# Coordinated Scheduling of Energy Storage Systems as a Fast Reserve Provider

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**Abstract**

The need for the operational reserve is growing due to the increase of variability and intermittency in both generation and demand sides. Hence, energy storage systems (ESSs) are considered as an alternative source of the reserve, while conventional generators are not efficient based on economic and environmental perspectives. This paper studies an enhanced model for ESSs' participation as a fast reserve provider. The day-ahead scheduling of ESSs within scenarios disturbs their stored energy in the sequence of hours. This issue can dramatically increase or decrease the stored energy of ESSs and threatens the safety of operational planning. The proposed model of this paper introduces coordination strategies for the deployment of fast reserves of ESSs. The stochastic model of this paper considers the fluctuations of wind speed and also the load forecasting errors as the source of uncertainties. A decomposition-based method is employed to reduce the complexity of the model dealing with a large number of variables. A modified version of the IEEE RTS-24 test system is used to evaluate different strategies for managing of ESSs' reservoir. The result shows that large deviations of the reservoir can make the operation of ESSs infeasible in uncoordinated strategies. Also, two proposed strategies for performance under normal and conservative criteria provide choices for system operators based on the desired level of security. Besides, the deployment of fast reserves of ESSs improves operation quality by the money-saving and increasing the quality of power delivery.

*Keywords:* Reserves; Storage; Flexibility; Wind power; Stochastic unit commitment.

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## Nomenclature

Abbreviations

| | |
|---|---|
| CG | Conventional Generators. |
| ESD | ESS self-discharge. |
| ESO | Electricity System Operator. |
| ESS | Energy Storage System. |
| FRP | Fast Reserve Provider. |
| GAMS | General algebraic modeling System. |
| LOC | Lost opportunity cost |
| NACE | Nonanticipativity Constraints ESSs. |
| SECE | Sufficient Energy for the Compensation of ESSs. |
| WFs | Wind Farms. |
| UC | Unit commitment. |

Indices and Sets

| | |
|---|---|
| $b, d, l$ | Indices of buses, demands, and lines. |
| $c, g, n$ | Indices of ESSs, generators, and wind farms. |
| $CI, CO$ | Indices of cut-in and cut-out wind speed. |
| Ch/Dis | Indices of charging/discharging status. |
| max/min | Indices of maximum/minimum values. |
| on/off | Indices of online and offline statuses of generators. |
| Ref | Index of reference bus. |
| $s,t$ | Indices of scenarios ($s_0$=base scenario) and time ($t_0$=initial state). |
| U/D | Indices of up/down directions of re-dispatches. |
| $\phi, \Lambda, \sigma, \xi, \beta$ | Sets of connected lines, demands, generators, wind farms, ESSs to bus $b$. |

Input Parameters

| | |
|---|---|
| $NC_g^{CG}, SC_g^{CG}, DC_g^{CG}$ | Fixed cost, start-up cost, and shut-down cost of conventional generators ($/MWh). |
| $Ru_g, Rd_g$ | Ramp rates in upward/downward (MW). |
| $SRu_g, SRd_g$ | Ramp rates in start-up/shut-down (MW). |
| $S_{\text{base}}$ | Base power of the per-unit system (MW). |
| $T_g^{on/off,\min}$ | Minimum online/offline periods of generators (h). |
| $W_{n,t}^s$ | Available wind power in different scenarios of wind speed (MW). |
| $X_l$ | Reactance of transmission lines (p.u.). |

| | |
|---|---|
| $\Gamma_s$ | Probability of occurrence for scenarios of uncertainties. |
| $\pi_c^{\text{Ch/Dis}}$ | Efficiency of ESS in charging/discharging modes. |
| $\alpha$ | Multiplier of the desired share of wind power absorption. |
| $\lambda^{CW}, \lambda_g^{CG}, \lambda_c^{Dis}, \lambda_c^{SDC}$ | Cost of wind curtailment, power generation of CGs, and discharge and SDC of ESSs ($/MWh). |
| $\lambda R_c^{(Ch/Dis),(U/D)}$ | Cost of reserve in upward/downward directions and in charging/discharging modes ($/MW). |
| $\gamma_c$ | Rate of daily self-discharge of ESSs (%). |

Variables

| | |
|---|---|
| $CW_{n,t}^s$ | Curtailed wind power (MW). |
| $F_{l,t}^s$ | Power flow of transmission lines (MW). |
| $FG_t$ | Hourly operational cost of conventional generators ($). |
| $FS_t$ | Hourly operational cost of ESSs ($). |
| $FW_t$ | Hourly operational cost of wind farms ($). |
| $E_{c,t}^s$ | Stored energy of ESSs (MWh). |
| $EC_{c,t}^s$ | Boundary variable of stored energy of ESSs (MWh). |
| $I_{g,t}, J_{c,t}^{(Ch/Dis),s}$ | Binary status variables of generators, and ESSs. |
| $L_{d,t}^s$ | Hourly active demand in different scenarios and at different buses (MW). |
| $P_{(g/c/n),t}^s$ | Active power generation of units (MW). |
| $P_{c,t}^{(Ch/Dis),s}$ | ESSs' charging /discharging variable (MW). |
| $r_{g,t}^{s,U/D}, R_{g,t}^{U,D}$ | Variation of active power (re-dispatches) within scenarios and purchased hourly reserves of generators in upward/downward (MW). |
| $r_{c,t}^{(Ch/Dis),s,U/D}, R_{c,t}^{(Ch/Dis),U/D}$ | Variation of active power (re-dispatches) within scenarios and purchased hourly reserves of ESSs in charging/discharging modes and in upward/downward (MW). |
| $st_g^t, sd_g^t$ | Start-up and shut-down binary variables. |
| $v_{n,t}^s$ | Wind speed variable (m/s). |
| $\theta_{b,t}^s$ | Voltage angle of buses (rad). |
| $\mu_{b,t}^{1,s}, \mu_{b,t}^{2,s}$ | Dual variables of the load balance constraint. |
| $S_t^s$ | Slack variable of the load curtailment in the sub-problems (MW). |

# 1. Introduction

Over the last years, there is a rapidly growing development in the integration of renewable energy technologies, which has intermittent power generation [1, 2]. In this regard, fast reserve providers (FRPs) as a balancing mechanism are applied in Great Britain by the National Grid Electricity System Operator (ESO). The FRPs are the fast and reliable provision of active power by increasing the generation or decreasing the consumption using a demand-side response program [3, 4]. The FRPs are used in addition to other energy balancing services, to control frequency changes that might arise from sudden, and sometimes unpredictable, changes in generation or demand [5].

## *1.1 Literature survey*

The conventional generators (CGs) cause environmental issues and have a high energy cost [6, 7]; hence, researchers explore new applications for energy storage systems (ESSs) [8, 9]. In this way, some studies use ESSs for real-time frequency restoration services. Hybrid ESSs are sized in [10] to address 1-min and 30-min fluctuations in wind power using a frequency distribution between different components. Authors of [11] apply sized ESSs to reduce the frequency variation due to uncertainties of load and renewable productions. On the other hand, ESSs are widely used for reserve deployments in daily operation planning. In [12], the application of demand response and ESSs in a stochastic model is explored.

In [13], a review on mechanical ESSs is presented in which the effect of coupling with solar and wind energies is discussed. A model for providing reserve capacity of adiabatic compressed air energy storage is provided in [14]. The utilization of ESSs in transportation systems to provide the rail-transport energy is studied in [15]. In that study, the mobility of ESSs is used for compensation of fluctuations caused by natural disasters and renewable energy systems. Also, authors of [16] employ a stochastic unit commitment (UC) with plug-in electric vehicles to capture the variability of renewables and also to reduce operational cost. Reference [17] considers a stochastic UC for the application of the battery-based railway system to address forecasting errors of load and wind generation. The ESSs and demand response are applied to provide more flexibility to address wind uncertainty using a robust model in [18], and they are used to maximize social welfare through a congestion management program in [19].

Although ESSs are considered as an alternative resource for operational reserves, the model for this application is not quite simple. Any variation in charging and discharging of ESSs can lead to insufficient stored energy for future scheduling. In [20], the active cooperation of ESSs is considered to address wind power fluctuations with scheduling ESSs in different scenarios regardless of the sufficiency of their stored energy.

Authors of [21] and [22] acknowledge previous studies do not consider the impact of lack of perfect information on the stored energy of ESSs within uncertainty realizations.

The proposed model of [21] considers two sets of variables for base and uncertainty scenarios; however, the solution is not protected against the possible sequences of re-dispatches in charging/discharging. Also, flexible performance ESSs in [22] is developed for real-time and limited look-ahead operation under uncertainty. Reference [8] introduces a cooperation model of flexible loads and ESSs for supplying ancillary services, in which the flexible loads restore the stored energy of ESSs in compensation mode.

Authors of [23] propose fixed statuses for charging and discharging during the base schedule and in scenarios of uncertainties. Reference [24] develops a model for managing sufficient energy for the compensation of ESSs to mitigate wind power fluctuations. That model only depends on the initial values of variables defined for checking the feasible range of ESSs' stored energy. The participation of ESSs and gas-fired generators in providing FRPs is proposed in [25], but the sufficiency of the energy of ESSs is not guaranteed in that model. Also, the evaluation of the reservoir of bulk ESSs in compensation for wind power fluctuations is neglected in [26].

The nonanticipativity constraints for the performance of ESSs mean that the storage devices cannot simultaneously operate in both charging and discharging modes. The above issue is another drawback of models for the performance of ESSs, which is disregarded in [23, 27, 28]. Reference [24] presents a model with the nonanticipativity constraints, but the impact of re-dispatches on the operational cost is not reflected in the robust framework. The usage of ESSs for mitigating wind power curtailment is explored in [29], where the nonanticipativity constraints and sufficiency of the reservoir are ignored in the scenario-based model.

### *1.2 Research gaps*

Table 1 compares the proposed model of this paper with available researches. The above literature reveals the gap in the management of ESSs under uncertainties. The ability of ESSs for extra charging and discharging depends on the stored energy, while they are committed to the base schedule through the operation period. The actual realization of scenarios is not clear at the planning stage; hence, the potential impact of compensation re-dispatches should be checked on the stored energy in the sequence of hours. In other words, the execution of ESS's compensation can dramatically increase or decrease their energy level, and it can be reached to the upper or lower limits. This paper aims to answer the following question: "what strategy can ensure a feasible solution with the application of ESSs in the management of uncertainties through the operation period?"

### *1.3 Contributions*

In previous work, the ramping services of ESSs are utilized to address only wind ramp events [30]. The present work tries to handle the sufficiency of the stored energy in ESSs while they are compensating for the wind energy fluctuations and load forecasting errors. ESSs will be re-dispatched within scenarios, while the proposed model checks a feasible range for their performance and regarding the nonanticipativity constraint of ESSs' performance.

The feasible range is calculated based on the impact of storage hourly re-dispatches on the stored energy through the remaining hours in the operation period. This impact is calculated through different strategies based on policies of ESOs, and it includes the possible increase or decrease resulting from the values of the hourly re-dispatches. The proposed model will help the ESO regarding the safety margin for the real-time operation, and let them be able to perform appropriate actions based on the selected strategy.

This paper employs a stochastic unit commitment considering conventional and fast reserves deployment from CGs and ESSs, respectively. The cost of reserves is explicitly considered in the model based on joint energy and reserve markets. The resulting model deals with a large number of variables, and a Benders decomposition method is adapted to reduce the complexity of the model.

Table 1

Comparison of the model of this paper with the existing researches.

| | | ESSs | | Uncertainty | | Compensation | | | Specifications | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ref. | Day-ahead | NACE | SECE | RES | Load/Other | CGs | ESSs | FRP | Linear | Decomposed | Uncertainty Model |
| [2] | ✓ | × | × | × | ✓ | ✓ | ✓ | ✓ | ✓ | × | Stochastic |
| [4] | × | × | × | × | ✓ | × | × | ✓ | × | × | Robust |
| [5] | × | × | × | × | × | ✓ | ✓ | ✓ | × | × | - |
| [8] | ✓ | ✓ | × | ✓ | × | ✓ | ✓ | ✓ | ✓ | × | Stochastic |
| [9] | ✓ | × | × | × | ✓ | × | × | × | ✓ | × | Robust |
| [10] | × | × | × | ✓ | × | × | ✓ | ✓ | × | × | - |
| [11] | × | × | × | ✓ | ✓ | × | ✓ | ✓ | × | × | - |
| [12] | ✓ | × | × | ✓ | ✓ | × | ✓ | × | ✓ | ✓ | Stochastic |
| [14] | ✓ | × | × | × | × | ✓ | ✓ | ✓ | ✓ | × | - |
| [15] | ✓ | × | × | × | × | ✓ | ✓ | ✓ | ✓ | × | - |
| [16] | ✓ | × | × | ✓ | × | × | ✓ | ✓ | ✓ | ✓ | Stochastic |
| [17] | ✓ | × | × | ✓ | ✓ | × | ✓ | ✓ | ✓ | ✓ | Stochastic |
| [18] | ✓ | ✓ | × | ✓ | × | ✓ | ✓ | ✓ | ✓ | × | Robust |
| [19] | ✓ | × | × | ✓ | × | ✓ | ✓ | ✓ | × | × | Chance-constrained |
| [20] | × | × | × | ✓ | ✓ | × | ✓ | ✓ | × | ✓ | Stochastic |
| [21] | × | × | × | ✓ | ✓ | ✓ | ✓ | ✓ | × | ✓ | Stochastic |
| [22] | ✓ | × | × | ✓ | × | ✓ | ✓ | ✓ | ✓ | × | Stochastic |
| [23] | ✓ | × | × | ✓ | × | ✓ | ✓ | ✓ | ✓ | × | Robust |
| [24] | ✓ | ✓ | × | ✓ | × | ✓ | ✓ | ✓ | ✓ | ✓ | Robust |
| [25] | ✓ | ✓ | × | ✓ | × | ✓ | ✓ | ✓ | × | × | Stochastic |
| [26] | ✓ | ✓ | × | ✓ | × | ✓ | ✓ | ✓ | × | × | Stochastic |
| [27] | ✓ | × | × | ✓ | × | × | ✓ | ✓ | ✓ | ✓ | Robust |
| [28] | × | × | × | ✓ | × | ✓ | ✓ | ✓ | ✓ | ✓ | Robust |
| [29] | ✓ | × | × | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | Chance-constrained |
| [30] | ✓ | ✓ | × | ✓ | × | ✓ | ✓ | ✓ | ✓ | ✓ | Stochastic |
| This paper | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | Stochastic |

The main contributions of this paper are organized as follows:

i) To develop a stochastic model for the participation of ESSs in fast reserves provision while checking the issues of neglecting the nonanticipativity constraint and sufficiency of the stored energy in ESSs' scheduling;

ii) To guarantee the storage performance in deploying the re-dispatches within scenarios by checking a feasible range of the stored energy. This feasible range is based on available energy in the base schedule.

### *1.4 Organization of the paper*

The remainder of this paper is organized as follows. Section 2 describes the stochastic UC considering the coordinated scheduling of ESSs as FRPs. Section 3 evaluates the proposed model, and Section 4 concludes the paper.

## 2. Stochastic UC model with coordinated scheduling of ESSs as fast reserve provider

### *2.1 Operation of wind farms*

The cost function of wind farms, presented by (1), includes the penalty cost of wind energy curtailment, in which $\Delta t$ is the time step of scheduling in the day-ahead scheduling, and it is equal to one hour. The constraints of wind generation are considered by (2)-(4). The wind generation is limited to the maximum available wind power by (2), and the value of wind power curtailments is calculated by (3). The minimum absorption of available wind power can be guaranteed by (4) based on ESOs' desired level.

$$FW_t = \sum_{n,s} \Gamma_s \, \lambda^{CW} CW_{n,t}^{s} \Delta t \tag{1}$$

$$P_{n,t}^{s} \leq W_{n,t}^{s} \tag{2}$$

$$CW_{n,t}^{s} = W_{n,t}^{s} - P_{n,t}^{s} \tag{3}$$

$$\sum_{s} \Gamma_s (CW_{n,t}^{s}) \leq \alpha W_{n,t}^{s}. \tag{4}$$

### *2.2 Coordinated ESS scheduling under uncertainties*

The generation cost of ESSs consists of two parts. The cost of charging ESSs is implicitly included through purchasing energy from generators (considered as a load), and the cost of ESS self-discharge (ESD) in daily operation and the interest of generation in discharging, which is reflected by (5). Also, the model jointly minimizes the reserve cost alongside the energy.

$$FS_t = \sum_{c} \Delta t \left( \lambda_c^{Dis} P_{c,t}^{Dis,s} + \lambda_c^{ESD} \gamma_c E_{c,t}^{s_0} \right) + \sum_{c} \left( \lambda R_c^{Dis,U} R_{c,t}^{Dis,U} + \lambda R_c^{Ch,U} R_{c,t}^{Ch,U} + \lambda R_c^{Dis,D} R_{c,t}^{Dis,D} + \lambda R_c^{Ch,D} R_{c,t}^{Ch,D} \right) \tag{5}$$

The stored energy of ESSs at the last hour is checked by (6) for the next day's feasible operation, which presents the energy at the end of the scheduling period must be equal to the initial value. The ESSs cannot be operated in both charging/discharging at the same time, which is considered by the nonanticipativity constraint of (7). The base scenario ensures the nonanticipativity for ESS scheduling, and the model lets the ESSs possible to be operated in a different status regarding the base schedule. The regular constraints of ESSs, including the maximum hourly charging and discharging, the impact of hourly dispatches on stored energy, and the limits of stored energy are considered by (9)-(12), respectively.

$$E_{c,t_0}^{s_0} = E_{c,t_{24}}^{s_0} \tag{6}$$

$$J_{c,t}^{Ch,s} + J_{c,t}^{Dis,s} \le 1 \tag{7}$$

$$P_{c,t}^{s} = P_{c,t}^{Dis,s} - P_{c,t}^{Ch,s} \tag{8}$$

$$0 \le P_{c,t}^{Dis,s} \le P_{c}^{Dis,\max} J_{c,t}^{Dis,s} \tag{9}$$

$$0 \le P_{c,t}^{Ch,s} \le P_{c}^{Ch,\max} J_{c,t}^{Ch,s} \tag{10}$$

$$E_{c,t}^{s} = \left(1-\gamma\right) E_{c,(t-1)}^{s_0} + \Delta t \left( P_{c,t}^{Ch,s} \pi_c^{Ch} - P_{c,t}^{Dis,s} / \pi_c^{Dis} \right) \tag{11}$$

$$E_{c}^{\min} \le E_{c,t}^{s} \le E_{c}^{\max}. \tag{12}$$

The relation between base schedule ($s_0$) and re-dispatches of ESSs in scenarios of uncertainties ($s \geq 1$) is considered by (13) and (14). Also, the upper and lower boundary of difference between base schedule and re-dispatches, presented by (15) and (16), indicate the required fast reserves of ESSs.

$$P_{c,t}^{Dis,s} = P_{c,t}^{Dis,s_0} + r_{c,t}^{Dis,s,U} - r_{c,t}^{Ch,s,D} \tag{13}$$

$$P_{c,t}^{Ch,s} = P_{c,t}^{Ch,s_0} + r_{c,t}^{Ch,s,U} - r_{c,t}^{Ch,s,D} \tag{14}$$

$$-R_{c,t}^{Dis,D} \le P_{c,t}^{Dis,s} - P_{c,t}^{Dis,s_0} \le R_{c,t}^{Dis,U} \tag{15}$$

$$-R_{c,t}^{Ch,D} \le P_{c,t}^{Ch,s} - P_{c,t}^{Ch,s_0} \le R_{c,t}^{Ch,U}. \tag{16}$$

As explained, without the coordination of stored energy in ESSs, their participation in fast reserve deployment can lead to infeasible solutions. In this regard, the boundary variables $EC_{c,t}^{D}$ and $EC_{c,t}^{U}$ are defined to preserve the possible impact of ESSs' compensation on the stored energy in the sequence of hours. In this paper, two types of policies are applied to calculate the boundary variables. Type 1 is considered by (17a) and (18a), which calculate the boundary variables only for the base scenario based on the expected value of re-dispatches.

$$EC_{c,t}^{U,s_0} = \left(1-\gamma\right)EC_{c,(t-1)}^{U,s_0} + \Delta t\left(\sum_s \Gamma_s \left(r_{c,t}^{Ch,s,U} - r_{c,t}^{Ch,s,D}\right)\pi_c^{Ch}\right) \tag{17a}$$

$$EC_{c,t}^{D,s_0} = \left(1-\gamma\right)EC_{c,(t-1)}^{D,s_0} + \Delta t\left(\sum_s \Gamma_s \left(r_{c,t}^{Dis,s,U} - r_{c,t}^{Dis,s,D}\right)/\pi_c^{Dis}\right). \tag{18a}$$

In type 2, a higher conservative policy is considered, which calculates the boundary variables within scenarios. In this way, the proposed boundary variables are considered by (17b) and (18b). Based on the selected policy, one set among the constraints (17a) and (18a) or (17b) and (18b) are selected as proposed (17) and (18). Accordingly, the defined boundary variables are used to check the possible impact on the ESSs' stored energy as (19) in upward and (20) in downward directions.

$$EC_{c,t}^{U,s} = \left(1-\gamma\right)EC_{c,(t-1)}^{U,s} + \Delta t\left(r_{c,t}^{Ch,s,U} - r_{c,t}^{Ch,s,D}\right)\pi_c^{Ch} \tag{17b}$$

$$EC_{c,t}^{D,s} = \left(1-\gamma\right)EC_{c,(t-1)}^{D,s} + \Delta t\left(r_{c,t}^{Dis,s,U} - r_{c,t}^{Dis,s,D}\right)/\pi_c^{Dis} \tag{18b}$$

$$E_c^{\min} \le E_{c,t}^{s_0} + EC_{c,t}^{U,s} \le E_c^{\max} \tag{19}$$

$$E_c^{\min} \le E_{c,t}^{s_0} - EC_{c,t}^{D,s} \le E_c^{\max}. \tag{20}$$

## 2.3 Conventional generators

The CGs are operated with the objective function presented by (21), which consists of the cost of energy production and the payment for conventional reserves. The energy cost includes the cost of production in different scenarios, the lost opportunity cost (LOC) for regulation down $r_{g,t}^{s,D}$, fixed cost, and the costs of start-up and shut-down. It should be noted, the cost of reserves provided by slow CGs is even higher than the fast-responding reserves provided by the ESSs.

$$FG_t = \sum_{s,g}\Gamma_s\left(NC_g^{CG}I_g^t + SC_g^{CG}st_g^t + DC_g^{CG}sd_g^t + \Delta t\left(\lambda_g^{CG}P_{g,t}^s + \lambda_g^{LOC}r_{g,t}^{s,D}\right)\right) + \sum_g\left(\lambda R_g^{CG,U}R_{g,t}^U + \lambda R_g^{CG,D}R_{g,t}^D\right) \tag{21}$$

The constraints associated with CGs are presented by (22)-(29). Constraint (22) indicates the start-up/shut-down variables. The minimum on/off time constraints are considered by the linearized form of (23) and (24). The relation between production in the base scenario and the scenarios of uncertainties is reflected by (25). The maximum and minimum generation limits are considered by (26). The ramp rates are considered by (27), and the start-up/shut-down ramp rates prevent any interferences with starting and shutting down the units. Also, constraints (28) and (29) calculate the hourly required upward and downward reserves.

$$st_g^t - sd_g^t = I_g^t - I_g^{(t-1)} \tag{22}$$

$$I_g^\tau \ge st_g^t \qquad \forall t \le \tau \le t + T_g^{\text{on,min}} - 1 \tag{23}$$

$$1-I_{g}^{\tau} \geq sd_{g}^{t} \qquad \forall t \leq \tau \leq t+T_{g}^{\text{off,min}}-1 \tag{24}$$

$$P_{g,t}^{s} = P_{g,t}^{s_0} + r_{g,t}^{s,U} - r_{g,t}^{s,D} \tag{25}$$

$$P_{g}^{\min} I_{g}^{t} \leq P_{g,t}^{s} \leq P_{g}^{\max} I_{g}^{t} \tag{26}$$

$$-SRd_{g} sd_{g}^{t} - Rd_{g} I_{g}^{(t-1)} \leq P_{g,t}^{s_0} - P_{g,(t-1)}^{s_0} \leq SRu_{g} st_{g}^{t} + Ru_{g} I_{g}^{(t-1)} \tag{27}$$

$$-R_{g,t}^{U} \leq r_{g,t}^{s,U} \leq Ru_{g} I_{g}^{t} \tag{28}$$

$$-R_{g,t}^{D} \leq r_{g,t}^{s,D} \leq Rd_{g} I_{g}^{t}. \tag{29}$$

## *2.4 Decomposed model of proposed stochastic UC*

The decomposed model of the problem consists of the main problem and one sub-problem. The sub-problem checks the feasibility for network constraints, while the values of state variables of the main problem are considered as fixed values. This paper combines the sub-problems of the base scenario and the scenarios of uncertainties to reduce the complexity and solution time. Fig. 1 depicts the iterative process of solving the proposed model, and the optimal solution is obtained when the sub-problem reaches the feasible answer.

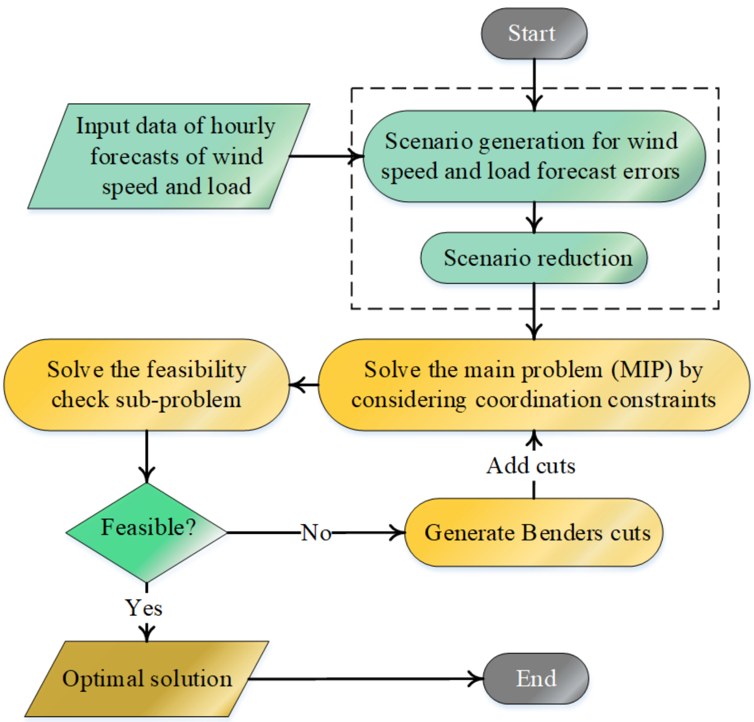



Fig. 1. Stochastic UC with coordinated scheduling of ESSs in uncertainties.

### 2.4.1 Main problem

The objective function of the main problem is the sum of the operational cost of generators, ESSs, and wind farms and is considered by (30). The constraints of the main problem consist of (1)-(29), while the constraints (17) and (18) will be selected between types 1 and 2 based on the operator's point of view.

$$\underset{\begin{pmatrix} P,I,J1/2, \\ r,R,R1/2 \end{pmatrix}}{Min} \sum_t \left( FG_t + FS_t + FW_t \right) \tag{30}$$

S.t. Eqs.(1) − (29)

### 2.4.2 Sub-problem - network feasibility check

The objective function of the sub-problem presented by (31), and constraints are (32)-(35). The sub-problem calculates power flow, and the positive slack variable of $S_t^s$ is added to the constraint of generation/consumption balance. This constraint is reflected by two equations of (34) and (35) to shape strong-cuts, which are defined in [31]. The $\mu_{b,t}^{1,s}$ and $\mu_{b,t}^{1,s}$ are the dual variables of constraints (34) and (35), respectively. If the slack variable of $S_t^s$ is greater than zero for each t and s, it means the problem is infeasible; consequently, a Benders cut will be generated by (36).

$$Min \sum_{t,s} S_t^s \tag{31}$$

$$\text{S.t.} \quad -\pi/2 \le \theta_{b,t}^s \le \pi/2 \quad ; \quad \theta_{b_{\text{ref}},t}^s = 0 \tag{32}$$

$$\left| F_{l,t}^s = s_{\text{base}} \left( \theta_{\text{from}(l),t}^s - \theta_{\text{to}(l),t}^s \right) / X_l \right| \le F_l^{\max} \tag{33}$$

$$\sum_{l \in \phi(b)} F_{t,l}^s + \sum_{d \in \Lambda(b)} L_{d,t}^s - S_t^s \le \sum_{g \in \sigma(b)} \hat{P}_{g,t}^s + \sum_{w \in \xi(b)} \hat{P}_{w,t}^s + \sum_{c \in \beta(b)} \hat{P}_{c,t}^s \tag{34}$$

$$-\sum_{l \in \phi(b)} F_{t,l}^s - \sum_{d \in \Lambda(b)} L_{d,t}^s - S_t^s \le -\sum_{g \in \sigma(b)} \hat{P}_{g,t}^s - \sum_{w \in \xi(b)} \hat{P}_{w,t}^s - \sum_{c \in \beta(b)} \hat{P}_{c,t}^s \tag{35}$$

$$S_t^s + \sum_b \left( \mu_{b,t}^{1,s} - \mu_{b,t}^{2,s} \right) \left[ \sum_{g \in \sigma(b)} \left( P_{g,t}^s - \hat{P}_{g,t}^s \right) + \sum_{w \in \xi(b)} \left( P_{w,t}^s - \hat{P}_{w,t}^s \right) + \sum_{c \in \beta(b)} \left( P_{c,t}^s - \hat{P}_{c,t}^s \right) \right] \le 0. \tag{36}$$

## 3. Simulation results

The model of ESSs as providers of fast reserves is evaluated on the standard RTS-24 test system. Five wind farms and five ESSs are added to the standard test system to analyze the performance of ESSs in compensation under wind power fluctuations and load forecasting errors. The scenarios of wind power and load are presented in Fig. 2, and it is considered over 90% of available wind power to be absorbed; consequently, higher values of reserves will be needed. The capacities of ESSs are 750MW, which fully charging and discharging cycles are 5 hours. Also, the initial values of ESSs' energy are 75MW and at the minimum value, and the total self-discharge of ESSs $\gamma$ is assumed 2% during the operation period [32]. Further data of the test system are given in [33]. All experiments are performed on the GAMS platform using CPLEX solver with the configuration of Intel i7 3630QM CPU 2.4 GHz and 8 GB of RAM. In this study, four strategies for consideration of the model of ESSs are defined based on Table 2 to investigate the corresponding impacts on different aspects of the operation. Strategy-3 and 4 construct the proposed model of this paper, in which they contain the normal and conservative criteria for managing the stored energy of ESSs.

### *3.1 Scenario generation for uncertainties*

This paper considers a random sampling method for generating scenarios of the uncertainties. The proposed method generates samples using probability distribution functions. Different probability functions are usually used to estimate the distributions of wind speed and the hourly load forecasting errors. This paper applies the Weibull distribution for wind speed and the normal distribution for load forecasting errors.

For scenarios of load forecasting errors, the random numbers are generated with the mean value of zero. After that, the calculated errors are added to the forecasted value to determine the corresponding scenario of the hourly load. In this way, the samples with deviations larger than a predefined value are eliminated to approximate a more exact distribution of load forecasting errors.

Table 2

Specifications of different strategies.

| Specifications | Strategy Number | | | |
|---|---|---|---|---|
| | 1 | 2 | 3* | 4** |
| Compensation of ESSs | × | ✓ | ✓ | ✓ |
| Coordination type 1 | × | × | ✓ | × |
| Coordination type 2 | × | × | × | ✓ |

* Strategy of normal criteria

** Strategy of conservative criteria

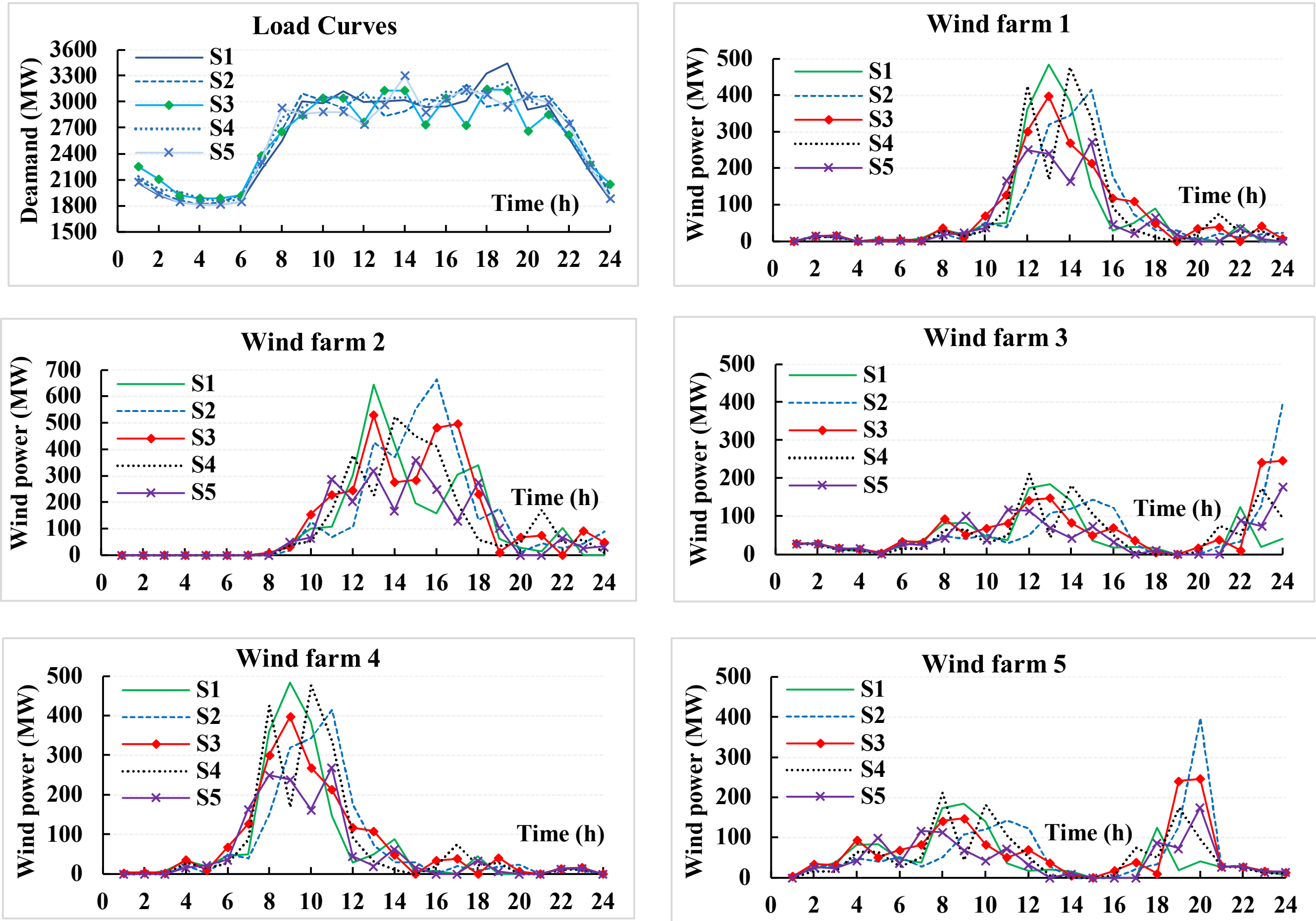



Fig. 2. Scenarios of load curve and wind power generation.

The scenarios of wind speed are generated using the forecasted mean value and an increasing standard diversion between 5% up to 15% during the operation horizon. The forecasted wind speed is obtained based on metrological data. After that, the output power of each wind turbine is calculated using the power curve represented by (37). Based on the close geographical area of turbines, the generation of wind farms is obtained by multiplying the output of one turbine into the number of active turbines.

$$W_{n,t}^{s} = \begin{cases} W_{n}^{\max} & v_{n}^{R} \le v_{n,t}^{s} \le v_{n}^{CO} \\ W_{n}^{\max} \dfrac{v_{n,t}^{s} - v_{n}^{CI}}{v_{n}^{R} - v_{n}^{CI}}; & v_{n}^{CI} \le v_{n,t}^{s} \le v_{n}^{R} \\ 0 & v_{n,t}^{s} \le v_{n}^{CI} \ \&\ v_{n,t}^{s} \ge v_{n}^{CO} \end{cases} \tag{37}$$

In this paper, 1000 samples are generated for wind and hourly load. A large number of scenarios increase the complexity of the model; hence, a scenario reduction using the SCENRED tool of General Algebraic Modeling System (GAMS) is applied to reach five scenarios.

### 3.2 *Commitment of units in the base scenario*

First of all, the result of the proposed model in strategy-4, which considers the coordination based on strict policies, is analyzed for the base scenario. Fig. 3 presents the total generation of CGs and wind farms, and also the total charging/discharging of ESSs. Also, Fig. 3 illustrates the load curve and the penetration of wind. It can be seen, the total generation curve is obtained as a desirable flat curve, and up to 31% penetration of wind energy is achieved. ESSs are mostly charged at off-load hours to be prepared for discharging at peak-load or in compensation mode.

### 3.3 *Reserves deployments*

Fig. 4 compares the deployments of reserves from CGs and ESSs through different strategies of ESS's model. It should be noted that the values of upward and downward reserves in charging and discharging mode will be used in different scenarios. Also, the total hourly reserve, which equals the sum of deployed reserves by five ESSs, is reported in Fig. 4; hence, the total values can be calculated in both charging and discharging modes in each hour, and it has no conflict with the nonanticipativity constraint. In strategy-1 (Fig. 4a), the whole required reserves are deployed by the CGs as ESSs do not participate in compensation. In strategy-3 and 4 (Fig. 4c and Fig. 4d), both CGs and ESSs participate in reserve deployments. The model of strategy-4 (Fig. 4d) employs more operational reserves from generators in comparison to strategy-3 (Fig. 4c) since the more conservative policy is applied for coordination of stored energy in the mode of compensation.

In strategy-2 (Fig. 4b), a large amount of upward reserves are deployed by increasing the discharge of ESSs. Also, almost whole downward reserves are provided by the generators at different hours. The reason is that uncoordinated reserve deployments of ESSs let them participate in re-dispatches without any impact on their main schedule. It means that they can produce energy with no need for replacement or recovery. This issue makes their energy production cheap since the cost of ESSs includes only a rate of interest for discharging. Hence, it is reasonable to return the energy of expensive generators.

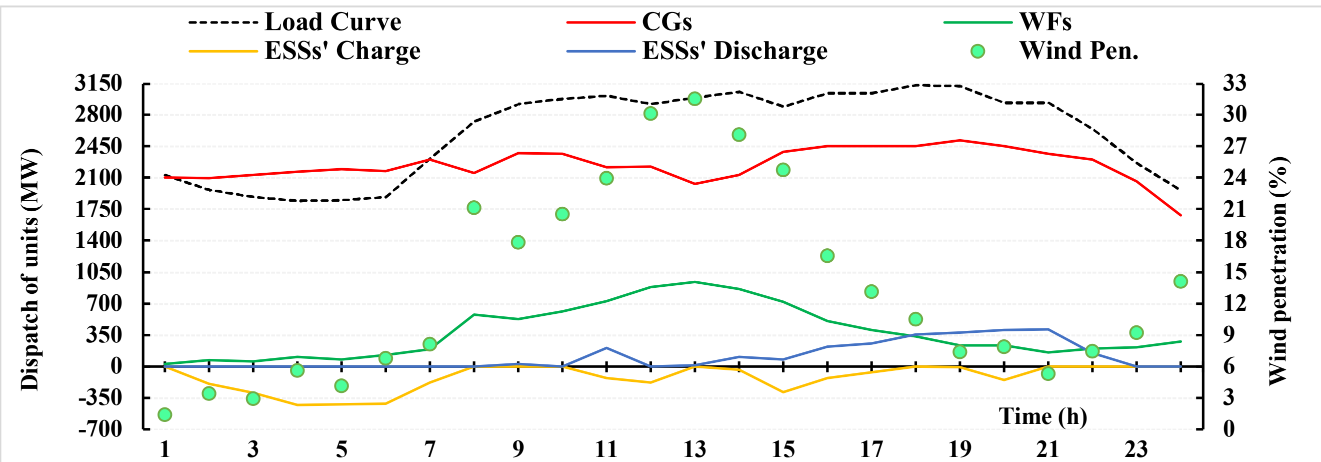
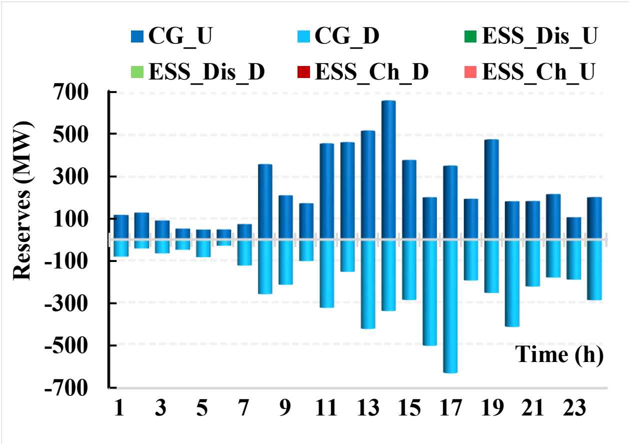
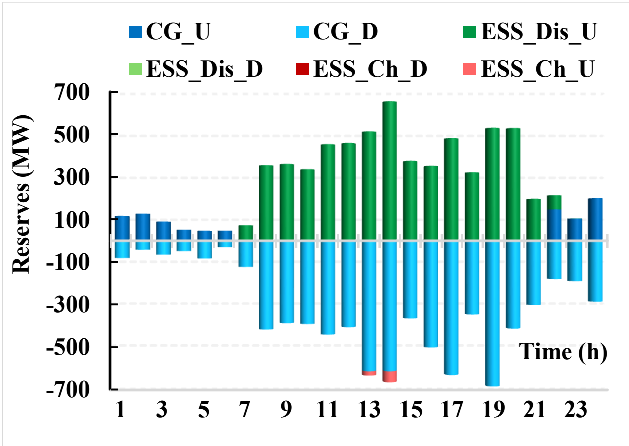


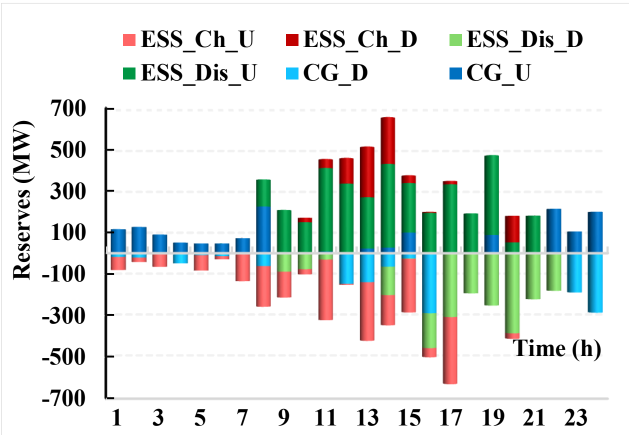

Fig. 3. Commitment of different types of units in the base scenario and strategy-4.



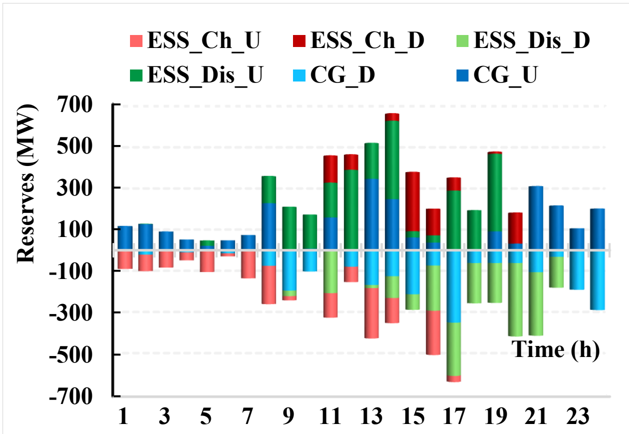

(a) Strategy-1: without ESS compensation.




(b) Strategy-2: without ESS coordination.




(c) Strategy-3: ESS compensation with normal coordination.



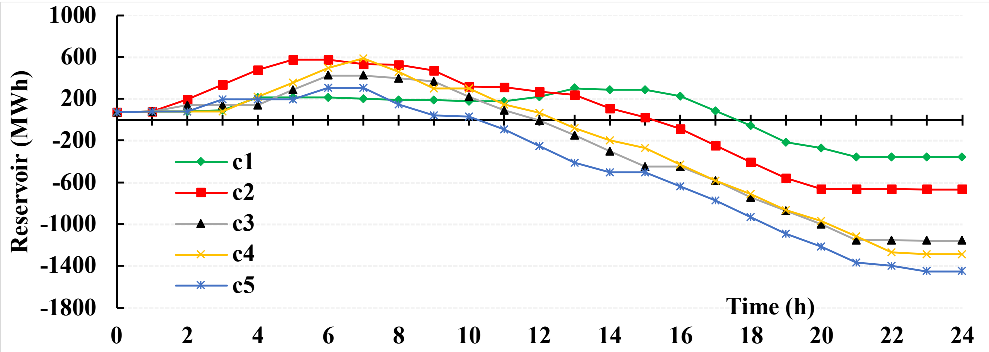

(d) Strategy-4: ESS compensation with conservative coordination.

Fig. 4. Total hourly reserve deployments in different strategies.

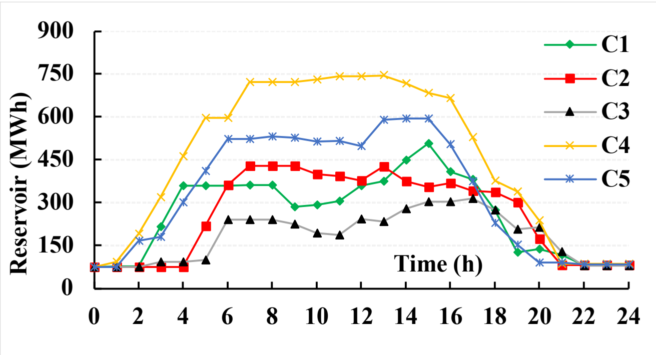
### *3.4 Reservoir of ESSs in the base scenario*

The stored energy in ESSs can be monitored from two perspectives. The first analysis checks the performance of ESSs in the mode of compensation to be feasible based on the resulting schedule at the base scenario. Fig. 5 presents the impact of successive re-dispatches on the base schedule of ESSs by adding the corresponding expected value.

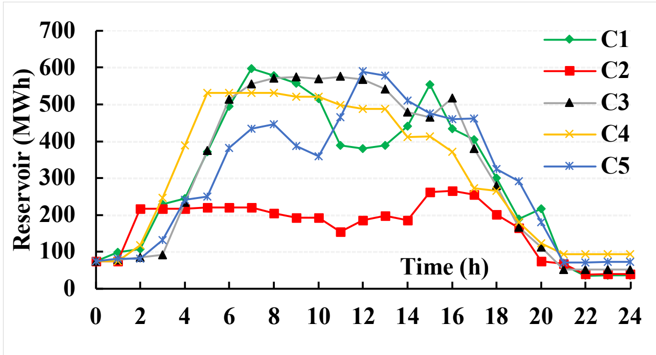
In Fig. 5a, the stored energy of ESSs is significantly dropped, and the lower limit has been exceeded for strategy-2. The above situation is caused by the successive discharging of ESSs in this strategy. As shown in Fig. 5b, the proposed coordination method of type 1 maintains the energy level in the permitted range during the operation period. Also, the obtained result for strategy-4 (the proposed coordination method of type 2) reveals an acceptable performance for the base scenario in Fig. 5c.




(a) Strategy-2: without ESS coordination.

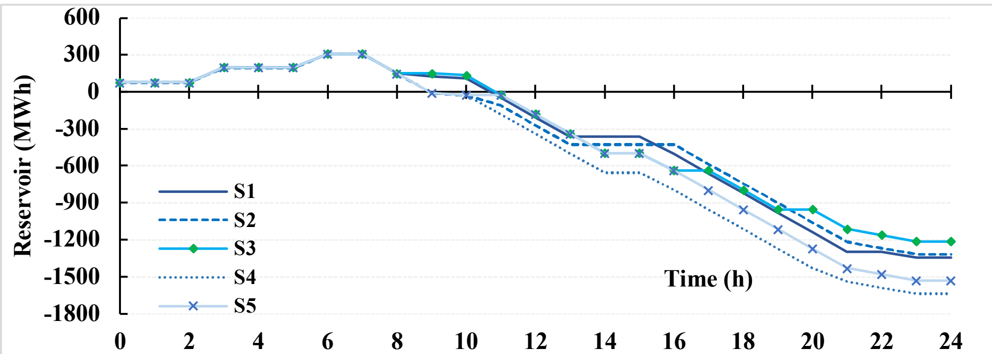



(b) Strategy-3: ESS compensation with normal coordination.

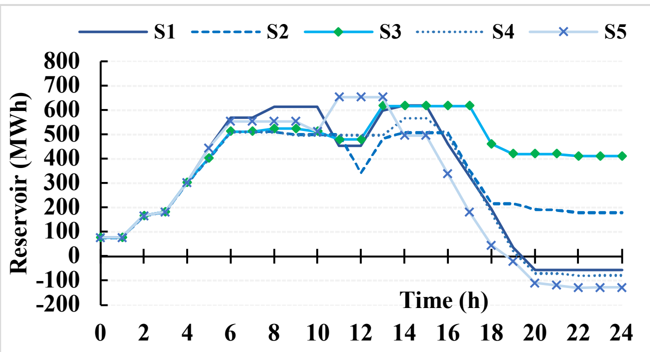



(c) Strategy-4: ESS compensation with conservative coordination.

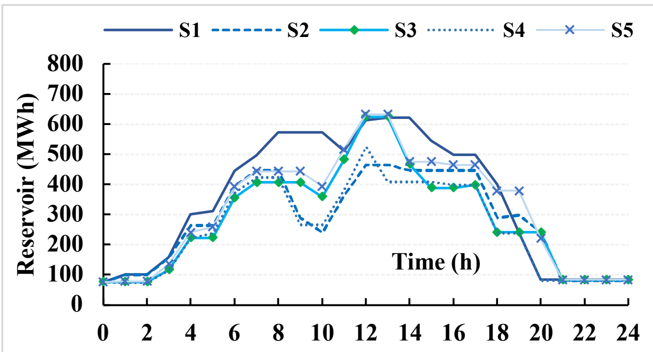
Fig. 5. Evaluation of stored energy of ESSs in the base scenario.




(a) Strategy-2: without ESS coordination.




(b) Strategy-3: ESS compensation with normal coordination.




(c) Strategy-4: ESS compensation with conservative coordination.

Fig. 6. Evaluation of stored energy of ESS C5 in different scenarios.

### 3.5 Reservoir of ESSs in different scenarios of uncertainties

The analysis of the energy level of ESSs within scenarios is a higher conservative approach since the actual realizations are not clear at the planning stage. Fig. 6 shows the performance of the ESS "C5", which has the worst condition, for different strategies in different scenarios. The values are calculated based on adding sequential re-dispatches from the first hour to check the maximum possible variations within scenarios.

It can be seen in Fig. 6a, the successive large reserve deployments in strategy-2 lead to a significant drop in the stored energy. In Fig. 6b, the use of strategy-3 shows that it can limit the corresponding energy drop of ESSs. The utilization of conservative strategy-4 (Fig. 6c) shows the stored energy is fully managed during the operation period for C5, while other ESSs also remain in the permitted range.

### 3.6 Analysis of UC results in scenarios

Table 3 presents the performance of the model in keeping generation/consumption balance within scenarios for the proposed model in strategy-4 and at hour 20. As shown, the uncertainties raised from the variable generation of wind farms and load forecasting errors are absorbed by the re-dispatches of CGs and ESSs. Also, the sum of productions in each scenario is equal to the corresponding total hourly load.

Table 3

Performance of units in different scenarios.

| AT: t=20 | | Re-dispatches in scenarios (MW) | | | | |
|---|---|---|---|---|---|---|
| | | **S1** | **S2** | **S3** | **S4** | **S5** |
| **ESSs** | **C1** | 148.7 | 148.7 | 0 | 148.7 | 148.7 |
| | **C2** | -51.7 | 0 | -121.9 | 0 | 0 |
| | **C3** | 0 | -79.2 | -79.2 | 0 | 0 |
| | **C4** | -0.5 | 0 | -0.5 | 0 | 0 |
| | **C5** | 0 | -93.8 | -150 | 0 | 0 |
| **CGs** | **G1** | 0 | -30.4 | -30.4 | 0 | 0 |
| | **G2** | 0 | -30.4 | -30.4 | 0 | 0 |
| | **G3** | 31.6 | 0 | 0 | 0 | 31.6 |
| **WFs** | **N1** | -7.5 | -15.1 | 18.6 | 6 | -15.1 |
| | **N2** | -9.1 | -24.5 | 30 | 11.2 | -37 |
| | **N3** | -5.3 | -5.3 | 11.8 | 0.8 | -5.3 |
| | **N4** | -5.1 | 18 | 1.3 | -5.1 | -5.1 |
| | **N5** | -129.6 | 229 | 77 | -73.6 | 6.6 |
| **Probability (%)** | | 0.229 | 0.167 | 0.192 | 0.325 | 0.087 |
| **Total Load** | | 2909.7 | 3055.1 | 2664.4 | 3026.1 | 3062.7 |

## *3.7 Analysis of operational costs*

The economic comparison of different strategies for the operation of ESS is performed in Table 4. The highest total operational cost is calculated for strategy-1 with no ESS's compensation services. The corresponding values to strategy-2 are lower than all strategies, while the ESSs supply large re-dispatches without any sufficient recovery.

The application of strategy-4 shows a slight increase in total cost since the higher conservative policy is applied in that case. The production cost of CGs follows a similar pattern with the same justifications.

The cost of ESSs' production is a little different since the ESSs highly participate in strategy-2, and it is higher than strategy-3 and 4. As discussed before, more energy will be exploited from ESSs in strategy-2 since the corresponding impact is not reflected in their stored energy. Thus, the higher values for the cost of reserves are calculated for strategy-2. The reason for this issue lies in the cost function of ESSs, in which their payment for purchasing energy is implicitly calculated in generators' cost. In this way, uncoordinated discharging does not consider energy recovery in previous or next hours. As a result, the proposed method of this paper successfully addresses the above issue by adopting strategy-3 and 4. The ESOs can employ the preferred strategy based on the operation policies and a trade-off between the economy and security.

## *3.8 Analysis of solution time*

The solution time and iterations for different strategies are reported in Table 5. It can be seen, strategy-1 has the fastest convergence, while strategy-3 presents the best performance between the cases with compensation of ESSs. In this regard, the solution time is a crucial factor to ESOs for selecting the best strategy for daily operation planning.

Table 4

Economic comparison of different strategies.

| | **Strategy Number** | | | |
|---|---|---|---|---|
| | **1** | **2** | **3** | **4** |
| **Total Cost ($)** | 401187 | 362273 | 382061 | 387307 |
| **CGs' Production ($)** | 362443 | 296694 | 347486 | 348922 |
| **ESSs' Production ($)** | 8804 | 27564 | 14687 | 14777 |
| **CGs' Reserve ($)** | 29531 | 21255 | 5619 | 11752 |
| **ESSs' Reserve ($)** | - | 16387 | 13873 | 11462 |
| **ESSs' Loss ($)** | 408 | 373 | 396 | 393 |

Table 5

Evaluation of solution time and iterations.

| | Strategy Number | | | |
|---|---|---|---|---|
| | **1** | **2** | **3** | **4** |
| **Iterations** | 3 | 7 | 4 | 8 |
| **Computing Time (sec)** | 13 | 38 | 31 | 173 |

## 4. Conclusion

A coordinated application of ESSs as a fast reserve provider was studied in this paper. The model used the services provided by conventional generators and ESSs to address the wind power fluctuations and load forecasting errors. The issues of insufficiency of ESSs' energy for compensation was the main concern of the proposed model. According to the risk level, desired by the system operators, two policies were considered to address this issue in which the conservative policy rejected deviations in scenarios of uncertainties. Based on the simulation results, the main findings of the proposed model are outlined as follows:

- The participation of ESSs for mitigating uncertainties led to large deviations in the reservoir based on former uncoordinated models. Also, the operational cost in uncoordinated compensation of ESSs was calculated lower than coordinated strategies, and this was originated from the ignorance of the required charging energy;
- In the uncoordinated strategy, almost all upward and downward reserves were deployed by the ESSs and the conventional generators, respectively. The reason was that the uncoordinated strategy made it possible for the ESSs to participate in mitigating uncertainties without any impact on their stored energy, and this was observed by large deviations of the reservoir in that case;
- The operational cost of the strategy with normal criteria is lower than conservative ones. However, the deviations were not absent within the realization of scenarios;
- The strategy with normal criteria provided a secure compensation of the ESSs based on the most probable situation, while the solution time was higher for the conservative model of the ESSs' coordination. On the other hand, the conservative strategy removed the possible variations in the reservoir of the ESSs within all scenarios of compensations.

It worth noting that considering the different applications of the proposed model for addressing other sources of uncertainties, including contingencies, implementing similar coordination for different types of storage devices in other energy systems like gas, heat, and water are interesting topics for future studies.

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