,t}^{ch}/TPR_t^{ch,th}/TPR_t^{ch,PV}$	Supplied charging power through each thermal unit/whole thermal units/ PV system for the BSS, MW

v_t^{dis}/v_t^{ch}	Binary variable appertaining to each operation mode of BSS, i.e., discharging/charging
$u_{g,t}/x_{g,t}/y_{g,t}$	Binary variable appertaining to online/start-up/shut-down status of thermal units
$EL_{t,s}^{BS}$	Stored energy in the BSS, MWh
$\rho_{t,s}^{+}/\rho_{t,s}^{+}$	Price ratios for upward/downward imbalance

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