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ORIGINAL RESEARCH

Merchant and regulated storage investment in energy and reserve markets: A Stackelberg game

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Abstract
With large-scale integration of renewable generation, energy storage is expected to play an important role in providing flexibility to energy systems. In this paper, the authors construct a trilevel Stackelberg game model to study the co-investment of merchant and regulated storage in energy and reserve markets. The upper-level problem is a profit-maximizing storage investment problem with a desired rate-of-return solved by a merchant investor. In the middle-level problem, the system operator (SO) makes regulated storage investment decisions to minimize system cost. In the lower-level problem, the SO clears energy and reserve markets. The proposed model captures interactions of regulated and merchant storage investment. Also, it clarifies how different ownership structures of storage influence merchant storage profitability and system cost structures in different capital cost of storage investment and wind penetration level scenarios. The numerical results conducted on a 6-bus illustrative example and the IEEE 24-bus Reliability test case validate the proposed model. The results show that both regulated and merchant storage can increase social welfare, and social welfare remains almost the same under different ownership structures of storage.

1 | INTRODUCTION

Energy storage (ES) is of primary importance for the transition towards a carbon-neutral energy system, which relies on a large-scale deployment of renewable energy sources [1]. The American Recovery and Reinvestment (ARRA) funding administered by US Department of Energy has supported 16 large-scale ES projects of a total capacity over 530 MW with $185 million [2]. Horizon 2020, the EU Framework Programme for Research and Innovation, has approved €1.34 billion to projects for ES on the grid and low-carbon mobility [3].

As a flexible resource, ES can perform spatiotemporal energy arbitrage to mitigate the effect of variability and uncertainty coming from renewable energy sources [4]. Furthermore, ES can provide reserve ancillary services to enhance grid's reliability and security [5, 6]. The US Federal Energy Regulatory Commission (FERC) allows ES facilities to participate in electricity and ancillary service markets [7]. Also, European Union issued regulation rules on provisions of reserve service of ES facilities [8]. In addition, the German transmission system operators (TSOs) published regulations on provisions of primary control reserve with battery ES system [9].

ES can be owned and operated by both the system operator (SO) and a private merchant [10–12]. The ownership structures of ES influence operation strategies and potential benefits for the whole energy system [13]. Hence, the studies have investigated the ES investment problem roughly falls into two groups: (1) centralized SO investment and (2) merchant investment.

In the first group, centralized regulated investment is made by the SO with the aim of minimizing the cost of the whole system. Reference [14] studies an ES siting and sizing problem to minimize the sum of ES investment cost and system operating cost on a realistic model of the Western Electricity Coordinating Council (WECC) system. In [15], a stochastic model is solved by the Branch and Bound algorithm to optimize the storage sizing. Reference [16] proposes a stochastic planning framework to optimize the capacity and year of installation of battery ES system in an isolated microgrid. Reference [17] presents a scenario-based chance-constrained model to investigate the ESS planning under different wind power utilization levels. Reference [18] proposes a comprehensive robust model to determine the optimal size, technology, number, and maximum depth of battery ES. Reference [19] proposes a chance-constrained investment model of battery storage system to enhance wind power utilization level, which is solved by the differential evolution algorithm.

In the second group, merchant storage is owned and operated by an independent private investor. The merchant storage determines optimal bidding and offering strategies to maximize its own profits [20–22]. In [23], a bilevel model is proposed to investigate the optimal merchant ES investment with a desired rate-of-return in energy and reserve markets. Reference [24] proposed an ES sizing model from the standpoint of a strategic investor who seeks to maximize its own profits through determining strategic investment and operational decisions. In [25], a model is proposed to optimize sizing and siting of the independent-locally operated battery storage system ensuring an acceptable risk and profit level. Reference [26] presents a bilevel optimal sizing model for user-side ES considering the scheduling strategies over its lifetime and the benefits obtained from energy arbitrage and peak load management. Reference [27] proposes an optimal sizing approach for ES, which aims at maximizing annual profit while ensuring reliable and resilient operation in typical and extreme fault scenarios. Reference [28] proposes a trilevel model to investigate co-planning of merchant storage and centralized transmission line.

Reference [10] extends the work of [28] by including regulated storage investment in addition to merchant storage. The problem is formulated as a trilevel model where the upper-level (UL) problem determines the SO's investment on transmission line and regulated storage, middle-level (ML) problem optimizes merchant storage, and lower-level (LL) problem clears the energy market. The trilevel problem is transferred into a bilevel structure and finally is iteratively solved using a cutting plane algorithm. In [11], a Stackelberg model is proposed to investigate the competition of regulated and merchant storage investments in the energy system. The UL problem is the merchant storage investment problem. The ML problem determines investment decisions of regulated storage and LL problem clears the energy market. The trilevel structure is reformulated as a mixed integer quadratic problem (MIQP), which can be solved by commercial solvers.

In Table 1, we compare several aspects of ES investment models adopted in related literature with the proposed model in this paper. We note from Table 1, while the ES investment problem in the energy-only market has been studied extensively [10, 11, 14, 17–19, 24–28], the participation of ES into the ancillary service market has received limited attention by the researchers [15, 16, 23]. In the light of this research gap, to the authors' best knowledge, the concurrent merchant and regulated storage investment in both energy and ancillary service markets has not been addressed in the literature.

This paper proposes a stochastic Stackelberg game model to study interactions between regulated and merchant storage investments. In contrast to [10], this paper excludes the transmission line expansion and focuses only on the storage investment of different ownerships. Furthermore, the trilevel structure of the Stackelberg game in this work is somehow similar to [11]. However, [11] only investigates the energy market and not the reserve service market which has a potential to be relevant revenue stream for battery storage owners. In addition, [11] lacks the investigation on optimal siting of storage investment and the detailed analysis on how different storage ownership structures (i.e. different ratios of merchant storage to regulated storage) influence the SO's expense structure and social welfare. The main contributions of this paper are summarized as follows:

- A trilevel Stackelberg game model is proposed to study the coordination of regulated and merchant storage investment in the joint energy and reserve market.
- The proposed model quantifies and analyzes the influence of storage ownership structures on the SO's expenses and the third party's (i.e. conventional generators) revenues. Also, profitability and revenue streams of merchant storage from providing different products (energy and reserve) are analyzed.
- The paper investigates impacts of capital costs of storage investment and wind penetration level on schemes of merchant and regulated storage investment, profitability, and social welfare.

The results of this work shed some light on how the merchant storage investor would behave in a fully open market and how different storage ownership structures would impact profits of various market participants and social welfare. Thus, the above analyses can provide policy makers and market regulators with critical evaluation of the impact of storage ownership structures on market outcomes and assistance on regulations and market designs.

The rest of this paper is organized as follows. Section 2 presents mathematical formulation of proposed model. The numerical analysis is presented in Section 3. The conclusions are drawn in Section 4.

2 | PROBLEM FORMULATION

Figure 1 shows the trilevel structure of the proposed Stackelberg game model. The UL problem determines the siting and sizing of merchant storage ensuring a desirable rate-of-return. The ML problem is the regulated storage investment problem, which is solved by the SO to minimize the system cost. In the LL problem, the SO clears energy and reserve markets. To solve this trilevel problem, the ML and LL problems can be merged as the LL' problem of which details are in Section 2.5.

2.1 | Assumptions

The proposed trilevel model are based on the following assumptions:

TABLE 1 Comparison of models adopted in related literature.

Reference	Storage investment		Investment decision		Market		Network
	Merchant	Regulated	Siting	Sizing	Energy	Ancillary service	
[14, 17–19]		√	√	√	√		√
[15, 16]		√		√	√	√	
[23]	√		√	√	√	√	√
[24, 26, 27]	√			√	√		
[25, 28]	√		√	√	√		√
[10]	√	√	√	√	√		√
[11]	√	√		√	√		√
This paper	√	√	√	√	√	√	√

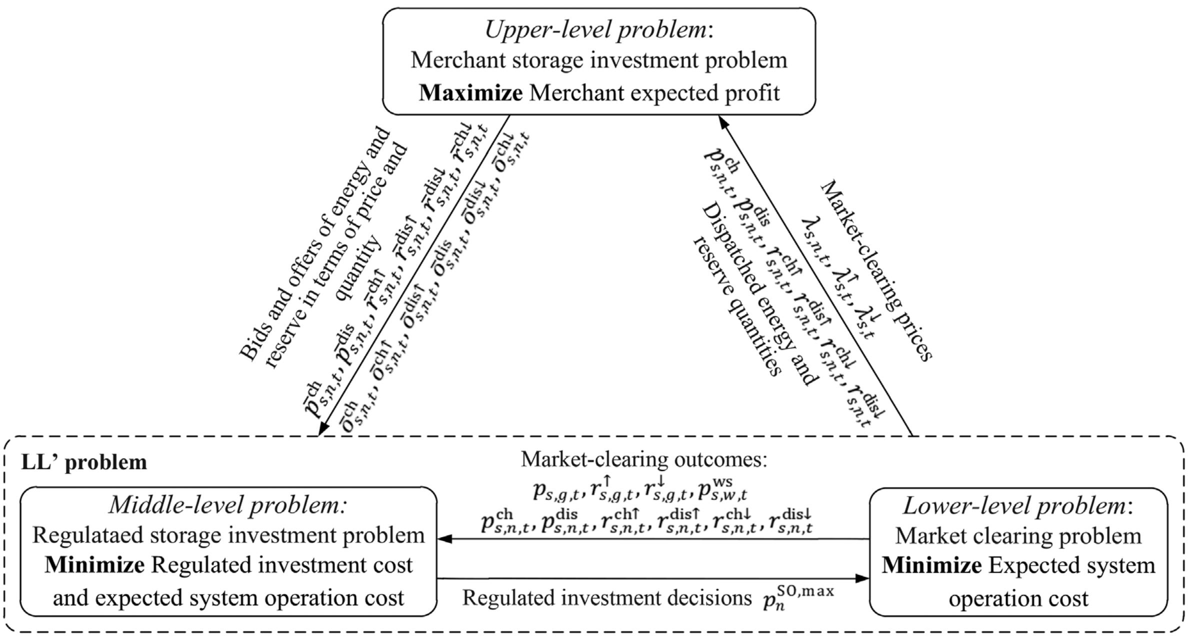

FIGURE 1 Trilevel structure of the proposed model.

1. The UL problem is solved from the perspective of the single merchant storage investor, which can also be extended to multiple merchant investors in an equilibrium problem with equilibrium constraints (EPEC) framework [29]. The ML problem takes the perspective of the SO to determine the investment decisions of regulated storage.
2. The UL and ML problems consider a single target year to optimize ES investment decisions. The degradation cost of ES is assumed to be included within the investment cost and when ES reaches to the end of its lifetime, the residual worth is zero [23].
3. The LL problem clears a day-ahead joint energy and reserve market from the viewpoint of the SO. Transmission network is represented by the DC power flow model. Energy and reserve prices are differentiated on a nodal and hourly basis using LMP. Energy and reserve are provided by conventional generators and ES units. Operating reserve can be categorized into regulating reserve, spinning reserve, and supplemental reserve [30]. This paper focuses on regulating reserve. Also, in the US, a two-part payment mechanism for regulating reserve, that is, a capacity payment and a performance payment is implemented. The performance payment is to reflect a regulation resource's accuracy in real time in response to the SO's automatic generator control signal. Similar to the storage investment models in [15, 16, 23], to strike a balance between accuracy and computational complexity, the real-time settlement is neglected in this work. Thus, only the regulating capacity payment in the day-ahead market is considered. The demand is inelastic.
4. Merchant storage is the only strategic participant in the joint energy and reserve market. Note that as a price-maker facility, the merchant storage can affect market clearing outcomes by biding and offering strategically in terms of energy quantity, energy price, reserve quantity, and reserve price.

5. To avoid non-convexity of unit commitment model, minimum up/down time and binary on/off statuses of conventional generators are neglected in the LL problem, as in [10–12, 20–24]. This assumption renders conventional generators more flexible than in realistic market. As the competitors of storage units in the joint energy and reserve market, generators of more flexibility may lead to underestimation of benefits provided by storage and more conservative storage investment. However, this assumption influences both the regulated and merchant storage investments generally, which is of no impact on the investigation of interactions and comparison of regulated and merchant storage in this paper.
6. In the leader–follower Stackelberg game, the merchant investor acts as the leader and the SO is the follower as in [11] since it is natural for the merchant investor to anticipate the SO's investment and operation behaviours. Also, in this way, we assume a situation where the leader (the merchant investor) can invest before the follower (SO) to provide an insight for policy makers and market regulators into what would happen if the investment market of the energy system was fully open to a private storage investor.

2.2 | Upper-level problem

The UL problem is the merchant storage investment problem, which is presented as follows:

$$\max_{\Xi_{\mathrm{UL}}} \ R - IC \tag{1}$$

$$IC = \sum_{n\in N} \left(C_{\mathrm{e}} e_n^{\max} + C_{\mathrm{p}} p_n^{\max} \right) \tag{2}$$

$$R = \sum_{s\in S} \pi_s \left(\sum_{t\in T} \sum_{n\in N} \lambda_{s,n,t} \left(p_{s,n,t}^{\mathrm{dis}} - p_{s,n,t}^{\mathrm{ch}} \right) + \times \lambda_{s,t}^{\downarrow} \left(r_{s,n,t}^{\mathrm{ch}\downarrow} + r_{s,n,t}^{\mathrm{dis}\downarrow} \right) + \lambda_{s,t}^{\uparrow} \left(r_{s,n,t}^{\mathrm{ch}\uparrow} + r_{s,n,t}^{\mathrm{dis}\uparrow} \right) \right) \tag{3}$$

subject to

$$R \geq \kappa \cdot IC, \tag{4}$$

$$p_n^{\max} \geq 0 \ \forall n, \tag{5}$$

$$e_{s,n,t} = \eta_c \, p_{s,n,t}^{\mathrm{ch}} - p_{s,n,t}^{\mathrm{dis}} / \eta_d \ \forall s, n, t = 1, \tag{6}$$

$$e_{s,n,t} = e_{s,n,t-1} + \eta_c p_{s,n,t}^{\mathrm{ch}} - p_{s,n,t}^{\mathrm{dis}} / \eta_d \ \forall s, n, t > 1, \tag{7}$$

$$e_{s,n,t} = 0 \ \forall s, n, t = 24, \tag{8}$$

$$e_{s,n,t} + \eta_c r_{s,n,t}^{\mathrm{ch}\downarrow} + r_{s,n,t}^{\mathrm{dis}\downarrow} / \eta_d \leq e_n^{\max} \ \forall s, n, t, \tag{9}$$

$$e_{s,n,t} - \eta_c r_{s,n,t}^{\mathrm{ch}\uparrow} - r_{s,n,t}^{\mathrm{dis}\uparrow} / \eta_d \geq 0 \ \forall s, n, t, \tag{10}$$

$$0 \leq \bar{p}_{s,n,t}^{\mathrm{ch}}, \bar{p}_{s,n,t}^{\mathrm{dis}} \leq p_n^{\max} \ \forall s, n, t, \tag{11}$$

$$0 \leq \bar{r}_{s,n,t}^{\mathrm{ch}\uparrow} \leq \bar{p}_{s,n,t}^{\mathrm{ch}} \ \forall s, n, t, \tag{12}$$

$$0 \leq \bar{r}_{s,n,t}^{\mathrm{dis}\uparrow} \leq p_n^{\max} - \bar{p}_{s,n,t}^{\mathrm{dis}} \ \forall s, n, t, \tag{13}$$

$$0 \leq \bar{r}_{s,n,t}^{\mathrm{dis}\downarrow} \leq \bar{p}_{s,n,t}^{\mathrm{dis}} \ \forall s, n, t, \tag{14}$$

$$0 \leq \bar{r}_{s,n,t}^{\mathrm{ch}\downarrow} \leq p_n^{\max} - \bar{p}_{s,n,t}^{\mathrm{ch}} \ \forall s, n, t, \tag{15}$$

$$\bar{o}_{s,n,t}^{\mathrm{ch}}, \bar{o}_{s,n,t}^{\mathrm{ch}\uparrow}, \bar{o}_{s,n,t}^{\mathrm{dis}\uparrow}, \bar{o}_{s,n,t}^{\mathrm{dis}}, \bar{o}_{s,n,t}^{\mathrm{dis}\downarrow}, \bar{o}_{s,n,t}^{\mathrm{ch}\downarrow} \geq 0 \ \forall s, n, t, \tag{16}$$

where $\Xi_{\mathrm{UL}} = \{\bar{p}_{s,n,t}^{\mathrm{ch}}, \bar{p}_{s,n,t}^{\mathrm{dis}}, \bar{r}_{s,n,t}^{\mathrm{ch}\uparrow}, \bar{r}_{s,n,t}^{\mathrm{dis}\uparrow}, \bar{r}_{s,n,t}^{\mathrm{dis}\downarrow}, \bar{r}_{s,n,t}^{\mathrm{ch}\downarrow}, \bar{o}_{s,n,t}^{\mathrm{ch}}, \bar{o}_{s,n,t}^{\mathrm{ch}\uparrow}, \bar{o}_{s,n,t}^{\mathrm{dis}\uparrow}, \bar{o}_{s,n,t}^{\mathrm{dis}}, \bar{o}_{s,n,t}^{\mathrm{dis}\downarrow}, \bar{o}_{s,n,t}^{\mathrm{ch}\downarrow}, p_n^{\max}, e_{s,n,t}\}$ is the set of primal variables of the UL problem.

The objective function (1) maximizes the profit of merchant storage, that is, the difference between merchant investment cost and expected revenues from providing energy and reserve service over characteristic days, as given in (2) and (3). Note that the energy price (i.e. $\lambda_{s,n,t}$), the upward and downward reserve prices (i.e. $\lambda_{s,t}^{\uparrow}$, $\lambda_{s,t}^{\downarrow}$), the dispatched charging and discharging quantities (i.e. $p_{s,n,t}^{\mathrm{ch}}$, $p_{s,n,t}^{\mathrm{dis}}$), and the dispatched upward and downward reserve quantities in charging and discharging modes (i.e. $r_{s,n,t}^{\mathrm{ch}\uparrow}$, $r_{s,n,t}^{\mathrm{dis}\uparrow}$, $r_{s,n,t}^{\mathrm{ch}\downarrow}$, $r_{s,n,t}^{\mathrm{dis}\downarrow}$) are determined by the SO in the LL problem. Following the convention in the literature, we assume fixed energy-to-power ratio of storage, that is, $e_n^{\max} / p_n^{\max} = a$, where a is constant.

Constraint (4) enforces the desired rate-of-return κ of merchant storage, $\kappa \geq 1$. The non-negativity of merchant storage investment decision on maximum power rating is constrained by (5). In this paper, the initial state of charge (SOC) is assumed to be zero. Constraints (6) and (7) represent SOC of merchant storage. Note that in the day-ahead market, storages only provide reserve commitments, which do not influence SOC in (6) and (7). The SOC at the end of the day is enforced to be equal to the initial SOC in (8). Constraints (9) and (10) restrain the minimum and maximum of SOC. Note that the ability of ES to provide up and down reserve is constrained by SOC in (9) and (10). The offer of charging and discharging power of merchant storage is limited by (11). Constraints (12) and (13) limit the offers of upward reserve provided by merchant storage in charging and discharging modes. Similarly, the offers of downward reserve are limited in (14) and (15). The non-negativity of prices offered by merchant storage in energy and reserve markets is enforced in (16).

2.3 | Middle-level problem

The ML problem is the regulated storage investment problem, which is formulated as follows:

$$\min_{\Xi_{\mathrm{ML}}} \sum_{n\in N}\left(C_{\mathrm{e}}e_n^{\mathrm{SO,max}} + C_{\mathrm{p}}p_n^{\mathrm{SO,max}}\right) + \sum_{s\in S}\pi_s\left(\sum_{t\in T}\left(\sum_{g\in G}\left(C_g p_{s,g,t} + C_g^{\uparrow} r_{s,g,t}^{\uparrow} + C_g^{\downarrow} r_{s,g,t}^{\downarrow}\right) + \sum_{n\in N}\begin{pmatrix}\bar{o}_{s,n,t}^{\mathrm{dis}} p_{s,n,t}^{\mathrm{dis}} - \bar{o}_{s,n,t}^{\mathrm{ch}} p_{s,n,t}^{\mathrm{ch}} + \bar{o}_{s,n,t}^{\mathrm{ch}\uparrow} r_{s,n,t}^{\mathrm{ch}\uparrow} \\ + \bar{o}_{s,n,t}^{\mathrm{dis}\uparrow} r_{s,n,t}^{\mathrm{dis}\uparrow} + \bar{o}_{s,n,t}^{\mathrm{ch}\downarrow} r_{s,n,t}^{\mathrm{ch}\downarrow} + \bar{o}_{s,n,t}^{\mathrm{dis}\downarrow} r_{s,n,t}^{\mathrm{dis}\downarrow}\end{pmatrix} + \sum_{w\in W}\left(C_w^{\mathrm{ws}} p_{s,w,t}^{\mathrm{ws}}\right)\right)\right) \tag{17}$$

subject to

$$p_n^{\mathrm{SO,max}} \geq 0 : \rho_n \ \forall n, \tag{18}$$

where $\Xi_{\mathrm{ML}} = \{p_n^{\mathrm{SO,max}}\}$ is the primal variable set of the ML problem.

The objective function (17) minimizes the cost of the whole system including regulated ES investment cost and expected operation cost of the whole system. The conventional generation investment is assumed to occur earlier. The first term represents the regulated ES investment cost. The second term represents the operating cost of conventional generators. The third term is the cost paid for the energy and reserve service provided by merchant storage. The fourth term is the curtailment cost of renewable generators. Constraint (18) restraints the non-negativity of regulated storage investment decisions on maximum power rating.

2.4 | Lower-level problem

The LL problem clears energy and reserve markets, which is solved by the SO as follows:

$$\min_{\Xi_{\mathrm{LL}}} \sum_{s\in S}\pi_s\left(\sum_{t\in T}\left(\sum_{g\in G}\left(C_g p_{s,g,t} + C_g^{\uparrow} r_{s,g,t}^{\uparrow} + C_g^{\downarrow} r_{s,g,t}^{\downarrow}\right) + \sum_{n\in N}\begin{pmatrix}\bar{o}_{s,n,t}^{\mathrm{dis}} p_{s,n,t}^{\mathrm{dis}} - \bar{o}_{s,n,t}^{\mathrm{ch}} p_{s,n,t}^{\mathrm{ch}} + \bar{o}_{s,n,t}^{\mathrm{ch}\uparrow} r_{s,n,t}^{\mathrm{ch}\uparrow} \\ + \bar{o}_{s,n,t}^{\mathrm{dis}\uparrow} r_{s,n,t}^{\mathrm{dis}\uparrow} + \bar{o}_{s,n,t}^{\mathrm{ch}\downarrow} r_{s,n,t}^{\mathrm{ch}\downarrow} + \bar{o}_{s,n,t}^{\mathrm{dis}\downarrow} r_{s,n,t}^{\mathrm{dis}\downarrow}\end{pmatrix} + \sum_{w\in W}\left(C_w^{\mathrm{ws}} p_{s,w,t}^{\mathrm{ws}}\right)\right)\right) \tag{19}$$

subject to

$$p_{s,g,t} + r_{s,g,t}^{\uparrow} \leq P_g : \bar{\alpha}_{s,g,t} \ \forall s,g,t, \tag{20}$$

$$p_{s,g,t} - r_{s,g,t}^{\downarrow} \geq 0 : \underline{\alpha}_{s,g,t} \ \forall s,g,t, \tag{21}$$

$$r_{s,g,t}^{\uparrow}, r_{s,g,t}^{\downarrow} \geq 0 : \underline{\gamma}_{s,g,t}^{\uparrow}, \underline{\gamma}_{s,g,t}^{\downarrow} \ \forall s,g,t, \tag{22}$$

$$p_{s,g,t} + r_{s,g,t}^{\uparrow} - \left(p_{s,g,t-1} - r_{s,g,t-1}^{\downarrow}\right) \leq RU_g : \bar{\beta}_{s,g,t} \ \forall s,g,t, \tag{23}$$

$$p_{s,g,t-1} + r_{s,g,t-1}^{\uparrow} - \left(p_{s,g,t} - r_{s,g,t}^{\downarrow}\right) \leq RD_g : \underline{\beta}_{s,g,t} \ \forall s,g,t, \tag{24}$$

$$0 \leq p_{s,w,t}^{\mathrm{ws}} \leq P_{s,w,t}^{\mathrm{wf}} : \underline{\mu}_{s,w,t}, \bar{\mu}_{s,w,t} \ \forall s,w,t, \tag{25}$$

$$0 \leq p_{s,n,t}^{\mathrm{dis}} \leq \bar{p}_{s,n,t}^{\mathrm{dis}} : \underline{\xi}_{s,n,t}^{\mathrm{dis}}, \bar{\xi}_{s,n,t}^{\mathrm{dis}} \ \forall s,n,t, \tag{26}$$

$$0 \leq p_{s,n,t}^{\mathrm{ch}} \leq \bar{p}_{s,n,t}^{\mathrm{ch}} : \underline{\xi}_{s,n,t}^{\mathrm{ch}}, \bar{\xi}_{s,n,t}^{\mathrm{ch}} \ \forall s,n,t, \tag{27}$$

$$0 \leq r_{s,n,t}^{\mathrm{ch}\uparrow} \leq \bar{r}_{s,n,t}^{\mathrm{ch}\uparrow} : \underline{\gamma}_{s,n,t}^{\mathrm{ch}\uparrow}, \bar{\gamma}_{s,n,t}^{\mathrm{ch}\uparrow} \ \forall s,n,t, \tag{28}$$

$$0 \leq r_{s,n,t}^{\mathrm{dis}\uparrow} \leq \bar{r}_{s,n,t}^{\mathrm{dis}\uparrow} : \underline{\gamma}_{s,n,t}^{\mathrm{dis}\uparrow}, \bar{\gamma}_{s,n,t}^{\mathrm{dis}\uparrow} \ \forall s,n,t, \tag{29}$$

$$0 \leq r_{s,n,t}^{\mathrm{dis}\downarrow} \leq \bar{r}_{s,n,t}^{\mathrm{dis}\downarrow} : \underline{\gamma}_{s,n,t}^{\mathrm{dis}\downarrow}, \bar{\gamma}_{s,n,t}^{\mathrm{dis}\downarrow} \ \forall s,n,t, \tag{30}$$

$$0 \leq r_{s,n,t}^{\mathrm{ch}\downarrow} \leq \bar{r}_{s,n,t}^{\mathrm{ch}\downarrow} : \underline{\gamma}_{s,n,t}^{\mathrm{ch}\downarrow}, \bar{\gamma}_{s,n,t}^{\mathrm{ch}\downarrow} \ \forall s,n,t, \tag{31}$$

$$0 \leq p_{s,n,t}^{\mathrm{SO,dis}} \leq p_n^{\mathrm{SO,max}} : \underline{\xi}_{s,n,t}^{\mathrm{SO,dis}}, \bar{\xi}_{s,n,t}^{\mathrm{SO,dis}} \ \forall s,n,t, \tag{32}$$

$$0 \leq p_{s,n,t}^{\mathrm{SO,ch}} \leq p_n^{\mathrm{SO,max}} : \underline{\xi}_{s,n,t}^{\mathrm{SO,ch}}, \bar{\xi}_{s,n,t}^{\mathrm{SO,ch}} \ \forall s,n,t, \tag{33}$$

$$e_{s,n,t}^{\mathrm{SO}} = \eta_c\, p_{s,n,t}^{\mathrm{SO,ch}} - p_{s,n,t}^{\mathrm{SO,dis}}/\eta_d : \varphi_{s,n,t}^{\mathrm{SO}} \ \forall s,n,t = 1, \tag{34}$$

$$e_{s,n,t}^{\mathrm{SO}} = e_{s,n,t-1}^{\mathrm{SO}} + \eta_c p_{s,n,t}^{\mathrm{SO,ch}} - p_{s,n,t}^{\mathrm{SO,dis}}/\eta_d : \varphi_{s,n,t}^{\mathrm{SO}} \ \forall s,n,t > 1, \tag{35}$$

$$e_{s,n,t}^{\mathrm{SO}} = 0 : \varphi_{s,n}^{\mathrm{SO,end}} \ \forall s,n,t = 24, \tag{36}$$

$$e_{s,n,t}^{\mathrm{SO}} + \eta_c r_{s,n,t}^{\mathrm{SO,ch}\downarrow} + r_{s,n,t}^{\mathrm{SO,dis}\downarrow}/\eta_d \leq e_n^{\mathrm{SO,max}} : \bar{\varphi}_{s,n,t}^{\mathrm{SO}} \ \forall s,n,t, \tag{37}$$

$$e_{s,n,t}^{\mathrm{SO}} - \eta_c r_{s,n,t}^{\mathrm{SO,ch}\uparrow} - r_{s,n,t}^{\mathrm{SO,dis}\uparrow}/\eta_d \geq 0 : \underline{\varphi}_{s,n,t}^{\mathrm{SO}} \ \forall s,n,t, \tag{38}$$

$$0 \leq r_{s,n,t}^{\mathrm{SO,ch}\uparrow} \leq p_{s,n,t}^{\mathrm{SO,ch}} : \underline{\gamma}_{s,n,t}^{\mathrm{SO,ch}\uparrow}, \bar{\gamma}_{s,n,t}^{\mathrm{SO,ch}\uparrow} \ \forall s,n,t, \tag{39}$$

$$0 \leq r_{s,n,t}^{\mathrm{SO,dis}\uparrow} \leq p_n^{\mathrm{SO,max}} - p_{s,n,t}^{\mathrm{SO,dis}} : \underline{\gamma}_{s,n,t}^{\mathrm{SO,dis}\uparrow}, \bar{\gamma}_{s,n,t}^{\mathrm{SO,dis}\uparrow} \forall s,n,t, \tag{40}$$

$$0 \leq r_{s,n,t}^{\mathrm{SO,dis}\downarrow} \leq p_{s,n,t}^{\mathrm{SO,dis}} : \underline{\gamma}_{s,n,t}^{\mathrm{SO,dis}\downarrow}, \bar{\gamma}_{s,n,t}^{\mathrm{SO,dis}\downarrow} \ \forall s,n,t, \tag{41}$$

$$0 \le r^{\mathrm{SO,ch}\downarrow}_{s,n,t} \le p^{\mathrm{SO,max}}_{n} - p^{\mathrm{SO,ch}}_{s,n,t} \;:\; \underline{\gamma}^{\mathrm{SO,ch}\downarrow}_{s,n,t}, \bar{\gamma}^{\mathrm{SO,ch}\downarrow}_{s,n,t} \forall s,n,t, \tag{42}$$

$$\sum_{g\in G} r^{\uparrow}_{s,g,t} + \sum_{n\in N}\left(r^{\mathrm{ch}\uparrow}_{s,n,t} + r^{\mathrm{dis}\uparrow}_{s,n,t} + r^{\mathrm{SO,ch}\uparrow}_{s,n,t} + r^{\mathrm{SO,dis}\uparrow}_{s,n,t}\right) = R^{\uparrow}_{s,t} \;:\; \lambda^{\uparrow}_{s,t}\ \forall s,t, \tag{43}$$

$$\sum_{g\in G} r^{\downarrow}_{s,g,t} + \sum_{n\in N}\left(r^{\mathrm{ch}\downarrow}_{s,n,t} + r^{\mathrm{dis}\downarrow}_{s,n,t} + r^{\mathrm{SO,ch}\downarrow}_{s,n,t} + r^{\mathrm{SO,dis}\downarrow}_{s,n,t}\right) = R^{\downarrow}_{s,t} \;:\; \lambda^{\downarrow}_{s,t}\ \forall s,t, \tag{44}$$

$$D_{s,n,t} - \sum_{g\in G_n} p_{s,g,t} - \sum_{w\in W_n}\left(P^{\mathrm{wf}}_{s,w,t} - p^{\mathrm{ws}}_{s,w,t}\right) + p^{\mathrm{SO,ch}}_{s,n,t} - p^{\mathrm{SO,dis}}_{s,n,t}$$
$$+p^{\mathrm{ch}}_{s,n,t} - p^{\mathrm{dis}}_{s,n,t} + \sum_{m\in\Omega_n} B_{nm}\left(\theta_{s,n,t} - \theta_{s,m,t}\right) = 0 \;:\; \lambda_{s,n,t}\ \forall s,n,t, \tag{45}$$

$$-F^{\max}_{nm} \le B_{nm}\left(\theta_{s,n,t} - \theta_{s,m,t}\right) \le F^{\max}_{nm} \;:\; \underline{\sigma}_{s,nm,t}, \bar{\sigma}_{s,nm,t} \forall s,n,m \in \Omega_n, t, \tag{46}$$

$$\theta_{s,n=\mathrm{ref},t} = 0 \;:\; \chi_{s,t}\ \forall s,t, \tag{47}$$

$$\theta_{\min} \le \theta_{s,n,t} \le \theta_{\max} \;:\; \underline{\tau}_{s,n,t}, \bar{\tau}_{s,n,t}\ \forall s,n,t, \tag{48}$$

where $\Xi_{\mathrm{LL}} = \{p_{s,g,t}, r^{\uparrow}_{s,g,t}, r^{\downarrow}_{s,g,t}, p^{\mathrm{ws}}_{s,w,t}, p^{\mathrm{SO,ch}}_{s,n,t}, p^{\mathrm{SO,dis}}_{s,n,t}, r^{\mathrm{SO,ch}\downarrow}_{s,n,t}, r^{\mathrm{SO,dis}\downarrow}_{s,n,t}, r^{\mathrm{SO,ch}\uparrow}_{s,n,t}, r^{\mathrm{SO,dis}\uparrow}_{s,n,t}, p^{\mathrm{ch}}_{s,n,t}, p^{\mathrm{dis}}_{s,n,t}, r^{\mathrm{ch}\uparrow}_{s,n,t}, r^{\mathrm{dis}\uparrow}_{s,n,t}, r^{\mathrm{ch}\downarrow}_{s,n,t}, r^{\mathrm{dis}\downarrow}_{s,n,t}, e^{\mathrm{SO}}_{s,n,t}, \theta_{s,n,t}\}$ is the primal variable set of the LL problem.

The objective function (19) minimizes the expected operation cost of the whole system. The power output of conventional generator is restrained by its upward and downward reserve provisions and its maximum output in (20) and (21). Constraint (22) enforces the non-negativity of upward and downward reserve provisions of conventional generators. Constraints (23) to (24) are conventional generators' upward and downward ramping limits. The curtailment of renewable generation is limited by the forecast power output in (25). The dispatched charging and discharging power of merchant storage is restrained by the submitted offers in (26) and (27). Similarly, (28) to (31) limit the dispatched upward and downward reserves provided by merchant storage. Similar with the constraints of merchant storage in the UL problem, (32) to (42) restraint the charging and discharging power, SOC, and reserve provisions of regulated storage. Constraints (43) and (44) enforce the upward and downward reserve balance. The nodal energy balance is enforced in (45). The active power flows on transmission lines are limited in (46). Constraint (47) enforces the angle at slack bus and (48) limits the minimum and maximum of nodal voltage angles.

2.5 | Solution technique

The trilevel problem proposed in this work cannot be solved directly. The solution technique is explained as follows: since the ML and LL problems are both solved by the SO and (17) actually includes (19), we first merge the ML (b) and LL problem (c) to obtain a new LL' problem (d):

$$\min\ (17) \tag{49}$$

$$\text{s.t. } (18),\ (20) - (48) \tag{50}$$

The Karush–Kuhn–Tucker (KKT) conditions of (d) are derived, as given in Appendix A, which are taken as the constraints of UL problem. Note that the KKT conditions provide the global optimality since (d) is linear and continuous. In this way, we get a single-level mathematical program with equilibrium constraints (MPEC).

There are two sources of non-linearity in MPEC that need to be linearized: (1) complementarity conditions in KKT conditions. (2) The bilinear terms in the objective function (1), that is, the product of prices and dispatched quantities in terms of energy and reserve of merchant storage. The complementarity conditions can be linearized by the Big-M method [31]. Following the strong duality theorem, the bilinear terms can be reformulated as linear terms as shown in Appendix B. Finally, the single-level MILP form of the proposed model is obtained, which can be solved directly by off-the-shelf solvers.

3 | NUMERICAL RESULTS

In this section, we investigate the proposed model using a 6-bus illustrative example and the IEEE 24-bus reliability test case. We consider the renewable generation as the source of uncertainty in this paper. The renewable curtailment is allowed at no cost. The reserve requirement is set to cover 3% system load and 5% of renewable generation forecast at each time period [23, 32].

The ES investment costs C_{e} and C_{p} are prorated by the capital recovery factor $\frac{r(1+r)^{\zeta}}{(1+r)^{\zeta}-1}\cdot\frac{1}{\mathrm{H}}$, where the interest rate $r = 5\%$, the lifetime $\zeta = 10$ years, and H is the number of days in the target year. Energy-to-power ratio of storage is fixed as $a = 4$ h. Charging and discharging efficiency $\eta_c = \eta_d = 0.9$.

The numerical experiments of all cases are performed on a PC with Intel Core i5-8250U CPU, clocking at 1.8 GHz and 8 GB RAM. The proposed MILP problem was implemented in Python 3.8.5 and solved via Gurobi 9.1.1 and CPLEX 12.9.0, with the MIP gap tolerance set to 0.0001.

3.1 | Illustrative example

The diagram of 6-bus test case is shown in Figure 2. The data of conventional generators are shown in Table 2. The data of hourly load, wind generation, and transmission lines are from [33]. A wind plant is at bus 5 and the wind penetration level is rescaled to 20% of the system load. The target year is

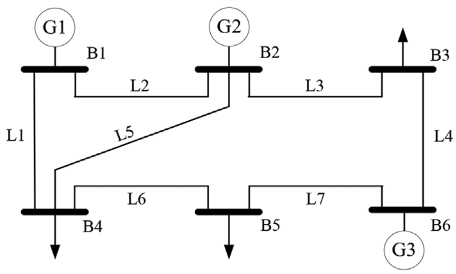

FIGURE 2 Six-bus system.

TABLE 2 Data of conventional generators.

Unit no.	Bus no.	P^{max} (MW)	RU/RD (MW)	C_g ($/MW)	$C_g^{\uparrow/\downarrow}$ ($/MW)
1	1	150	40	20	6
2	2	100	25	25	7.5
3	6	100	20	40	12

represented by a single characteristic day. The following two cases are studied in the illustrative example:

Case 1: Only regulated storage investment is considered.
Case 2: The MILP model proposed in this paper.

Case 1 is a convex linear optimization problem solved by the SO, which can provide the globally optimal storage investment decisions. Case 2 presents the concurrent investment of regulated and merchant storage according to the methodology presented in Section 2. In addition, we also consider the base case, that is, no storage case, which is the economical dispatch problem in energy and reserve markets without storage units. The total system cost (i.e. generator cost) obtained in no storage case is $84903. Note that the total system cost here is the prorated cost per day.

Three scenarios of capital cost of ES investment are considered: $143/kWh (low), $198/kWh (medium), and $248/kWh (high) in both case studies [34].

Table 3 elaborates the optimal siting and sizing of storage in Case 1 and Case 2 with different capital costs of storage investment and rate-of-returns. The results in Table 3 suggest that rate-of-return $\varkappa$ influences the merchant storage capacity installed, which then affects regulated storage investment indirectly. In the low capital cost scenario (when $\varkappa = 1$), 26.68 MWh merchant storage is installed at bus 2, bus 4, and bus 5. When $\varkappa$ increases from 1.0 to 1.05, the merchant storage installed does not change since (4) is not binding. Then with the increase of $\varkappa$, less merchant but more regulated storage is installed. When $\varkappa = 1.2$, only 24.88 MWh regulated storage is invested at bus 4 and bus 5, and the investment scheme of Case 2 is the same with Case 1. In the medium capital cost scenario, we can see the similar trend with different rate-of-returns. In the high capital cost scenario, the capital cost is too high to install storage in Case 1. In Case 2, although no regulated storage is installed but there still exists merchant storage investment.

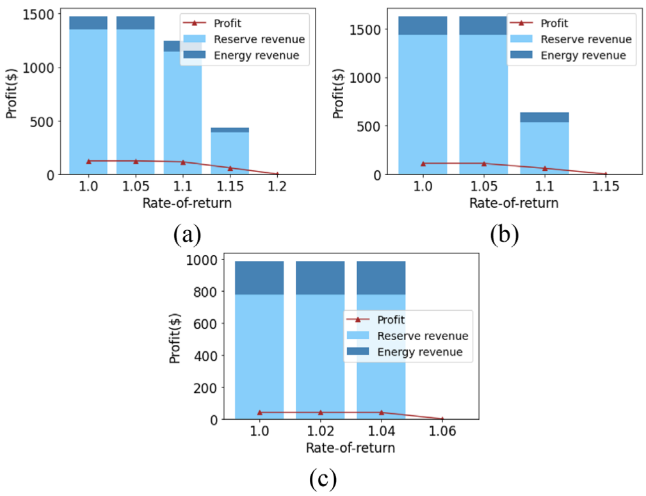

FIGURE 3 Revenues and profits of merchant storage in three capital cost of investment scenarios: (a) low, (b) medium, (c) high.

When $\varkappa$ is increased to 1.06, there is no storage investment in the system. Furthermore, the results in Table 3 show that generally increasing capital cost of investment reduces the storage locations and capacity installed.

Table 4 gives system costs of the SO with different capital costs in two cases. Note that in Case 2, the cost of merchant service represents the cost paid for energy and reserve service provided by merchant storage, that is, the revenues of merchant storage. Total cost of the whole system is the sum of generator cost, cost of merchant service, and regulated investment cost.

From the results in Table 4 we can see that in the three scenarios, with different ownership structures of storage, the total costs of Case 1 and Case 2 are the same. Also, with more regulated storage and less merchant storage installed, the generator cost increases, which shows merchant storage takes part of the market share of generators to achieve more revenues compared with regulated storage. For instance, in the low capital cost scenario, the generator cost increases from $82781 ($\varkappa = 1.0$) to $82995 ($\varkappa = 1.2$). Furthermore, compared with the total cost $84,903 in the base case, the total costs in low and medium capital cost scenarios decrease by $645 and $198, respectively (to $84,258 in the low capital cost scenario and to $84,705 in the medium capital cost scenario) suggesting that merchant storage and regulated storage can both reduce the system cost. In the high capital cost scenario, the total cost $84,903 is the same with the base case, showing merchant storage investment does not change total cost of the system. In Case 1 and Case 2, increasing capital cost of investment generally results in less storage investment and higher total cost of the system.

Figure 3 shows the energy and reserve revenues and profits of merchant storage in three capital cost scenarios. Profit is the difference between storage revenue and investment cost. In the three scenarios, generally increasing rate-of-return leads to the decrease of energy and reserve revenues and profit since less merchant storage is installed. Also, the reserve revenues are usually much higher than energy revenues.

TABLE 3 Investment schemes with different capital costs of investment and rare-of-returns.

Capital cost of investment		**Low**				**Medium**				**High**			
Case1	**Regulated storage, MWh (bus)**	**11.04 (b4) 13.84 (b5)**				**5.77 (b4) 12.07 (b5)**				**0(−)**			
	Total storage, MWh	**24.88**				**17.84**				**0**			
Case2	Rate-of-return	1.0/1.05	1.1	1.15	1.2	1.0	1.05	1.1	1.15	1.0	1.02	1.04	1.06
	Merchant storage, MWh (bus)	3.44 (b2) 0.53 (b4) 22.71 (b5)	0.61 (b2) 2.60 (b4) 19.17 (b5)	1.02 (b4) 6.48 (b5)	0(−)	3.00 (b4) 18.62 (b5)	3.00 (b4) 18.62 (b5)	8.27 (b5)	0(−)	10.75 (b5)	10.75 (b5)	10.75 (b5)	0(−)
	Regulated storage, MWh (bus)	0(−)	3.96 (b5)	9.23 (b4) 8.51 (b5)	11.04 (b4) 13.84 (b5)	0(−)	0(−)	4.61 (b4) 7.25 (b5)	5.77 (b4) 12.07 (b5)	0(−)	0(−)	0(−)	0(−)
	Total storage, MWh	26.68	26.34	25.24	24.88	21.62	21.62	20.14	17.84	10.75	10.75	10.75	0

TABLE 4 System costs with different capital costs of investment and rate-of-returns.

Capital cost of investment	**Cost**	**Case 2**				**Case 1**
Low	Rate-of-return	1.0/1.05	1.1	1.15	1.2	–
	Generator cost ($)	82,781	82,808	82,920	82,995	82,995
	Cost of merchant service ($)	1477	1249	438	0	–
	Regulated investment cost ($)	0	201	900	1263	1263
	Total cost ($)	84,258	84,258	84,258	84,258	84,258
Medium	Rate-of-return	1.0	1.05	1.1	1.15	–
	Generator cost ($)	83,077	83,077	83,232	83,452	83,452
	Cost of merchant service ($)	1628	1628	639	0	–
	Regulated investment cost ($)	0	0	834	1253	1253
	Total cost ($)	84,705	84,705	84,705	84,705	84,705
High	Rate-of-return	1.0	1.02	1.04	1.06	–
	Generator cost ($)	83,917	83,917	83,917	84,903	84,903
	Cost of merchant service ($)	986	986	986	0	–
	Regulated investment cost ($)	0	0	0	0	0
	Total cost ($)	84,903	84,903	84,903	84,903	84,903

From the results for different capital cost scenarios, it can be observed that regulated and merchant storages are both invested to provide energy arbitrage and reserve service to reduce generator cost. However, we can observe that the profitability ability of merchant storage is stronger than regulated storage. We present a special case that when capital cost is too high to install storage units from the perspective of the SO, the merchant investor can still achieve enough profits to support its investment decisions. This finding coincides with the theorem proved in [11, 12] that regulated storage always yields zero profit, while merchant storage seeks to maximize its profits ensuring a desired rate-of-return, which is guaranteed by constraint (4) in this paper. Different investment targets contribute to different operation modes of regulated and merchant storage.

3.2 | IEEE 24-Bus reliability test case

The proposed model is also applied to the IEEE 24-Bus Reliability Test Case [35]. We consider three levels of wind penetration: 5%, 10%, and 15%, distributed equally at bus 21 and 23 and reduce the hourly wind generation data of Alberta Electric System Operator (AESO) in 2020 [36] to three characteristic days using the fast forward selection method [37]. The capacity of transmission line connecting the bus pair (14,16) is reduced to 400 MW.

The results for three wind penetration levels are given in Table 5. We can observe that storages installed at bus 14, which is congested. The three sets of results for different wind penetration levels show the similar trends of investment schemes and system costs, and therefore we only analyze the 10% wind

TABLE 5 Investment schemes with different wind penetration levels and rare-of-returns.

Wind level	5%				10%				15%			
Rate-of-return	1.0	1.34	1.38	1.4	1.0	1.2	1.3	1.4	1.0/1.2	1.24	1.28	1.3
Merchant storage, MWh (bus)	82.39 (b14)	82.39 (b14)	73.06 (b14)	0(-)	53.37 (b14)	53.37 (b14)	30.59 (b14)	0(−)	29.80 (b14)	28.79 (b14)	20.46 (b14)	0(−)
Regulated storage, MWh (bus)	0(−)	0(−)	0(−)	48.08 (b14)	0(−)	0(−)	15.20 (b14)	32.33 (b14)	0(−)	0(−)	0(−)	16.57 (b14)
Total storage, MWh	82.39	82.39	73.06	48.08	53.37	53. 37	45.79	32.33	29.80	28.79	20.46	16.57

TABLE 6 System costs with different wind penetration levels and rare-of-returns.

Wind level	Cost	–			
5%	Rate-of-return	1.0	1.34	1.38	1.4
	Generator cost ($)	347,730	347,730	348,250	350,927
	Cost of merchant service ($)	5635	5635	5116	0
	Regulated investment cost ($)	0	0	0	2439
	Total cost ($)	353,365	353,365	353,366	353,366
10%	Rate-of-return	1.0	1.2	1.3	1.4
	Generator cost ($)	338,866	338,866	339,522	340,671
	Cost of merchant service ($)	3444	3444	2018	0
	Regulated investment cost ($)	0	0	771	1640
	Total cost ($)	342,310	342,310	342,311	342,311
15%	Rate-of-return	1.0/1.2	1.24	1.28	1.3
	Generator cost ($)	329,898	329,954	330,436	330,924
	Cost of merchant service ($)	1867	1811	1329	0
	Regulated investment cost ($)	0	0	0	841
	Total cost ($)	331,765	331,765	331,765	331,765

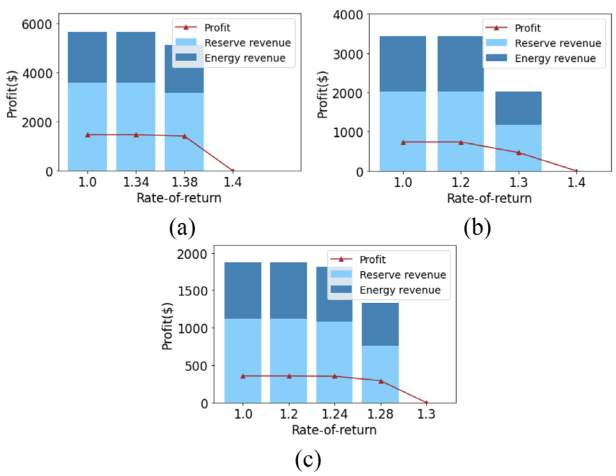

FIGURE 4 Revenues and profits of merchant storage in three wind penetration level scenarios: (a) 5%, (b) 10%, (c) 15%.

penetration scenario. For 10% wind penetration, when $\varkappa = 1$ and $\varkappa = 1.2$, 53.37 MWh merchant storage is installed and the merchant investment schemes are the same, because (4) is inactive. With the increase of $\varkappa$, more regulated and less merchant

TABLE 7 Dimension of the single-level MILP model.

Number of continuous variables	$3N_b + N_s N_b + N_s N_t (9N_g + 3N_w + 57N_b + 2N_l + 3)$
Number of binary variables	$N_b + N_s N_t (6N_g + 2N_w + 28N_b + 2N_l)$
Number of constraints	$1 + 6N_b + 2N_s N_b + N_s N_t (27N_g + 9N_w + 149N_b + 8N_l + 3)$

storage is installed. When $\varkappa$ is increased to 1.4, it is a too high profitability requirement to invest in merchant storage and thus only 32.33 MWh regulated storage is installed.

The system cost results for different wind penetration levels are presented in Table 6. Generally, increasing wind penetration level reduces the system cost. Furthermore, we note that generally higher $\varkappa$ leads to less merchant and more regulated storage installed, which increases generator cost; however, total cost remains basically the same.

It is interesting to note that higher wind penetration level leads to less storage investment. The results of Table 6 suggest that increasing wind penetration levels significantly reduces conventional generator costs, thereby reducing the need for storage investment, as merchant storage achieves profits by capturing

TABLE 8 Comparison of computation time and solutions of different solvers.

Test case	Scenario	Rate of return	Objective ($)		Time(s)	
			Gurobi	CPLEX	Gurobi	CPLEX
6-bus	Low	1.0	123.23	123.23	2.71	4.62
		1.1	113.54	113.54	4.15	8.27
		1.15	57.07	57.07	4.30	7.29
		1.2	0	0	1.79	3.67
	Medium	1.0	108.87	108.87	1.80	4.65
		1.05	108.87	108.87	1.80	4.64
		1.1	58.10	58.10	3.39	5.63
		1.15	0	0	1.73	4.01
	High	1.0	39.81	39.81	1.45	3.72
		1.02	39.81	39.81	1.49	3.55
		1.04	39.81	39.81	1.41	3.72
		1.06	0	0	1.98	3.91
24-bus	5%	1.0	1454.20	1454.20	174.77	543.48
		1.34	1454.20	1454.20	221.63	484.07
		1.38	1408.69	1408.69	247.23	457.85
		1.4	0	0	117.61	158.54
	10%	1.0	736.14	736.14	179.60	513.43
		1.2	736.14	736.14	182.36	509.38
		1.3	465.65	465.65	125.52	545.53
		1.4	0	0	109.18	163.46
	15%	1.0	354.72	354.72	105.86	336.86
		1.24	350.52	350.52	104.40	454.69
		1.28	290.66	290.66	106.83	423.34
		1.3	0	0	110.71	128.01

market share that previously belonged to conventional generators. For instance, when $\kappa = 1$, in the three wind penetration level scenarios, the decrease in generator cost of $347,730; $338,866; and $329,898 corresponds to the decrease in merchant storage investment of 82.39, 53.37, and 29.80 MWh, respectively. In this way, higher wind penetration level reduces generator cost, storage investment cost, and total cost of the system.

Figure 4 shows energy and reserve revenues and profits of merchant storage in three wind penetration level scenarios in the 24-bus test case. We can see that with higher rate-of-returns, less merchant storage investments lead to less revenues and profits achieved by merchant storage. The reserve revenues are higher than energy revenues.

3.3 | Analysis of computational complexity and accuracy

The single-level MILP model solved in this work is NP-hard, of which computational complexity is determined by its number of variables and constraints. The numbers of binary and continuous variables and constraints are given in Table 7.

In Table 8, we compare computation time and solutions of Gurobi and CPLEX for the 6-bus illustrative example and the 24-bus test case under different capital cost of investment (Low, Medium, and High) and wind penetration level (5%, 10%, and 15%) scenarios. The computation time of the 6-bus illustrative example is in 10 s. The 24-bus test case with 3 characteristic days can be solved in 10 min. Also, the solutions output by Gurobi and CPLEX are the same, verifying optimality and accuracy of solutions.

4 | CONCLUSION

This paper proposes a Stackelberg game model to study interactions of merchant and regulated storage in energy and reserve markets. Merchant and regulated storage seeks to maximize its own profit and minimize system cost respectively. The case studies explore how the coupling factors, that is, rate-of-return, capital investment cost, and wind penetration level influence ownership structures, merchant storage profitability, and social welfare. From the numerical results, we conclude that increasing rate-of-return of merchant storage results in less merchant and more regulated storage investment. Both regulated and merchant storage can enhance social welfare. We also present a special case where only exists merchant storage in the system and the total system cost stays unchanged regardless of the amount of the installed merchant storage capacity, which is determined by the investment cost and required rate-of-return κ. Although different desired rate-of-returns of merchant storage lead to different storage ownership structures in the system, social welfare remains almost the same.

Furthermore, we observe that the profitability of merchant storage is stronger than regulated storage, as merchant storage has the capability to acquire a greater market share that was previously held by generators. The stacked revenue streams from energy and reserve markets increase the profitability of merchant storage investment, improving viability and prospect of merchant storage. Finally, this paper demonstrates the importance of including reserve market revenue stream when the decision on the storage investment is made and merchant storage has the potential to increase or at very least maintain social welfare without any negative impact.

In the future work, the proposed Stackelberg game model can be extended to a more competitive market environment. For example, the proposed model adopts a simplified setting that there exists only one merchant storage investor in the market. It would be interesting to explore the competition of multiple storage investors and its influence on social welfare and merchant storage profits. Another extension is to investigate storage investment of different ownership structures in a more comprehensive model incorporating various strategic participants, for example, conventional generators, renewable generators, and demand response aggregators.

NOMENCLATURE

Sets and Indices

- N set of buses, indexed by n, m.
- G set of conventional generators, indexed by g.
- W set of renewable generators, indexed by w.
- S set of characteristic days, indexed by s.
- T set of hourly operating intervals in a day, from 1 to 24, indexed by t.

Parameters

- π_s probability of characteristic day s
- a energy-to-power ratio of storage [h]
- κ rate of return
- C_{e} prorated daily investment cost of storage per MWh [$/MWh]
- C_{p} prorated daily investment cost of storage per MW [$/MW]
- $C_g^{\uparrow/\downarrow}$ upward/downward reserve price offered by generator g [$/MWh]
- C_g energy price offered by generator g [$/MWh]
- C^{ws} wind curtailment cost per MWh [$/MWh]
- η_c/η_d charging and discharging efficiencies of storage
- P_g capacity of generator g [MW]
- $P_{s,w,t}^{\mathrm{wf}}$ forecast power offer of renewable generator w at time t on characteristic day s [MW]
- $R_{s,t}^{\uparrow/\downarrow}$ upward/downward reserve requirement at time t on characteristic day s [MW]
- RU_g ramp up limit of generator g [MW/h]
- RD_g ramp down limit of generator g [MW/h]
- $D_{s,n,t}$ demand at bus n at time t on characteristic day s [MW]
- B_{nm} susceptance of transmission line (n, m) [S]
- $F_{nm}^{\max}$ capacity of transmission line (n, m) [MW]
- N_{s} the number of characteristic days
- N_{b} the number of buses
- N_{l} the number of transmission lines
- N_{g} the number of conventional generators
- N_{w} the number of renewable generators
- N_{t} the number of operating intervals

Upper-level variables

- $p_n^{\max}$ maximum power rating of merchant storage at bus n [MW]
- $\bar{p}_{s,n,t}^{\mathrm{ch/dis}}$ quantity offer of charging/discharging power by merchant storage at bus n at time t on characteristic day s [MW]
- $\bar{r}_{s,n,t}^{\mathrm{ch}\uparrow/\downarrow}$ quantity offer of upward/downward reserve by merchant storage in charging mode at bus n at time t on characteristic day s [MW]
- $\bar{r}_{s,n,t}^{\mathrm{dis}\uparrow/\downarrow}$ quantity offer of upward/downward reserve by merchant storage in discharging mode at bus n at time t on characteristic day s [MW]
- $\bar{o}_{s,n,t}^{\mathrm{ch/dis}}$ price bid/offer of merchant storage in charging/discharging mode at bus n at time t on characteristic day s [$/MWh]
- $\bar{o}_{s,n,t}^{\mathrm{ch}\uparrow/\downarrow}$ price offer of upward/downward reserve by merchant storage in charging mode at bus n at time t on characteristic day s [$/MWh]
- $\bar{o}_{s,n,t}^{\mathrm{dis}\uparrow/\downarrow}$ price offer of upward/downward reserve by merchant storage in discharging mode at bus n at time t on characteristic day s [$/MWh]
- $e_{s,n,t}$ stored energy of merchant storage at bus n at time t on characteristic day s [MWh]

Lower-level variables

- $p_n^{\mathrm{SO,max}}$ maximum power rating of regulated storage at bus n [MW]
- $p_{s,g,t}$ power output of generator g at time t on characteristic day s [MW]

$r_{s,g,t}^{\uparrow/\downarrow}$ upward/downward reserve provided by generator g at time t on characteristic day s [MW]

$p_{s,w,t}^{\mathrm{ws}}$ wind curtailment of renewable generator w at time t on characteristic day s [MW]

$p_{s,n,t}^{\mathrm{SO,ch/dis}}$ charging/discharging power of regulated storage at bus n at time t on characteristic day s [MW]

$r_{s,n,t}^{\mathrm{SO,ch}\uparrow/\downarrow}$ upward/downward reserve quantity offered by regulated storage in charging mode at bus n at time t on characteristic day s [MW]

$r_{s,n,t}^{\mathrm{SO,dis}\uparrow/\downarrow}$ upward/downward reserve quantity offered by regulated storage in discharging mode at bus n at time t on characteristic day s [MW]

$p_{s,n,t}^{\mathrm{ch/dis}}$ dispatched charging/discharging power of merchant storage at bus n at time t on characteristic day s [MW]

$r_{s,n,t}^{\mathrm{ch}\uparrow/\downarrow}$ dispatched upward/downward reserve offered by merchant storage in charging mode at bus n at time t on characteristic day s [MW]

$r_{s,n,t}^{\mathrm{dis}\uparrow/\downarrow}$ dispatched upward/downward reserve offered by merchant storage in discharging mode at bus n at time t on characteristic day s [MW]

$e_{s,n,t}^{\mathrm{SO}}$ stored energy of regulated storage at bus n at time t on characteristic day s [MWh]

$\theta_{s,n,t}$ voltage angle at bus n at time t on characteristic day s [rad]

Dual variables

ρ, $\alpha, \gamma, \mu, \xi, \varphi, \lambda, \sigma, \chi, \tau$ dual variables corresponding to constraints are defined after a colon. See Section 2 for details

AUTHOR CONTRIBUTIONS

Peiyao Guo: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing-original draft preparation, Thomas Hamacher: Conceptualization, Validation, Supervision. Vedran S. Peri?: Conceptualization, Validation, Project administration, Funding acquisition, Writing-review & editing, Supervision.

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The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Research data are not shared.

CREDIT CONTRIBUTION STATEMENT

Peiyao Guo: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing-original draft preparation, **Thomas Hamacher**: Conceptualization, Validation, Supervision. **Vedran S. Perić**: Conceptualization, Validation, Project administration, Funding acquisition, Writing-review & editing, Supervision.

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APPENDIX A: KKT CONDITIONS OF LOWER-LEVEL PROBLEM

The KKT conditions of the LL problem (d) are presented as follows:

$$(34) - (36), (43) - (45), (47) \tag{A1}$$

$$0 \le p_n^{\mathrm{SO,max}} \perp \rho_n \ge 0 \; \forall n \tag{A2}$$

$$0 \le P_g - p_{s,g,t} - r_{s,g,t}^{\uparrow} \perp \bar{\alpha}_{s,g,t} \ge 0 \; \forall s, g, t \tag{A3}$$

$$0 \le p_{s,g,t} - r_{s,g,t}^{\downarrow} \perp \underline{\alpha}_{s,g,t} \ge 0 \; \forall s, g, t \tag{A4}$$

$$0 \le r_{s,g,t}^{\downarrow} \perp \underline{\gamma}_{s,g,t}^{\downarrow} \ge 0 \; \forall s, g, t \tag{A5}$$

$$0 \le r_{s,g,t}^{\uparrow} \perp \underline{\gamma}_{s,g,t}^{\uparrow} \; \forall s, g, t \tag{A6}$$

$$0 \le RU_g + \left(p_{s,g,t-1} - r_{s,g,t-1}^{\downarrow}\right) - \left(p_{s,g,t} + r_{s,g,t}^{\uparrow}\right) \perp \bar{\beta}_{s,g,t} \ge 0 \; \forall s, g, t \tag{A7}$$

$$0 \le RD_g - \left(p_{s,g,t-1} + r_{s,g,t-1}^{\uparrow}\right) + \left(p_{s,g,t} - r_{s,g,t}^{\downarrow}\right) \perp \underline{\beta}_{s,g,t} \ge 0 \; \forall s, g, t \tag{A8}$$

$$0 \le p_{s,w,t}^{\mathrm{ws}} \perp \underline{\mu}_{s,w,t} \ge 0 \; \forall s, w, t \tag{A9}$$

$$0 \le P_{s,w,t}^{\mathrm{wf}} - p_{s,w,t}^{\mathrm{ws}} \perp \bar{\mu}_{s,w,t} \ge 0 \; \forall s, w, t \tag{A10}$$

$$0 \le p_{s,n,t}^{\mathrm{dis}} \perp \underline{\xi}_{s,n,t}^{\mathrm{dis}} \ge 0 \; \forall s, n, t \tag{A11}$$

$$0 \le \bar{p}_{s,n,t}^{\mathrm{dis}} - p_{s,n,t}^{\mathrm{dis}} \perp \bar{\xi}_{s,n,t}^{\mathrm{dis}} \ge 0 \; \forall s, n, t \tag{A12}$$

$$0 \le p_{s,n,t}^{\mathrm{ch}} \perp \underline{\xi}_{s,n,t}^{\mathrm{ch}} \ge 0 \; \forall s, n, t \tag{A13}$$

$$0 \le \bar{p}_{s,n,t}^{\mathrm{ch}} - p_{s,n,t}^{\mathrm{ch}} \perp \bar{\xi}_{s,n,t}^{\mathrm{ch}} \ge 0 \; \forall s, n, t \tag{A14}$$

$$0 \le r^{\mathrm{ch}\uparrow}_{s,n,t} \perp \underline{\gamma}^{\mathrm{ch}\uparrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A15}$$

$$0 \le \bar{r}^{\mathrm{ch}\uparrow}_{s,n,t} - r^{\mathrm{ch}\uparrow}_{s,n,t} \perp \bar{\gamma}^{\mathrm{ch}\uparrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A16}$$

$$0 \le r^{\mathrm{dis}\uparrow}_{s,n,t} \perp \underline{\gamma}^{\mathrm{dis}\uparrow}_{s,n,t} \ge 0 \; \forall s, \forall n, \forall t \tag{A17}$$

$$0 \le \bar{r}^{\mathrm{dis}\uparrow}_{s,n,t} - r^{\mathrm{dis}\uparrow}_{s,n,t} \perp \bar{\gamma}^{\mathrm{dis}\uparrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A18}$$

$$0 \le r^{\mathrm{dis}\downarrow}_{s,n,t} \perp \underline{\gamma}^{\mathrm{dis}\downarrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A19}$$

$$0 \le \bar{r}^{\mathrm{dis}\downarrow}_{s,n,t} - r^{\mathrm{dis}\downarrow}_{s,n,t} \perp \bar{\gamma}^{\mathrm{dis}\downarrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A20}$$

$$0 \le r^{\mathrm{ch}\downarrow}_{s,n,t} \perp \underline{\gamma}^{\mathrm{ch}\downarrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A21}$$

$$0 \le \bar{r}^{\mathrm{ch}\downarrow}_{s,n,t} - r^{\mathrm{ch}\downarrow}_{s,n,t} \perp \bar{\gamma}^{\mathrm{ch}\downarrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A22}$$

$$0 \le p^{\mathrm{SO,dis}}_{s,n,t} \perp \underline{\xi}^{\mathrm{SO,dis}}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A23}$$

$$0 \le p^{\mathrm{SO,max}}_{n} - p^{\mathrm{SO,dis}}_{s,n,t} \perp \bar{\xi}^{\mathrm{SO,dis}}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A24}$$

$$0 \le p^{\mathrm{SO,ch}}_{s,n,t} \perp \underline{\xi}^{\mathrm{SO,ch}}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A25}$$

$$0 \le p^{\mathrm{SO,max}}_{n} - p^{\mathrm{SO,ch}}_{s,n,t} \perp \bar{\xi}^{\mathrm{SO,ch}}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A26}$$

$$0 \le e^{\mathrm{SO,max}}_{n} - e^{\mathrm{SO}}_{s,n,t} - r^{\mathrm{SO,ch}\downarrow}_{s,n,t}\eta_c - r^{\mathrm{SO,dis}\downarrow}_{s,n,t}/\eta_d \perp \bar{\varphi}^{\mathrm{SO}}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A27}$$

$$0 \le e^{\mathrm{SO}}_{s,n,t} - r^{\mathrm{SO,ch}\uparrow}_{s,n,t}\eta_c - r^{\mathrm{SO,dis}\uparrow}_{s,n,t}/\eta_d \perp \underline{\varphi}^{\mathrm{SO}}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A28}$$

$$0 \le r^{\mathrm{SO,ch}\uparrow}_{s,n,t} \perp \underline{\gamma}^{\mathrm{SO,ch}\uparrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A29}$$

$$0 \le p^{\mathrm{SO,ch}}_{s,n,t} - r^{\mathrm{SO,ch}\uparrow}_{s,n,t} \perp \bar{\gamma}^{\mathrm{SO,ch}\uparrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A30}$$

$$0 \le r^{\mathrm{SO,dis}\uparrow}_{s,n,t} \perp \underline{\gamma}^{\mathrm{SO,dis}\uparrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A31}$$

$$0 \le p^{\mathrm{SO,max}}_{n} - p^{\mathrm{SO,dis}}_{s,n,t} - r^{\mathrm{SO,dis}\uparrow}_{s,n,t} \perp \bar{\gamma}^{\mathrm{SO,dis}\uparrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A32}$$

$$0 \le r^{\mathrm{SO,dis}\downarrow}_{s,n,t} \perp \underline{\gamma}^{\mathrm{SO,dis}\downarrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A33}$$

$$0 \le p^{\mathrm{SO,dis}}_{s,n,t} - r^{\mathrm{SO,dis}\downarrow}_{s,n,t} \perp \bar{\gamma}^{\mathrm{SO,dis}\downarrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A34}$$

$$0 \le r^{\mathrm{SO,ch}\downarrow}_{s,n,t} \perp \underline{\gamma}^{\mathrm{SO,ch}\downarrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A35}$$

$$0 \le p^{\mathrm{SO,max}}_{n} - p^{\mathrm{SO,ch}}_{s,n,t} - r^{\mathrm{SO,ch}\downarrow}_{s,n,t} \perp \bar{\gamma}^{\mathrm{SO,ch}\downarrow}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A36}$$

$$0 \le B_{nm}\left(\theta_{s,n,t} - \theta_{s,m,t}\right) + F^{\max}_{nm} \perp \underline{\sigma}_{s,nm,t} \ge 0 \; \forall s,n,m \in \Omega_n, t \tag{A37}$$

$$0 \le F^{\max}_{nm} - B_{nm}\left(\theta_{s,n,t} - \theta_{s,m,t}\right) \perp \bar{\sigma}_{s,nm,t} \ge 0 \; \forall s,n,m \in \Omega_n, t \tag{A38}$$

$$0 \le \theta_{s,n,t} - \theta_{min} \perp \underline{\tau}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A39}$$

$$0 \le \theta_{max} - \theta_{s,n,t} \perp \bar{\tau}_{s,n,t} \ge 0 \; \forall s,n,t \tag{A40}$$

$$C_g + \left(\bar{\alpha}_{s,g,t} - \underline{\alpha}_{s,g,t}\right) + \left(\bar{\beta}_{s,g,t} - \underline{\beta}_{s,g,t}\right) + \left(\underline{\beta}_{s,g,t+1} - \bar{\beta}_{s,g,t+1}\right) - \lambda_{s,n(g),t} = 0 \; \forall s,g,t \tag{A41}$$

$$C^{\uparrow}_g + \bar{\alpha}_{s,g,t} + \bar{\beta}_{s,g,t} + \underline{\beta}_{s,g,t+1} - \underline{\gamma}^{\uparrow}_{s,g,t} - \lambda^{\uparrow}_{s,t} = 0 \; \forall s,g,t \tag{A42}$$

$$C^{\downarrow}_g + \underline{\alpha}_{s,g,t} + \underline{\beta}_{s,g,t} + \bar{\beta}_{sg,t+1} - \underline{\gamma}^{\downarrow}_{s,g,t} - \lambda^{\downarrow}_{s,t} = 0 \; \forall s,g,t \tag{A43}$$

$$C^{\mathrm{ws}}_w + \bar{\mu}_{s,w,t} - \underline{\mu}_{s,w,t} + \lambda_{s,n(w),t} = 0 \; \forall s,w,t \tag{A44}$$

$$\bar{\xi}^{\mathrm{SO,ch}}_{s,n,t} - \underline{\xi}^{\mathrm{SO,ch}}_{s,n,t} - \eta_c\varphi^{\mathrm{SO}}_{s,n,t} - \bar{\gamma}^{\mathrm{SO,ch}\uparrow}_{s,n,t} + \bar{\gamma}^{\mathrm{SO,ch}\downarrow}_{s,n,t} + \lambda_{s,n,t} = 0 \; \forall s,n,t \tag{A45}$$

$$\bar{\xi}^{\mathrm{SO,dis}}_{s,n,t} - \underline{\xi}^{\mathrm{SO,dis}}_{s,n,t} + \varphi^{\mathrm{SO}}_{s,n,t}/\eta_d + \bar{\gamma}^{\mathrm{SO,dis}\uparrow}_{s,n,t} - \bar{\gamma}^{\mathrm{SO,dis}\downarrow}_{s,n,t} - \lambda_{s,n,t} = 0 \forall s,n,t \tag{A46}$$

$$\bar{\varphi}^{\mathrm{SO}}_{s,n,t}\eta_c + \bar{\gamma}^{\mathrm{SO,ch}\downarrow}_{s,n,t} - \underline{\gamma}^{\mathrm{SO,ch}\downarrow}_{s,n,t} - \lambda^{\downarrow}_{s,t} = 0 \; \forall s,n,t \tag{A47}$$

$$\bar{\varphi}^{\mathrm{SO}}_{s,n,t}/\eta_d + \bar{\gamma}^{\mathrm{SO,dis}\downarrow}_{s,n,t} - \underline{\gamma}^{\mathrm{SO,dis}\downarrow}_{s,n,t} - \lambda^{\downarrow}_{s,t} = 0 \forall s,n,t \tag{A48}$$

$$\underline{\varphi}^{\mathrm{SO}}_{s,n,t}\eta_c + \bar{\gamma}^{\mathrm{SO,ch}\uparrow}_{s,n,t} - \underline{\gamma}^{\mathrm{SO,ch}\uparrow}_{s,n,t} - \lambda^{\uparrow}_{s,t} = 0 \; \forall s,n,t \tag{A49}$$

$$\underline{\varphi}^{\mathrm{SO}}_{s,n,t}/\eta_d + \bar{\gamma}^{\mathrm{SO,dis}\uparrow}_{s,n,t} - \underline{\gamma}^{\mathrm{SO,dis}\uparrow}_{s,n,t} - \lambda^{\uparrow}_{s,t} = 0 \; \forall s,n,t \tag{A50}$$

$$-\bar{o}^{\mathrm{ch}}_{s,n,t} + \bar{\xi}^{\mathrm{ch}}_{s,n,t} - \underline{\xi}^{\mathrm{ch}}_{s,n,t} + \lambda_{s,n,t} = 0 \; \forall s,n,t \tag{A51}$$

$$\bar{o}^{\mathrm{dis}}_{s,n,t} + \bar{\xi}^{\mathrm{dis}}_{s,n,t} - \underline{\xi}^{\mathrm{dis}}_{s,n,t} - \lambda_{s,n,t} = 0 \; \forall s,n,t \tag{A52}$$

$$\bar{o}^{\mathrm{ch}\uparrow}_{s,n,t} + \bar{\gamma}^{\mathrm{ch}\uparrow}_{s,n,t} - \underline{\gamma}^{\mathrm{ch}\uparrow}_{s,n,t} - \lambda^{\uparrow}_{s,t} = 0 \; \forall s,n,t \tag{A53}$$

$$\bar{o}^{\mathrm{dis}\uparrow}_{s,n,t} + \bar{\gamma}^{\mathrm{dis}\uparrow}_{s,n,t} - \underline{\gamma}^{\mathrm{dis}\uparrow}_{s,n,t} - \lambda^{\uparrow}_{s,t} = 0 \; \forall s,n,t \tag{A54}$$

$$\bar{o}^{\mathrm{ch}\downarrow}_{s,n,t} + \bar{\gamma}^{\mathrm{ch}\downarrow}_{s,n,t} - \underline{\gamma}^{\mathrm{ch}\downarrow}_{s,n,t} - \lambda^{\downarrow}_{s,t} = 0 \; \forall s, n, t \tag{A55}$$

$$\bar{o}^{\mathrm{dis}\downarrow}_{s,n,t} + \bar{\gamma}^{\mathrm{dis}\downarrow}_{s,n,t} - \underline{\gamma}^{\mathrm{dis}\downarrow}_{s,n,t} - \lambda^{\downarrow}_{s,t} = 0 \; \forall s, n, t \tag{A56}$$

$$\varphi^{\mathrm{SO}}_{s,n,t} - \varphi^{\mathrm{SO}}_{s,n,t+1} + \bar{\varphi}^{\mathrm{SO}}_{s,n,t} - \underline{\varphi}^{\mathrm{SO}}_{s,n,t} = 0 \; \forall s, n, t < 24 \tag{A57}$$

$$\varphi^{\mathrm{SO}}_{s,n,t} + \bar{\varphi}^{\mathrm{SO}}_{s,n,t} - \underline{\varphi}^{\mathrm{SO}}_{s,n,t} + \varphi^{\mathrm{SO,end}}_{s,n} = 0 \; \forall s, n, t = 24 \tag{A58}$$

$$\sum_{m\in\Omega_n} B_{nm}\left(\lambda_{s,n,t} - \lambda_{s,m,t} - \underline{\sigma}_{s,nm,t} + \underline{\sigma}_{s,mn,t} + \bar{\sigma}_{s,nm,t} - \bar{\sigma}_{s,mn,t}\right)$$
$$+ \bar{\tau}_{s,n,t} - \underline{\tau}_{s,n,t}\left(+\chi_{s,t}\right)_{n=\mathrm{ref}} = 0 \; \forall s, n, t \tag{A59}$$

$$C^{\mathrm{SO}}_{\mathrm{e}} a + C^{\mathrm{SO}}_{\mathrm{p}} - \rho_n - \sum_{s\in S}\sum_{t\in T}\pi_s\left(\xi^{\mathrm{SO,ch}}_{s,n,t} + \xi^{\mathrm{SO,dis}}_{s,n,t} + a\bar{\varphi}^{\mathrm{SO}}_{s,n,t}\right.$$
$$\left. + \bar{\gamma}^{\mathrm{SO,dis}\uparrow}_{s,n,t} + \bar{\gamma}^{\mathrm{SO,ch}\downarrow}_{s,n,t}\right) = 0 \; \forall n \tag{A60}$$

APPENDIX B: LINEARIZATION OF BILINEAR TERMS IN OBJECTIVE FUNCTION (1)

The linearization process of bilinear terms in objective function (1) is presented in this Appendix. First, the strong duality equality of the lower-lower problem (d) is derived as follows:

$$\sum_{n\in N}\left(C^{\mathrm{SO}}_{e} e^{\mathrm{SO,max}}_{n} + C^{\mathrm{SO}}_{p} p^{\mathrm{SO,max}}_{n}\right)$$
$$+ \sum_{s\in S}\pi_s\left(\sum_{t\in T}\left(\sum_{g\in G}\left(C_g p_{s,g,t} + C^{\uparrow}_{g} r^{\uparrow}_{s,g,t} + C^{\downarrow}_{g} r^{\downarrow}_{s,g,t}\right)\right.\right.$$
$$+ \sum_{n\in N}\left(\bar{o}^{\mathrm{dis}}_{s,n,t} p^{\mathrm{dis}}_{s,n,t} - \bar{o}^{\mathrm{ch}}_{s,n,t} p^{\mathrm{ch}}_{s,n,t} + \bar{o}^{\mathrm{ch}\uparrow}_{s,n,t} r^{\mathrm{ch}\uparrow}_{s,n,t} + \bar{o}^{\mathrm{dis}\uparrow}_{s,n,t} r^{\mathrm{dis}\uparrow}_{s,n,t}\right.$$
$$\left.\left.\left. + \bar{o}^{\mathrm{ch}\downarrow}_{s,n,t} r^{\mathrm{ch}\downarrow}_{s,n,t} + \bar{o}^{\mathrm{dis}\downarrow}_{s,n,t} r^{\mathrm{dis}\downarrow}_{s,n,t}\right) + \sum_{w\in W}\left(C^{\mathrm{ws}}_{w} p^{\mathrm{ws}}_{s,w,t}\right)\right)\right) = \varepsilon$$
$$- \sum_{s\in S}\pi_s\sum_{t\in T}\sum_{n\in N}\left(\bar{\xi}^{\mathrm{dis}}_{s,n,t}\bar{p}^{\mathrm{dis}}_{s,n,t} + \bar{\xi}^{\mathrm{ch}}_{s,n,t}\bar{p}^{\mathrm{ch}}_{s,n,t} + \bar{\gamma}^{\mathrm{ch}\uparrow}_{s,n,t}\bar{r}^{\mathrm{ch}\uparrow}_{s,n,t}\right.$$
$$\left. + \bar{\gamma}^{\mathrm{dis}\uparrow}_{s,n,t}\bar{r}^{\mathrm{dis}\uparrow}_{s,n,t} + \bar{\gamma}^{\mathrm{dis}\downarrow}_{s,n,t}\bar{r}^{\mathrm{dis}\downarrow}_{s,n,t} + \bar{\gamma}^{\mathrm{ch}\downarrow}_{s,n,t}\bar{r}^{\mathrm{ch}\downarrow}_{s,n,t}\right) \tag{B1}$$

where $\epsilon = -\pi_s \sum_{s\in S}\sum_{g\in G}\sum_{t\in T}(\bar{\alpha}_{s,g,t}P_g + \bar{\beta}_{s,g,t}RU_g + \underline{\beta}_{s,g,t}RD_g) + \sum_{s\in S}\pi_s\sum_{t\in T}(-\sum_{w\in W}\bar{\mu}_{s,w,t}P^{\mathrm{wf}}_{s,w,t} + (\lambda^{\uparrow}_{s,t}R^{\uparrow}_{s,t} + \lambda^{\downarrow}_{s,t}R^{\downarrow}_{s,t}) + \sum_{n\in N}\lambda_{s,n,t}(D_{s,n,t} - \sum_{w\in W_n}P^{\mathrm{wf}}_{s,w,t}) - \sum_{n\in N}\sum_{m\in\Omega_n}(\underline{\sigma}_{s,nm,t}F^{\max}_{nm} + \bar{\sigma}_{s,nm,t}F^{\max}_{nm})$

$$\left.\left. - \sum_{n\in N}\left(\theta_{\max}\bar{\tau}_{s,n,t} - \theta_{\min}\underline{\tau}_{s,n,t}\right)\right)\right) \tag{B2}$$

From (A12), (A14), (A16), (A18), (A20), and (A22), we can obtain

$$\bar{\xi}^{\mathrm{dis}}_{s,n,t}\bar{p}^{\mathrm{dis}}_{s,n,t} = \bar{\xi}^{\mathrm{dis}}_{s,n,t} p^{\mathrm{dis}}_{s,n,t} \; \forall s, n, t \tag{B3}$$

$$\bar{\xi}^{\mathrm{ch}}_{s,n,t}\bar{p}^{\mathrm{ch}}_{s,n,t} = \bar{\xi}^{\mathrm{ch}}_{s,n,t} p^{\mathrm{ch}}_{s,n,t} \; \forall s, n, t \tag{B4}$$

$$\bar{\gamma}^{\mathrm{ch}\uparrow}_{s,n,t}\bar{r}^{\mathrm{ch}\uparrow}_{s,n,t} = \bar{\gamma}^{\mathrm{ch}\uparrow}_{s,n,t} r^{\mathrm{ch}\uparrow}_{s,n,t} \; \forall s, n, t \tag{B5}$$

$$\bar{\gamma}^{\mathrm{dis}\uparrow}_{s,n,t}\bar{r}^{\mathrm{dis}\uparrow}_{s,n,t} = \bar{\gamma}^{\mathrm{dis}\uparrow}_{s,n,t} r^{\mathrm{dis}\uparrow}_{s,n,t} \; \forall s, n, t \tag{B6}$$

$$\bar{\gamma}^{\mathrm{dis}\downarrow}_{s,n,t}\bar{r}^{\mathrm{dis}\downarrow}_{s,n,t} = \bar{\gamma}^{\mathrm{dis}\downarrow}_{s,n,t} r^{\mathrm{dis}\downarrow}_{s,n,t} \; \forall s, n, t \tag{B7}$$

$$\bar{\gamma}^{\mathrm{ch}\downarrow}_{s,n,t}\bar{r}^{\mathrm{ch}\downarrow}_{s,n,t} = \bar{\gamma}^{\mathrm{ch}\downarrow}_{s,n,t} r^{\mathrm{ch}\downarrow}_{s,n,t} \; \forall s, n, t \tag{B8}$$

From (A11), (A13), (A15), (A17), (A19), and (A21)

$$\underline{\xi}^{\mathrm{dis}}_{s,n,t} p^{\mathrm{dis}}_{s,n,t} = 0 \; \forall s, n, t \tag{B9}$$

$$\underline{\xi}^{\mathrm{ch}}_{s,n,t} p^{\mathrm{ch}}_{s,n,t} = 0 \; \forall s, n, t \tag{B10}$$

$$\underline{\gamma}^{\mathrm{ch}\uparrow}_{s,n,t} r^{\mathrm{ch}\uparrow}_{s,n,t} = 0 \; \forall s, n, t \tag{B11}$$

$$\underline{\gamma}^{\mathrm{dis}\uparrow}_{s,n,t} r^{\mathrm{dis}\uparrow}_{s,n,t} = 0 \; \forall s, n, t \tag{B12}$$

$$\underline{\gamma}^{\mathrm{dis}\downarrow}_{s,n,t} r^{\mathrm{dis}\downarrow}_{s,n,t} = 0 \; \forall s, n, t \tag{B13}$$

$$\underline{\gamma}^{\mathrm{ch}\downarrow}_{s,n,t} r^{\mathrm{ch}\downarrow}_{s,n,t} = 0 \; \forall s, n, t \tag{B14}$$

Substituting (B3)–(B14) in (B1) yields

$$\sum_{n\in N}\left(C^{\mathrm{SO}}_{e} e^{\mathrm{SO,max}}_{n} + C^{\mathrm{SO}}_{p} p^{\mathrm{SO,max}}_{n}\right)$$
$$+ \sum_{s\in S}\pi_s\sum_{t\in T}\left(\sum_{g\in G}\left(C_g p_{s,g,t} + C^{\uparrow}_{g} r^{\uparrow}_{s,g,t} + C^{\downarrow}_{g} r^{\downarrow}_{s,g,t}\right)\right.$$
$$+ \sum_{n\in N}\left(\left(\bar{o}^{\mathrm{dis}}_{s,n,t} + \bar{\xi}^{\mathrm{dis}}_{s,n,t} - \underline{\xi}^{\mathrm{dis}}_{s,n,t}\right)p^{\mathrm{dis}}_{s,n,t} + \left(-\bar{o}^{\mathrm{ch}}_{s,n,t} + \bar{\xi}^{\mathrm{ch}}_{s,n,t} - \underline{\xi}^{\mathrm{ch}}_{s,n,t}\right)p^{\mathrm{ch}}_{s,n,t}\right.$$
$$+ \left(\bar{o}^{\mathrm{ch}\uparrow}_{s,n,t} + \bar{\gamma}^{\mathrm{ch}\uparrow}_{s,n,t} - \underline{\gamma}^{\mathrm{ch}\uparrow}_{s,n,t}\right)r^{\mathrm{ch,UP}}_{s,n,t} + \left(\bar{o}^{\mathrm{dis}\uparrow}_{s,n,t} + \bar{\gamma}^{\mathrm{dis}\uparrow}_{s,n,t} - \underline{\gamma}^{\mathrm{dis}\uparrow}_{s,n,t}\right)r^{\mathrm{dis}\uparrow}_{s,n,t}$$
$$\left. + \left(\bar{o}^{\mathrm{ch}\downarrow}_{s,n,t} + \bar{\gamma}^{\mathrm{ch}\downarrow}_{s,n,t} - \underline{\gamma}^{\mathrm{ch}\downarrow}_{s,n,t}\right)r^{\mathrm{ch}\downarrow}_{s,n,t} + \left(\bar{o}^{\mathrm{dis}\downarrow}_{s,n,t} + \bar{\gamma}^{\mathrm{dis}\downarrow}_{s,n,t} - \underline{\gamma}^{\mathrm{dis}\downarrow}_{s,n,t}\right)r^{\mathrm{dis}\downarrow}_{s,n,t}\right)$$
$$\left. + \sum_{w\in W}\left(C^{\mathrm{ws}}_{w} p^{\mathrm{ws}}_{s,w,t}\right)\right) = \epsilon \tag{B15}$$

From (A51), (A52), (A53), (A54), (A55), and (A56)

$$\lambda_{s,n,t} = \bar{o}^{\text{ch}}_{s,n,t} - \left(\bar{\xi}^{\text{ch}}_{s,n,t} - \underline{\xi}^{\text{ch}}_{s,n,t}\right) \ \forall s, n, t \tag{B16}$$

$$\lambda_{s,n,t} = \bar{o}^{\text{dis}}_{s,n,t} + \left(\bar{\xi}^{\text{dis}}_{s,n,t} - \underline{\xi}^{\text{dis}}_{s,n,t}\right) \ \forall s, n, t \tag{B17}$$

$$\lambda^{\uparrow}_{s,t} = \bar{o}^{\text{ch}\uparrow}_{s,n,t} + \left(\bar{\gamma}^{\text{ch}\uparrow}_{s,n,t} - \underline{\gamma}^{\text{ch}\uparrow}_{s,n,t}\right) \ \forall s, n, t \tag{B18}$$

$$\lambda^{\uparrow}_{s,t} = \bar{o}^{\text{dis}\uparrow}_{s,n,t} + \left(\bar{\gamma}^{\text{dis}\uparrow}_{s,n,t} - \underline{\gamma}^{\text{dis}\uparrow}_{s,n,t}\right) \ \forall s, n, t \tag{B19}$$

$$\lambda^{\downarrow}_{s,t} = \bar{o}^{\text{ch}\downarrow}_{s,n,t} + \left(\bar{\gamma}^{\text{ch}\downarrow}_{s,n,t} + \underline{\gamma}^{\text{ch}\downarrow}_{s,n,t}\right) \ \forall s, n, t \tag{B20}$$

$$\lambda^{\downarrow}_{s,t} = \bar{o}^{\text{dis}\downarrow}_{s,n,t} + \left(\bar{\gamma}^{\text{dis}\downarrow}_{s,n,t} + \underline{\gamma}^{\text{dis}\downarrow}_{s,n,t}\right) \ \forall s, n, t \tag{B21}$$

Substitute (B17)–(B21) into (B15), the bilinear terms in (1) can be rewritten as

$$\begin{aligned}
&\sum_{s\in S}\sum_{t\in T}\sum_{n\in N}\pi_s\left(\lambda_{s,n,t}\left(p^{\text{dis}}_{s,n,t} - p^{\text{ch}}_{s,n,t}\right) + \lambda^{\uparrow}_{s,t}\left(r^{\text{ch}\uparrow}_{s,n,t} + r^{\text{dis}\uparrow}_{s,n,t}\right)\right. \\
&\left. + \lambda^{\downarrow}_{s,t}\left(r^{\text{ch}\downarrow}_{s,n,t} + r^{\text{dis}\downarrow}_{s,n,t}\right)\right) = -\sum_{n\in N}\left(C^{\text{SO}}_{e}e^{\text{SO,max}}_{n} + C^{\text{SO}}_{p}p^{\text{SO,max}}_{n}\right) \\
&- \sum_{s\in S}\pi_s\sum_{t\in T}\left(\sum_{g\in G}\left(C_g p_{s,g,t} + C^{\uparrow}_{g}r^{\uparrow}_{s,g,t} + C^{\downarrow}_{g}r^{\downarrow}_{s,g,t}\right)\right. \\
&\left. + \sum_{w\in W}C^{\text{ws}}_{w}p^{\text{ws}}_{s,w,t}\right) + \epsilon
\end{aligned} \tag{B22}$$

Thus, the objective function (1) can be linearized as follows:

$$\begin{aligned}
&\max_{\Xi_{\text{UL}}} -\sum_{n\in N}\left(C_e e^{\max}_{n} + C_p p^{\max}_{n} + C^{\text{SO}}_{e}e^{\text{SO,max}}_{n} + C^{\text{SO}}_{p}p^{\text{SO,max}}_{n}\right) \\
&- \sum_{s\in S}\pi_s\sum_{t\in T}\left(\sum_{g\in G}\left(C_g p_{s,g,t} + C^{\uparrow}_{g}r^{\uparrow}_{s,g,t} + C^{\downarrow}_{g}r^{\downarrow}_{s,g,t}\right) + \sum_{w\in W}C^{\text{ws}}_{w}p^{\text{ws}}_{s,w,t}\right) + \epsilon
\end{aligned} \tag{B23}$$