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ORIGINAL RESEARCH PAPER

Assessment of energy storage systems as a reserve provider in stochastic network constrained unit commitment

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Abstract

Recently, the provision of the reserve from energy storage systems (ESSs) is introduced as a source for ancillary services to address the uncertainties of renewable power generations. The performance of ESSs is analysed while they are applied as a provider of regulation reserves. It has been revealed that previous stochastic models neglect the impact of corrective dispatches, related to the provision of regulation reserves, on the energy level stored in the ESSs, which can lead to large deviations. This study coordinates the stored energy of ESSs to be feasible regarding the dispatches in the base schedule and rescheduling within scenarios. Also, the wind speed fluctuations are considered as the source of uncertainty, and scenarios of wind energy are generated using the Weibull distribution function. The IEEE 24-Bus standard test system is applied for the examination of the proposed model. The results show that the proposed model can manage the performance of ESSs in rescheduling within scenarios, while the coordinated reserve provision of ESSs can remove the concerns about insufficient stored energy of ESSs.

1 | INTRODUCTION

The variable generation of wind farms concerns energy system operators since environmental aspects support their fast expansion [1,2]. Many studies suggest regulation reserves as remedial actions; however, thermal generators are expensive for providing reserves according to the environmental and economic aspects [3,4]. In this way, researchers introduced alternative sources for regulation reserve, which include demand response programmes [5], energy storage systems (ESSs) [6,7], and virtual power plants [8,9].

1.1 | Literature survey

The national laboratory of the US Department of Energy categorized different types of reserves based on their usage and their response time [10]. The operating reserve is defined as the capacity that can be used to support the balance of active power. The operating reserve is also separated into event and non-event reserves, and non-events are continuous events that happen so often like the forecasting error of load or variability of renewable generations [10]. The non-event reserves consist of the regulation reserve (faster) and following reserve (slower) based on the speed of variation [11]. Based on the dynamic of imbalances, regulation reserves are regularly used for covering the fluctuation of renewable generation, and the following reserves are applied for balancing load forecasting errors.

The utility-scale ESSs have a broad application in power systems [12,13]. Application of ESSs for covering wind ramp events is studied in [14], and Reference [15] considers the application of mobile energy storage to facilitate energy transfer between energy systems with separated operators. The exploitation of flexibility services like operating reserves from ESSs is desirable for energy system operators (ESOs) [16,17]. In this regard, electricity markets should be arranged based on scheduling reserves alongside the energy productions [18,19]. Reference [20] considered the explicit presentation of reserve cost provided by ESSs, while Reference [21] explored a secondary market for reserves.

In general, stochastic and robust models are common descriptions of unit commitment problems dealing with uncertainties [22,23]. The stochastic models consider different scenarios for reflecting the uncertainties [24]. Also, the stochastic models usually consider a scenario for the most probable condition of uncertain variables which calls the base schedule (or base case) [25,26]. The base case ensures a specific schedule for the commitment of units through the operation period, and the reserve values can be defined based on the state variables of the base schedule [27,28].

The application of ESSs for supplying hourly reserve depends on their available energy and the sequential dispatches [12]. The performance of ESSs in different scenarios is challenging due to the dependence of stored energy on performance in previous hours [29]. In this way, the ignorance of such dependency can cause large deviations in the stored energy when the sequential realizations of reserves happen in one direction [30]. So, the impact of ESSs' compensation within scenarios should be reflected in the base schedule of ESSs. Also, the dependency of ESS scheduling can be considered within scenarios, but it is highly conservative and not practical [29].

The issue of insufficient energy of ESSs for reserve procurement is not appropriately covered in previous studies [31,32], and it is remarked as a concern of scheduling within scenarios in [33]. That article considers a look-ahead model for limited hours of operation. Also, a limited look-ahead feasible range of compensation (LA-FRC) for ESSs' rescheduling at contingencies and wind power variations is presented in [30]. The authors of this article presented, in [12], a model for coordinated compensation of ESSs and flexible loads, where the flexible loads are utilized to recover the ESSs' reservoir after their immediate re-dispatches within wind power fluctuations on different time scales. The use of ESSs as ancillary service providers is suggested in References [34] and [35], while the corresponding impact on the stored energy is not reflected.

Table 1 presents the novel aspects of this article in comparison to the previous researches in this area. Based on the literature, there is a research gap in the model of ESSs while they are used as reserve providers in stochastic unit commitment problems. The issue is that in the stochastic models of previous studies, the impact of switching between different scenarios of uncertainties is not anticipated, and it can lead to large deviations as it is evaluated in this article. This article addresses this gap by considering a coordinated model for ESSs, and ESOs would be able to use the ESS ancillary services with a higher level of reliability.

1.2 | Contributions

This article intended a stochastic network-constrained unit commitment (SNC-UC) to supply reserves using both conventional generators and ESSs. The motivations and backgrounds of this article are recapitulated in Figure 1. The fluctuation of wind power generation is considered as the source of uncertainty, and regulation reserves are considered for compensation. This article prepares adequate regulation reserves for the day-ahead market; hence, the real-time reserve applications can be managed by the operator decisions. Also, the cost function of reserves is counted as ancillary services for both generators and ESSs in the framework of joint reserve and energy markets. This article considers coordination between hourly base schedule (base condition is the expected scenario of wind speed) and reserves deployment of ESSs to prevent unexpected large deviations in their stored energy.

In brief, the contributions of this article can be summarized as follows:

- Developing the model of ESSs to be used as reserve providers;
- To coordinate the stored energy of storage facilities for feasible participation in reserve provision.

1.3 | Organization of the paper

The rest of this article is organized as follows. Section 2 describes the SNC-UC model by considering the ESSs' coordinated reserve provision. Section 3 presents the numerical analysis of the implementation proposed model on the standard test system, and the conclusion is outlined in Section 4.

2 | MODEL DESCRIPTION

The model of SNC-UC for the day-ahead energy and reserve market, considering coordinated compensation of ESSs, is formulated in this section.

2.1 | SNC-UC with ancillary service of ESSs

The proposed SNC-UC problem considers two sets of variables for base schedule and rescheduling in scenarios of wind power. The base schedule variables ensure a feasible solution for the most probable situation based on the expected value of uncertainties. The objective function of the SNC-UC problem is considered by (1), which includes the payments for purchasing energy and reserves from generators and ESSs. The operational constraints of generators are (2)–(11), and wind farms limits are reflected by (12) and (13). The objective function of generators consists of the cost of start-up/shutdown, no-load operational cost, and the cost of generation and reserves. Also, the values of ESSs' discharging and reserves are added to the cost function. The ESS charging is considered as a demand in the load balance; consequently, the cost of other generation units, including wind farms and generators, implicitly contains the cost of ESS charging.

TABLE 1 Comparison of the literature with the proposed model of this article

References	Stochastic model	Linear model	Day-ahead scheduling	ESS base schedule	Compensation of ESSs	Reserve of ESSs	ESS reserve optimality	Reservoir coordination
[1,4]	✓	✓	✓	✓	-	-	-	-
[2]	✓	✓	✓	-	✓	-	-	-
[8,31]	-	✓	✓	-	✓	-	-	-
[9]	✓	✓	✓	-	✓	✓	-	-
[12,17]	✓	✓	✓	✓	✓	✓	✓	-
[13]	-	✓	-	-	✓	-	-	-
[14,35]	✓	✓	✓	✓	✓	-	-	-
[16,19,33]	✓	✓	✓	-	✓	✓	✓	-
[18]	✓	-	-	-	✓	-	-	-
[20]	-	✓	✓	-	-	✓	✓	-
[29]	-	✓	✓	-	✓	✓	✓	-
[30]	✓	-	✓	-	✓	✓	✓	LA-FRC
[32]	-	✓	✓	-	✓	✓	✓	-
[34]	✓	✓	✓	-	✓	-	-	-
This article	✓	✓	✓	✓	✓	✓	✓	✓

Abbreviation: ESS, energy storage system.

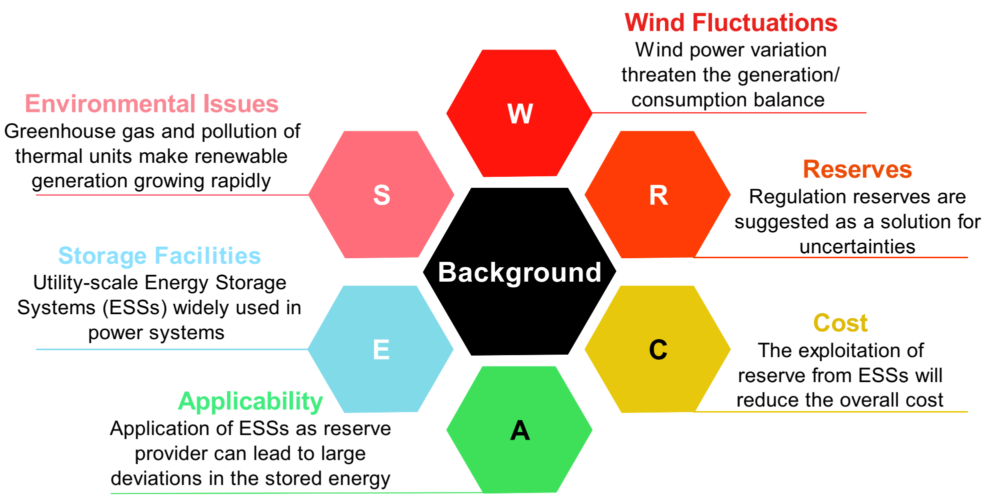

FIGURE 1 Motivations and background

$$\min \quad OF = \sum_t \Bigg[\sum_g \mu_1^t \Big(NC_g I_g^t + SC_g Su_g^t + DC_g Sd_g^t + \sum_{b,s} \left(\lambda_s^t C_g^b p_{g,b}^{t,s} \right) + Cr_g \left(r_g^{t,U} + r_g^{t,D} \right) \Big) + \sum_c \mu_2^t \Big(C_c p_c^{\mathrm{Dis},t,B} + Cr_c \left(r_c^{\mathrm{Ch},t,U} + r_c^{\mathrm{Ch},t,D} + r_c^{\mathrm{Dis},t,U} + r_c^{\mathrm{Dis},t,D} \right) \Big) \Bigg]$$
$$St. \qquad (2) - (30) \tag{1}$$

$$Su_g^t - Sd_g^t = I_g^t - I_g^{(t-1)}, \forall t, \forall g \tag{2}$$

$$Su_g^t \le I_g^{t'}, \forall t \le t' \le t + T_{g,\mathrm{on}}^{\min} - 1, \forall g \tag{3}$$

$$Sd_g^t \le 1 - I_g^{t'}, \forall t \le t' \le t + T_{g,\mathrm{off}}^{\min} - 1, \forall g \tag{4}$$

$$p_g^t - p_g^{(t-1)} \le Ru_g I_g^{(t-1)} + RSu_g Su_g^t, \forall t, \forall g \tag{5}$$

$$p_g^{(t-1)} - p_g^t \le Rd_g I_g^{(t-1)} + RSd_g Sd_g^t, \forall t, \forall g \tag{6}$$

$$p_g^{t,s} = \sum_b p_{g,b}^{t,s}, \forall t, \forall s, \forall g \tag{7}$$

$$p_g^{\min} I_g^t \le p_g^{t,s}, \forall t, \forall s, \forall g \quad (8)$$

$$p_{g,b}^{t,s} \le p_{g,b}^{\max} I_g^t, \forall t, \forall s, \forall g, \forall b \quad (9)$$

$$\left(p_g^{t,s} - p_g^{t,B}\right) \le r_g^{t,U} \le Ru_g I_g^t, \forall t, \forall s, \forall g \quad (10)$$

$$\left(p_g^{t,B} - p_g^{t,s}\right) \le r_g^{t,D} \le Rd_g I_g^t, \forall t, \forall s, \forall g \quad (11)$$

$$p_w^{t,s} \le W_w^{t,s}, \forall t, \forall s, \forall w \quad (12)$$

$$\sum_s \lambda_s^t \left(W_w^{t,s} - p_w^{t,s}\right) \le \alpha \times \sum_s \lambda_s^t W_w^{t,s}, \forall t, \forall w \quad (13)$$

The binary variables of start-up/shut-down are determined by (2). The generators' minimum online/offline periods are considered by (3) and (4), and also upward/downward ramp rate limits are reflected by (5) and (6). Constraint (7) calculates the total production of each generator, and generation limits are presented by (8) and (9). The hourly required reserves of generators in upward and downward are calculated by (10) and (11), while the corresponding upper bounds are limited by the ramp rates. Also, the maximum possible curtailment of wind power is 10% of the corresponding expected values as reflected by (13). The maximum power flow of lines for the base schedule and in each t is limited by (14). Also, the power flow constraint in each t and s (for rescheduling within scenarios) is considered in (15).

$$\gamma_i^l \left| \sum_{g \in \beta(i)} p_g^{t,B} + \sum_{c \in \phi(i)} p_c^{t,B} + \sum_s \sum_{w \in \psi(i)} \left(\lambda_s^t p_w^{t,s}\right) - pl_i^t \right| \le F_l^{\max}, \forall t \quad (14)$$

$$\gamma_i^l \left| \sum_{g \in \beta(i)} p_g^{t,s} + \sum_{c \in \phi(i)} p_c^{t,s} + \sum_{w \in \psi(i)} \left(p_w^{t,s}\right) - pl_i^t \right| \le F_l^{\max}, \forall t, \forall s \quad (15)$$

2.2 | The ESS model with coordinated compensation

The model of ESSs for the base schedule is considered by (16)–(20). Constraint (16) updates the stored energy of ESSs based on hourly dispatches of base schedule, and the corresponding limits are evaluated by (17). The required energy for the next day operation of ESSs is considered by (18). Also, the maximum charging and discharging limits of ESSs in the base schedule are presented by (19) and (20).

$$E_c^{t,B} = E_c^{(t-1),B} + p_c^{\mathrm{Ch},t,B} \eta_c^{\mathrm{Ch}} - p_c^{\mathrm{Dis},t,B} / \eta_c^{\mathrm{Dis}}, \forall t, \forall c \quad (16)$$

$$E_c^{\min} \le E_c^{t,B} \le E_c^{\max}, \forall t, \forall c \quad (17)$$

$$E_c^{t_0,B} = E_c^{t_{24},B}, \forall c \quad (18)$$

$$p_c^{\mathrm{Ch},t,B} \le p_c^{\mathrm{Ch},\max} j_c^{t,B}, \forall t, \forall s, \forall c \quad (19)$$

$$p_c^{\mathrm{Dis},t,B} \le p_c^{\mathrm{Dis},\max} \left(1 - j_c^{t,B}\right), \forall t, \forall s, \forall c \quad (20)$$

This article considers the scheduling of ESSs within scenarios using the variables with indices of s. Constraint (21) calculates the stored energy of ESSs for rescheduling in different scenarios, which employs the variable of the base schedule of the previous hour '$E_c^{(t-1),B}$'. The corresponding limits of the stored energy in scenarios are checked by (22). Constraints (23) and (24) limit the re-dispatches of ESSs in charging and discharging, respectively. The performance of ESSs as a provider of the regulation reserve can impose a negative impact on their stored energy. Constraints (21)–(24) evaluate the hourly performance of ESSs within scenarios. The above constraint of (21) is mostly used in previous studies for the calculation of stored energy, in which the effect of deploying reserves is not reflected in it. Therefore, the energy level of ESSs in the base schedule does not include the corresponding impact of reserve provision in scenarios.

$$E_c^{t,s} = E_c^{(t-1),B} + p_c^{\mathrm{Ch},t,s} \eta_c^{\mathrm{Ch}} - p_c^{\mathrm{Dis},t,s} / \eta_c^{\mathrm{Dis}}, \forall t, \forall s, \forall c \quad (21)$$

$$E_c^{\min} \le E_c^{t,s} \le E_c^{\max}, \forall t, \forall s, \forall c \quad (22)$$

$$p_c^{\mathrm{Ch},t,s} \le p_c^{\mathrm{Ch},\max} j_c^{t,s}, \forall t, \forall s, \forall c \quad (23)$$

$$p_c^{\mathrm{Dis},t,s} \le p_c^{\mathrm{Dis},\max} \left(1 - j_c^{t,s}\right), \forall t, \forall s, \forall c \quad (24)$$

It should be noted that the variable of ESS energy within scenarios '$E_c^{t,s}$' is updated using the energy of ESS in the base schedule '$E_c^{(t-1),B}$' (not using the variable of energy within the same scenario), and this will make the final solution compatible with switching between scenarios. The model presented in this article considers the dependency of base schedule and corrective dispatches (in scenarios) for ESSs' energy level by considering (25)–(28). Accordingly, the hourly reserves of ESSs are obtained, which are defined as the upper bound of differences between the dispatches in base schedule and rescheduling in scenarios.

$$p_c^{\mathrm{Ch},t,s} - p_c^{\mathrm{Ch},t,B} \le r_c^{\mathrm{Ch},t,U}, \forall t, \forall s, \forall c \quad (25)$$

$$p_c^{\mathrm{Ch},t,B} - p_c^{\mathrm{Ch},t,s} \le r_c^{\mathrm{Ch},t,D}, \forall t, \forall s, \forall c \quad (26)$$

$$p_c^{\mathrm{Dis},t,s} - p_c^{\mathrm{Dis},t,B} \le r_c^{\mathrm{Dis},t,U}, \forall t, \forall s, \forall c \quad (27)$$

$$p_c^{\mathrm{Dis},t,B} - p_c^{\mathrm{Dis},t,s} \le r_c^{\mathrm{Dis},t,D}, \forall t, \forall s, \forall c \quad (28)$$

To prevent large deviations in the stored energy, this article coordinates the performance of ESSs in the base schedule and scenarios by considering (29) and (30). These equations link and limit the corrective dispatches of ESSs in scenarios with the base values. Although the dispatches in scenarios can be different from the base schedule, the expected values must be equal to the base dispatches.

$$p_c^{\mathrm{Ch},t,B} = \sum_s \left(\lambda_s^t p_c^{\mathrm{Ch},t,s}\right), \forall t, \forall c \quad (29)$$

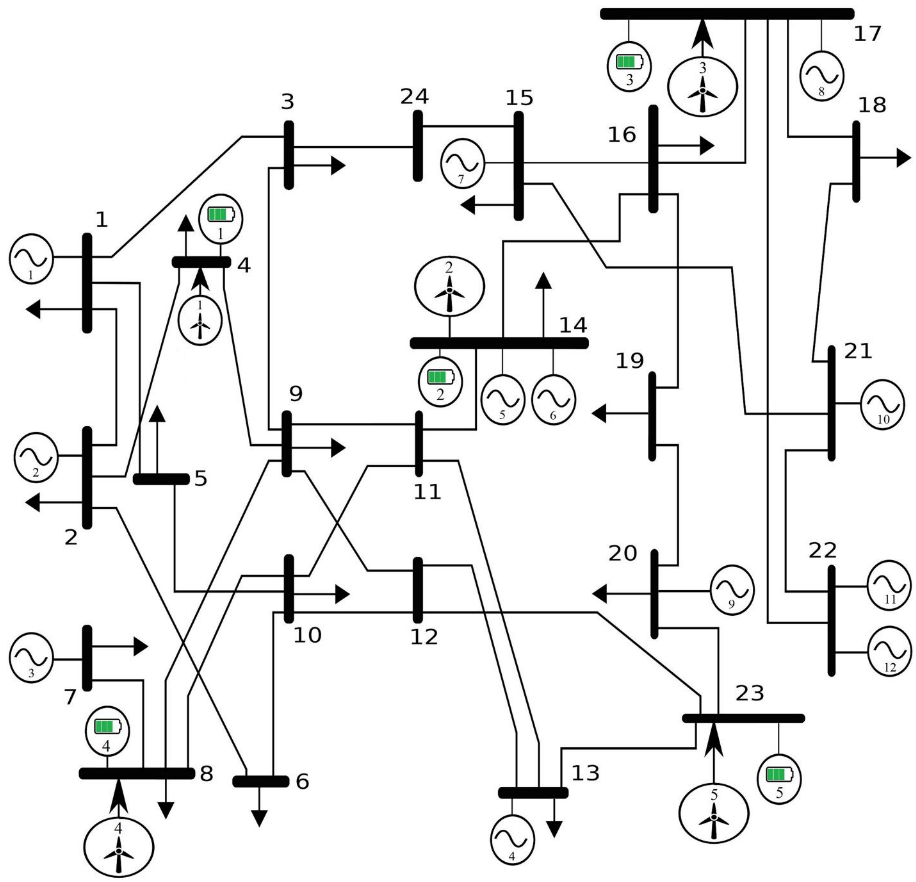

FIGURE 2 Single line diagram of IEEE RTS 24-bus test system

$$p_c^{\mathrm{Dis},t,B} = \sum_s \left(\lambda_s^t p_c^{\mathrm{Dis},t,s}\right), \forall t, \forall c \tag{30}$$

Accordingly, the above constraints separately check the expected values of charging and discharging to be equal to the dispatches in the base schedule. Furthermore, these constraints ensure the hourly sequences of corrective dispatches through the equation of (16).

3 | NUMERICAL RESULTS

The evaluation of the proposed SNC-UC in various study cases is compared in this section. Also, different aspects of the proposed SNC-UC and the performance of ESSs in coordinated reserve deployment are analysed within scenarios of wind power and in the base schedule. The proposed SNC-UC model is implemented using CPLEX in general algebraic modelling system (GAMS), on a laptop with Intel i7-core 2.4 GHz and 8 GB of RAM.

3.1 | Scenario generation of wind power

The production of wind farms varies with wind speed fluctuations. This article assumes that the variations have a distribution based on Weibull function. It is assumed that the mean value of sampling is equal to the meteorological wind forecast. It is also assumed that the standard diversion increased uniformly during the operation period. So, the scenario generation process is started with a random sampling of wind speed, and 2000 scenarios are generated. After that, the power generation of wind farms is calculated using the generated samples of wind speed and the power curve of turbines. Too many scenarios make it difficult to solve a stochastic problem. So, the number of scenarios is reduced using the SCENRED tool based on the mix of fast backward/forward method, which is developed by the GAMS [36]. The reduction of scenarios by SCENRED is performed based on probability distance, and five scenarios are selected as the most effective scenarios in this study. This article assumes all turbines experience the same wind speed; hence, the output power of wind farms is calculated by multiplying the output of one turbine into the number of available wind turbines.

3.2 | Test system

The IEEE 24-Bus test system of Figure 2 based on data in [37] is used to evaluate the performance of the proposed model. This test system includes 12 generators, five wind

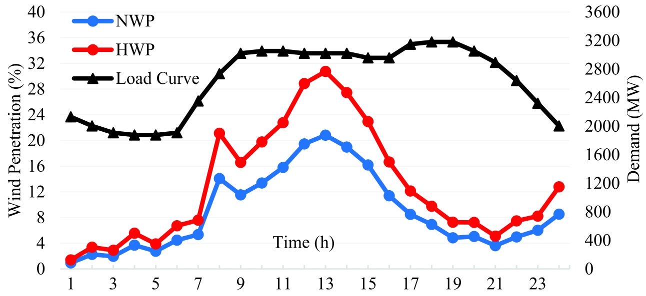

FIGURE 3 Load curve and different wind penetrations

farms, and five ESSs with the capability of deployment regulation reserves. The maximum hourly charging and discharging of ESSs is 150 MW with an efficiency of 95%. Also, the ESSs are fully charged from the minimum charge level in 5 hours. The detailed information of the test system is available in [38]. Two levels of normal wind penetration (NWP) and high wind penetration (HWP) are considered to reflect the impact of penetration of wind power on experiment results. The load curve of the test system and hourly wind penetration levels are presented in Figure 3. Also, forecast data of wind power are presented in Table 2, and data of generators are shown in Table 3. The values of normalized cost multipliers are presented in Table 4 for different hours.

3.3 | Case studies

Six cases are studied as defined in Table 5 based on different conditions of wind penetration, ESSs' participation as a reserve provider, and application of reserve coordination on ESSs. The basic model of all cases is the SNC-UC with considering the cost of energy and reserves. These cases are defined to show the performance of various approaches to ESSs' reserve model. The proposed model of this article is used in Cases 1-3 and 2-3, which they consider coordinated scheduling of ESSs for the deployment of reserve services.

3.4 | Results

First of all, the SNC-UC will be analysed regarding the commitment of units for Case 2-3, and then the coordination of ESSs' stored energy will be examined in different cases.

The base schedule of ESSs is presented in Figure 4. The performance of ESSs in the base schedule reveals that the main charging hours are between hours 2 and 8, which coincide with off-peak hours. Also, some of the ESSs are charged between hours 12 and 16 just before the peak-load hours. This can be justified by the higher level of ESSs' performance in the compensation mode at peak-load hours.

TABLE 2 Wind forecast data

Time (h)	w1 (MW)	w2 (MW)	w3 (MW)	w4 (MW)	w5 (MW)
1	0	0	27.84	1.22	1.22
2	13.81	0	27.9	0.71	25.77
3	13.67	0	13.67	1.69	27.28
4	0.49	0	13.52	26.3	63.98
5	1.43	0	1.43	12.38	62.35
6	1.25	0	27.72	49.65	49.65
7	1.61	0	27.72	95.69	64.06
8	28.52	2.8	69.09	323.91	153.39
9	14.59	38.43	70.3	299.39	100.19
10	44.15	94.72	44.15	319.31	110.65
11	108.52	199.38	70.91	269	76.22
12	321.17	269.57	151.99	86.28	53.01
13	321.13	428.17	109.91	63.94	20.65
14	335.48	359.87	116.76	43.63	4.59
15	269.99	359.98	78.68	9.53	0
16	79.66	357.23	48.51	14.78	5.39
17	51.1	286.2	16.2	23.93	23.93
18	46.99	206.35	5.46	18.91	52.78
19	15.15	99.25	0	14.15	102.69
20	15.05	36.96	5.27	5.08	169.32
21	31.02	67.21	31.02	0	27.84
22	26.37	58.25	71.91	13.49	27.53
23	17.58	43.24	121.34	13.69	13.69
24	6.63	42.39	215.26	0.32	13.1

Figure 5 represents the hourly production percentages of generators for Case 2-3. It can be seen that the generators with low costs like g8–g10 are prominently dispatched with 100% of capacity. Also, the commitment of generators depends on the network's topology and the congestion of transmission lines. So, the utilization of some of the expensive units like g1, g2, and g6 is reduced in off-peak hours.

The adequate reserve to address wind power fluctuations is displayed in Figure 6. Cases 1-2 and 2-2 represent reserve deployments of generators, while ESSs do not participate in compensation. It can be observed that relatively close and large values are deployed by ESSs in Cases 1-2 and 2-2 (up to 1000 MW) for different penetration of wind power. The model of these cases (the model of previous studies) uses ESSs' reserves upward followed by downward re-dispatch of generators to reduce the operational cost. The reason is that ESSs produce a large amount of energy with no payment for charging to recover the energy level in these cases. This issue happens

TABLE 3 Data of generators

	Generation cost				Generation data					
	b1	**b2**	**b3**	**b4**	P_g^{min}	P_g^{max}	$T_{g,on}^{min}$	$T_{g,off}^{max}$	Ru_g	Rd_g
g1	11.46	11.96	13.89	15.97	30.4	152	8	4	152	152
g2	11.46	11.96	13.89	15.97	30.4	152	8	4	152	152
g3	18.6	20.03	21.67	22.72	75	300	8	8	300	300
g4	19.2	20.32	21.22	22.13	206.85	591	12	10	540	540
g5	23.41	23.78	26.84	30.4	12	60	4	2	60	60
g6	9.92	10.25	10.68	11.26	54.25	155	8	8	155	155
g7	9.92	10.25	10.68	11.26	54.25	155	8	8	155	155
g8	5.31	5.38	5.53	5.66	100	400	1	1	400	400
g9	5.31	5.38	5.53	5.66	100	400	1	1	400	400
g10	0	0	0	0	300	300	0	0	300	300
g11	9.92	10.25	10.68	11.26	108.5	310	8	8	310	310
g12	10.08	10.66	11.09	11.72	140	350	24	48	240	240

TABLE 4 Values of hourly cost multipliers

Time (h)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
μ_1^t	0.67	0.63	0.6	0.59	0.59	0.6	0.74	0.86	0.95	0.96	0.96	0.95
μ_2^t	0.88	0.94	0.98	1	1	0.98	0.8	0.69	0.62	0.61	0.61	0.62
Time (h)	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
μ_1^t	0.95	0.95	0.93	0.93	0.99	1	1	0.96	0.91	0.83	0.73	0.63
μ_2^t	0.62	0.62	0.63	0.63	0.6	0.59	0.59	0.61	0.65	0.71	0.81	0.94

TABLE 5 Specifications of test cases (1-3 and 2-3 are the proposed model)

Cases	Wind Penetration	Deployment reserves from ESSs	Coordination of ESSs' Reserve
1-1	Normal	–	–
1-2	Normal	✓	–
1-3	Normal	✓	✓
2-1	High	–	–
2-2	High	✓	–
2-3	High	✓	✓

Abbreviation: ESS, energy storage system.

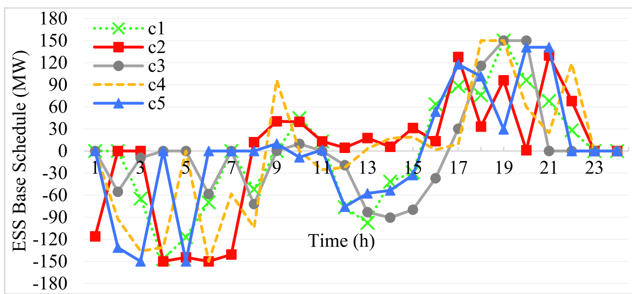

FIGURE 4 Charging/discharging of ESSs in base schedule for Case 2-3

because the model does not consider any coordination for reserve deployments. Furthermore, in Cases 1-3 and 2-3, the significant share of required upward (273 MW in NWP and 389 MW in HWP) and downward reserves (220 MW in NWP and 317 MW in HWP) are deployed by the ESSs, and no uncounted deployments of reserves are observed. Also, higher reserve deployment can be seen in Case 2-3 with HWP in comparison to Case 1-3.

As mentioned, the uncoordinated compensation of ESSs imposes a negative impact on their reservoir. The evaluation of ESSs' stored energy is performed from two aspects to analyse the reservoir condition under the above services. The first analysis is driven based on the effect of ESSs' rescheduling on the stored energy within the base schedule. In this way, Figure 7 evaluates the impact of ESSs' active compensation on the expected value of hourly stored energy in different cases. It can be seen that in Cases 1-2 and 2-2, large deviations occur during the operation period without the use of coordinate ESS compensation. These deviations are up to 3000 MWh and 3250 MWh in Cases 1-2 and 2-2, respectively. Cases 1-3 and 2-3 reflect the result of coordinated ESS active compensation. These cases can be compared with Cases 1-2 and 2-2; so, it is revealed that the expected value of stored energy does not exceed the limits through the operation period.

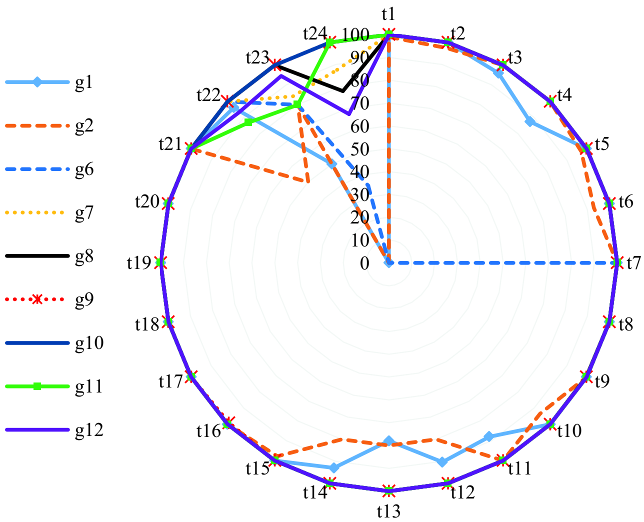

FIGURE 5 Production percentages of generators in Case 2-3 (%)

For a more detailed analysis of ESSs' energy, Figure 8 compares cases for C1 (one of ESSs) in different scenarios. In this analysis, the impact of successive re-dispatches in each scenario is evaluated on the ESSs' stored energy. It can be observed that the stored energy will be dramatically dropped into large negative values (2424 MWh Case 2-1 and 2791 MWh in Case 2-2). As shown in Figure 8b,d, the deviation of stored energy is significantly reduced by applying the proposed coordination. For example, in scenario 5, and at hour 23, the stored energy dropped from -2791 MWh in Case 2-2 to -566 MWh in Case 2-3, which represents the only 20% of deviation of stored energy in Case 2-2. Hence, the remaining deviations can be compensated by appropriate real-time decisions of operators. It should be noted that the exact accordance of one scenario during the operation period is not probable. So, the above analysis can be regarded as a strict evaluation. As it is expected, by increasing wind power penetration in Case 2-3, the deviations are increased in comparison with Case 1-3.

The cost analysis is a fundamental feature for comparing different models. Hence, Table 6 compares the cost of generation and reserves for different cases. In Cases 1-1 and 2-1, the highest operational costs are obtained. Also, generation costs in Cases 1-2 and 2-2 are significantly reduced in comparison with the above cases, while the reserve costs are increased. Also, the generation and total costs in Cases 1-2 and 2-2 are significantly lower than Cases 1-3 and 2-3, and the reason is that ESSs are discharging large amounts of energy in multiple hours without sufficient charging for the

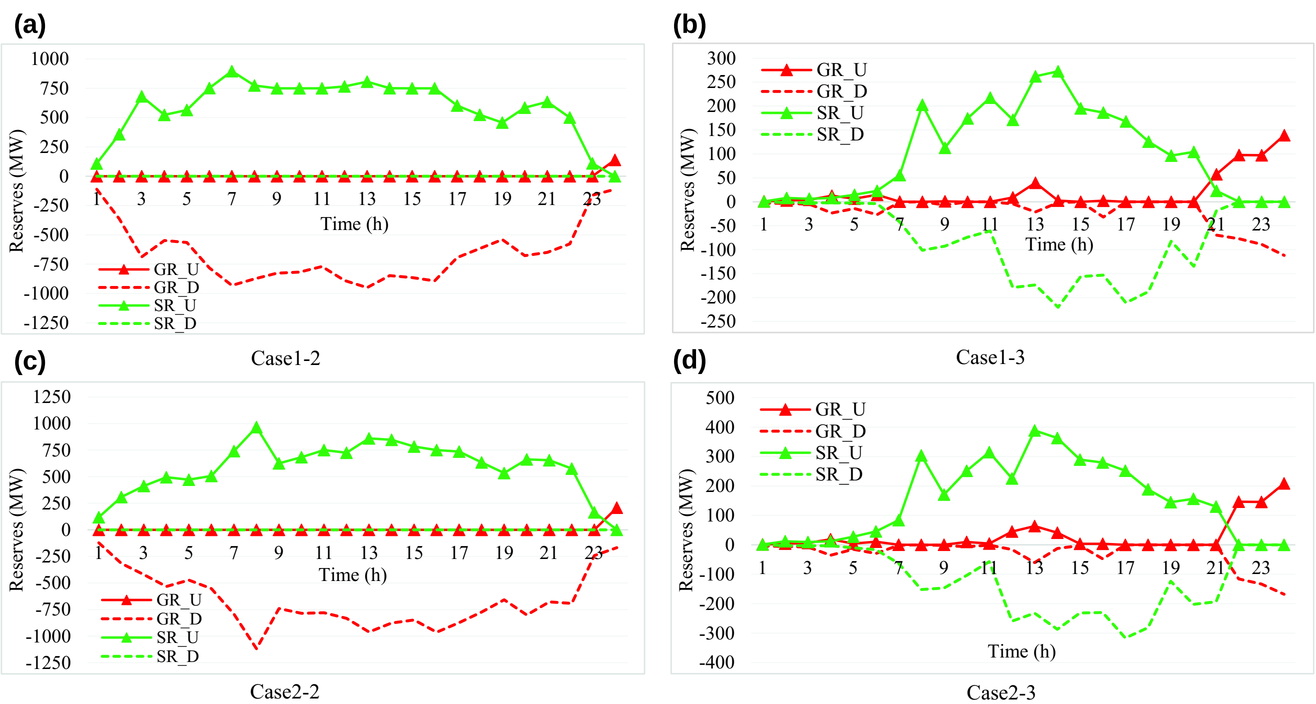

FIGURE 6 Hourly reserve deployments in different cases. (GR_U and GR_D are reserves provided by generators, and SR_U and SR_D are reserves provided by ESSs)

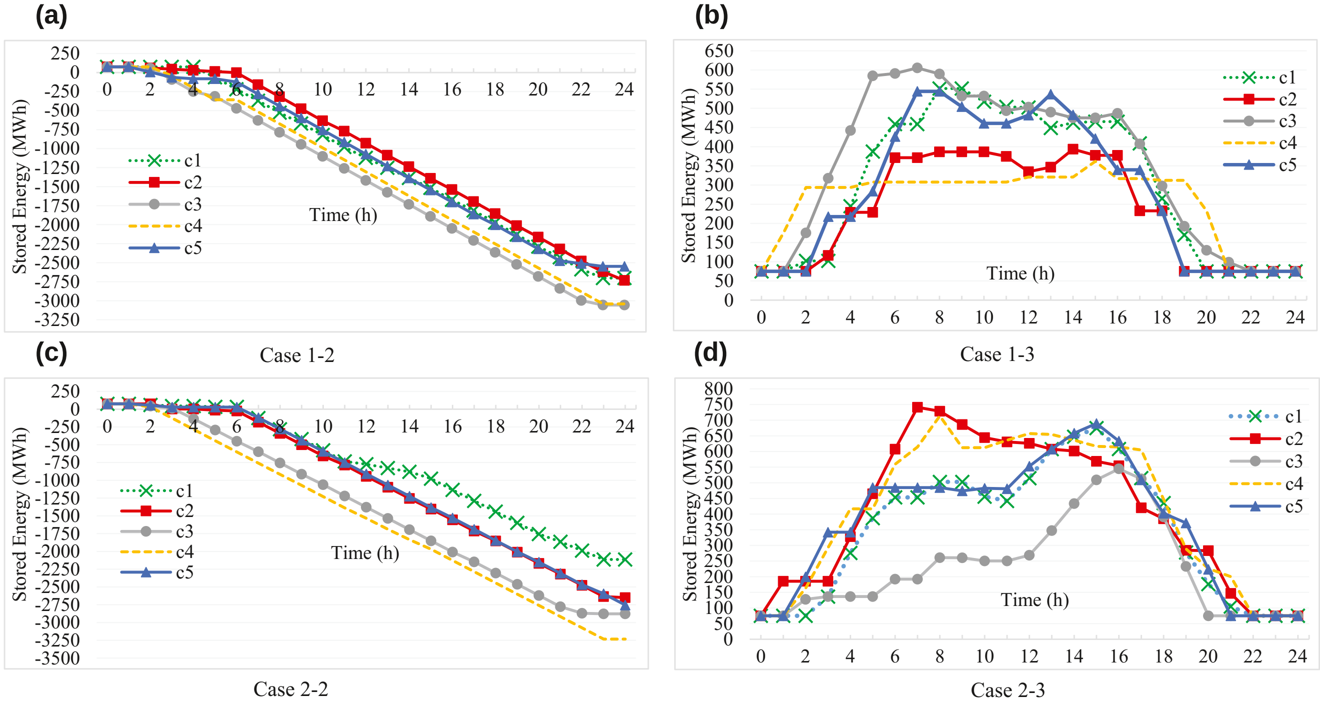

FIGURE 7 Expected value of ESSs' stored energy in different cases

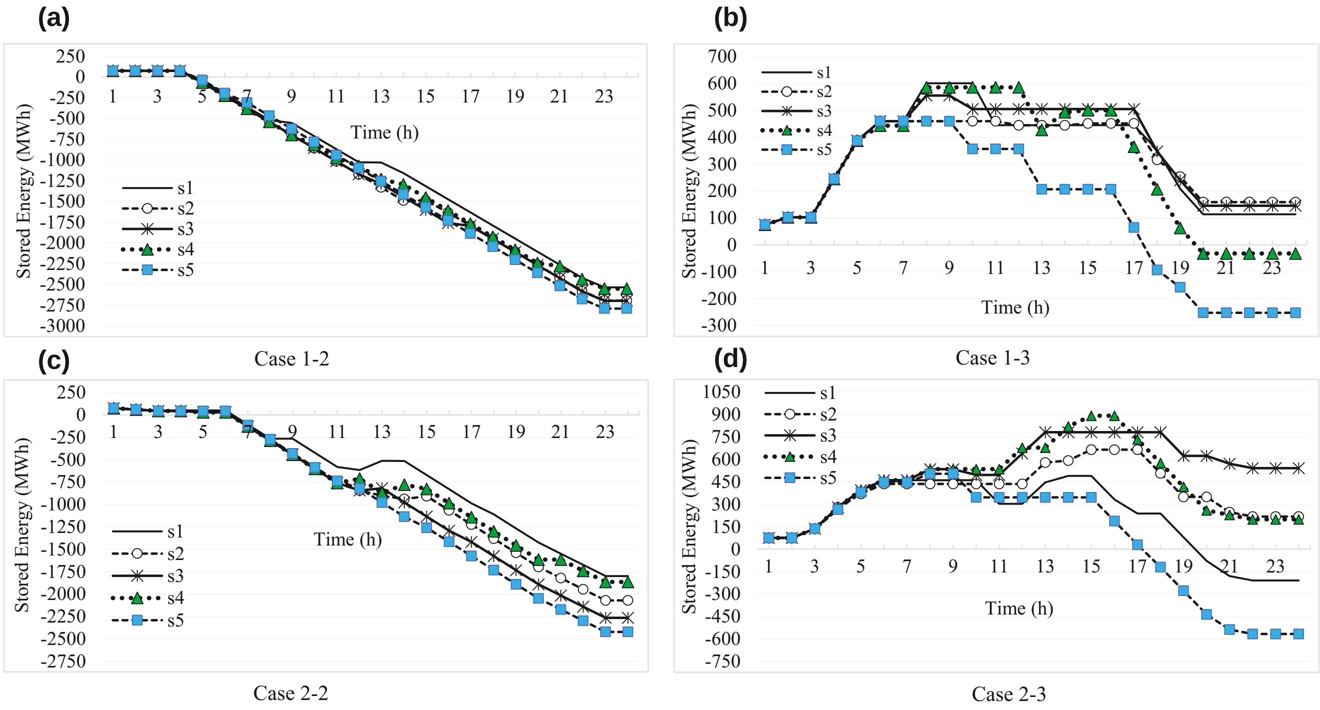

FIGURE 8 Stored energy of C1 in different scenarios

recovery of the reservoir. The total cost of Case 2-3 is reduced to $394,263, which is lower than Case 1-3 due to the application of more wind energy; however, the reserve cost is increased due to the increased level of uncertainties.

The solution time is compared in Table 7 for different cases. As can be obtained, the solution time is low in all cases, and applying the proposed model for the coordinated reserve deployment of ESSs does not significantly impact the convergence speed.

TABLE 6 Comparison of operational cost

Cases	Generation cost ($)	Reserve cost ($)	Total cost ($)
1-1	425,038	17,529	442,567
1-2	265,011	88,662	353,673
1-3	419,838	14,227	434,065
2-1	379,215	24,893	404,109
2-2	237,662	84,651	322,313
2-3	373,242	21,021	394,263

TABLE 7 Comparison of solution time in different cases

Cases	1-1	1-2	1-3	2-1	2-2	2-3
Solution time (sec)	14.96	7.15	17	7.2	7.9	18.67

4 | CONCLUSION

This article developed a coordinated model for the exploitation of regulation reserves from ESSs to address wind energy fluctuations in an SNC-UC problem. To capture the issue of the insufficient reservoir in ESSs' compensation, the model coordinates the values of re-dispatches and the base schedule. Based on the results, the following conclusions are revealed:

- The proposed model successfully deployed regulation reserves from both generators and ESSs, and ESSs provided a large share of reserves in upward and downward directions. Also, the expected values of ESS's reservoir are matched to the scheduling values of the base scenario;
- Considering that the ESS participation in reserve deployments reduced the operational cost by decreasing the need for regulation reserves;
- The uncoordinated models resulted in a lower cost, and the reason is that those models do not consider the cost of ESS charging for participation in reserve deployments. Additionally, uncoordinated compensation of ESSs for uncertainties can lead to large deviations (up to -2791 MWh) in their stored energy;
- The analysis of ESSs' reservoir within scenarios shown that the deviations are reduced by 80%, compared to the uncoordinated cases. Consequently, the remaining deviation can be removed by real-time decisions;
- The proposed model is computationally not complicated, and the coordination method does not significantly increase the solution time.

The model complexity is a barrier to implement the accurate models of ESSs for the day-ahead scheduling models. The model presented by this article does not consider the ESS degradation cost, the cycle life of ESSs, and the response time of different types of reserves, which can be incorporated considering the coordinated model of ESS compensation as future studies.

CONFLICT OF INTEREST

There is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data derived from public domain resources.

NOMENCLATURE

Indices

b	generators' blocks, $b \in \{1, \cdots, Nb\}$
c	ESSs, $c \in \{1, \cdots, Nc\}$
g	generators, $g \in \{1, \cdots, Ng\}$
i	buses, $i \in \{1, \cdots, Ni\}$
l	transmission lines, $l \in \{1, \cdots, Nl\}$
s	scenarios, $s \in \{1, \cdots, Ns\}$
t	time, $t \in \{1, \cdots, Nt\}$
w	wind farms, $w \in \{1, \cdots, Nw\}$
B	base schedule
Ch/Dis	charge/discharge modes of ESSs
U/D	up/down directions of re-dispatches

Sets

β	generators that connected to bus i
ϕ	ESSs that connected to bus i
ψ	wind farms that connected to bus i

Parameters

$C_{g/c}$	cost of purchasing energy [$/MWh]
$Cr_{g/c}$	cost of purchasing reserve capacity [$/MW]
DC_g	shut-down cost of generators [$]
$Fl_l^{\max}$	maximum flow of transmission lines [MW]
NC_g	no-load cost of generators [$]
pl_i^t	active power of demand [MW]
Ru_g, Rd_g	ramp up/down limits [MW/h]
RSu_g, RSd_g	start-up/shut-down Ramp limits [MW/h]
SC_g	start-up cost of generators [$]
$T_{g,\text{on/off}}^{\min}$	minimum on/off time duration of generators [h]
α	acceptable rate of wind power curtailment
γ_i^l	shift factor in line l per injection at bus i
μ_1^t, μ_2^t	normalized cost multipliers for each hour
λ_s^t	probability of each scenario[%]
η_c^{Ch}, η_c^{Dis}	efficiency multiplier of storage devices in charging and discharging modes [%]

Variables

$E_c^{t,B/s}$	energy stored in ESSs [MWh]
I_g^t	on/off binary variables of generators
$j_c^{t,B/s}$	on/off binary variables of ESSs
OF	total operational cost [$]
$p_g^{t,B/s}$	power generation of generators [MW]
$p_{g,b}^{t,s}$	power dispatch of generators' blocks [MW]

$p_c^{t,B/s}$	Power dispatch of ESSs [MW]
$p_c^{\mathrm{Ch},t,B/s}$	power charging of ESSs [MW]
$p_c^{\mathrm{Dis},t,B/s}$	power discharging of ESSs [MW]
$p_w^{t,s}$	power generation of wind farms [MW]
$r_{g,t}^{U/D}$	reserve provided by generators [MW]
$r_{g,t}^{\mathrm{Ch},U/D}$	reserve of ESSs in charging mode [MW]
$r_{g,t}^{\mathrm{Dis},U/D}$	reserve of ESSs in discharging mode [MW]
Sd_g^t	binary variable of shut-down status
Su_g^t	binary variable of start-up status

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