# Strategic Investment in Transmission and Energy Storage in Electricity Markets

Kunpeng Tian, Weiqing Sun, and Dong Han

***Abstract*—The variability of renewable energy and transmission congestion provide opportunities for arbitrage by merchants in deregulated electricity markets. Merchants strategically invest to maximize their profits. This paper proposes a joint investment framework for renewable energy, transmission lines, and energy storage using the Stackelberg game model. At the upper level, merchants implement investment and operation strategies for deregulated transmission and energy storage to maximize profits. At the middle level, central planners seek to maximize social welfare through investments in centralized renewable energy and energy storage. At the lower level, independent system operators jointly optimize the energy and reserve markets to minimize the total operating costs. Merchants are remunerated through financial rights, which are a settlement method based on locational marginal price. The trilevel optimization problem is reformulated as a tractable single-level one using Karush-Kuhn-Tucker (KKT) conditions and strong duality theory. The interaction between merchants and central planners is studied with an example based on the IEEE 30-bus test system. The assignment of weight coefficients to the corresponding stochastic scenarios can help merchants avoid investment risk, and their effectiveness is verified with the IEEE 118-bus test system.**

***Index Terms*—Strategic investment, Stackelberg game model, financial right, locational marginal price, merchant, central planner.**

## NOMENCLATURE

### A. Indices and Sets

| | |
|---|---|
| $i$, $j$ | Indices of nodes |
| $l$, $H$ | Index and set of discrete capacity level for candidate lines |
| $LC\|+i$, $LC\|-i$ | Sets of lines receiving and sending at node $i$ |
| $N$, $LC$, $LE$ | Sets of nodes, candidate lines, and existing lines |
| $N_{es}^s$, $N_{es}^c$ | Sets of deregulated and regulated energy storages (ESs) |
| $N_g$, $N_{res}$, $N_d$ | Sets of thermal generator (TG), renewable energy (RE), and load demand |
| $q$, $Q$ | Index and set of scenarios |
| $t$, $T$ | Index and set of operating time intervals |

### B. Parameters

| | |
|---|---|
| $\eta_c$, $\eta_d$ | Charging and discharging efficiencies of ESs |
| $\theta_{i,\min}$, $\theta_{i,\max}$ | The minimum and maximum phase angles |
| $\rho$ | Rate of return on merchant investments |
| $\rho_{line}^{fs}$, $\rho_{es}^{fs}$ | Policy subsidies for candidate lines and ESs |
| $\tau_{es}^s$, $\tau_{es}^c$ | Energy-to-power ratios for deregulated and regulated ESs |
| $\varpi_q$ | Probability of scenario $q$ |
| $b_{l,ij}^s$, $b_{ij}^e$ | Susceptances of candidate and existing lines |
| $c_{ij}^l$ | Capital cost of line capacity block $l$ |
| $c_{es}^o$, $c_{es}^r$ | Degradation and regulation costs of ESs |
| $c_{es}^s$, $c_{es}^c$ | Capital costs of deregulated and regulated ESs |
| $c_{res}$, $c_{res}^{cut}$ | Capital cost and penalty cost of RE |
| $C_{\max}^{line}$, $C_{\max}^{s,es}$ | Capital budgets for candidate lines and ESs |
| $M$ | A sufficiently large constant |
| $N_{i,\max}^{res}$, $N_{i,\max}^{c,es}$ | The maximum capacities for RE and regulated ESs |
| $p_{\max}^{l,ij}$, $p_{\max}^{e,ij}$ | Flow limits on candidate and existing lines |
| $p_{d,i}^t$ | Nominal value of load demand |
| $\hat{P}_{res}^t$, $R_{rps}$ | Nominal value and target of RE production |
| $P_{i,\min}^g$, $P_{i,\max}^g$ | The minimum and maximum power of TG |
| $ru_{i,\max}^g$, $rd_{i,\max}^g$ | Ramp-down and ramp-up limits of TG |
| $rc_{i,\max}^{g,u}$, $rc_{i,\max}^{g,d}$ | The maximum regulation up and regulation down capacities of TG |
| $R_{rc}^u$, $R_{rc}^d$ | Upward and downward regulatory demands |

### C. Variables

| | |
|---|---|
| $\theta_i^t$, $\theta_j^t$ | Phase angles of each node |
| $\lambda_i^t$ | Locational marginal price (LMP) |

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| | |
|---|---|
| $\lambda_{rc,u}^{t}$, $\lambda_{rc,d}^{t}$ | Upward and downward regulation prices |
| $C_{line}$, $x_{ij}^{l}$ | Investment cost and status of candidate lines |
| $C_{es}^{s}$, $C_{es}^{s,o}$ | Capital and operation costs of deregulated ESs |
| $C_{es}^{c}$, $C_{es}^{c,o}$ | Capital and operation costs of regulated ESs |
| $C_{res}$, $C_{res}^{cut}$ | Investment and penalty costs of RE |
| $C_{g}^{o}$, $p_{g,i}^{t}$ | Operation cost and production power of TG |
| $e_{es,i}^{s,t}$, $e_{es,i}^{c,t}$ | Storage levels of deregulated and regulated ESs |
| $n_{es,i}^{s}$, $n_{es,i}^{c}$ | Capacities of deregulated and regulated ESs |
| $n_{res,i}$, $p_{res,i}^{t}$ | Capacity and production power of RE |
| $p_{inj,i}^{s,t}$, $p_{out,i}^{s,t}$ | Receiving and sending power at node $i$ |
| $p_{l,ij}^{s,t}$, $p_{e,ij}^{t}$ | Flow power of candidate and existing lines |
| $p_{es,d,i}^{s,t}$, $p_{es,c,i}^{s,t}$ | Discharging and charging of deregulated ESs |
| $p_{es,d,i}^{c,t}$, $p_{es,c,i}^{c,t}$ | Discharging and charging of regulated ESs |
| $r_{es,u,i}^{s,t}$, $r_{es,d,i}^{s,t}$ | Upward and downward regulation capacities by provided deregulated ESs |
| $r_{es,u,i}^{c,t}$, $r_{es,d,i}^{c,t}$ | Upward and downward regulation capacities by provided regulated ESs |
| $r_{g,d,i}^{t}$, $r_{g,u,i}^{t}$ | Upward and downward regulation capacities by provided TG |
| $R_{es}^{em}$, $R_{es}^{fs}$ | Market and policy revenues of deregulated ESs |
| $R_{line}^{em}$, $R_{line}^{fs}$ | Market and policy revenues of deregulated lines |

### *D. Coefficients and Other Variables*

| | |
|---|---|
| $A$, $B$, $C$ | Coefficients of objective function |
| $D$, $E_q$, $F_q$ | Coefficients of primal constraint |
| $G_q$, $H_q$, $I_q$ | Coefficients of Karush-Kuhn-Tucker (KKT) constraint |
| $X$, $Y_q$, $Z_q$ | Investment decision, operational variables and dual variables in scenario $q$ |

## I. Introduction

LARGE-SCALE renewable energy is integrated into the power system, which is a technically feasible candidate for realizing sustainable development of humans [1]. With the increase of renewable energy in the power system, regulatory departments have become greatly concerned with transmission congestion. The joint planning of a power system can relieve transmission congestion and enhance the production of renewable energy [2]. Transmission lines and energy storage can transfer energy spatially and temporally [3]. The capacity of transmission lines is discrete, and transmission planning is performed to satisfy load demand and large-scale renewable energy integration [4]. The energy storage capacity can be relaxed to be continuous (if the unit capacity is small). The co-planning of transmission lines and energy storage becomes attractive to tackle the uncertainty inherent in renewable energy [5]. The scalable planning of renewable energy, transmission lines, and energy storage has drawn extensive attention.

In the literature, different modeling techniques are used to study the joint investment and operation of the power system from different aspects. From the perspective of market mechanisms, previous studies on co-planning can be divided into centralized and deregulated mechanisms [6]. The right to dispatch control of a power asset (e.g., a generator, energy storage, or a transmission line) belongs to the central planner or merchant in two market mechanisms [7]. Joint planning utilizes two market mechanisms, which are summarized as follows.

In the centralized market mechanism, central planners seek to maximize the social welfare and reduce the energy consumption cost for end-users [8]. Several articles have highlighted the importance of joint planning to minimize the total cost from the perspective of central planners [9]. For joint planning generation and transmission, a trilevel robust optimization model has been proposed to minimize the total cost of a system [10]. An adaptive robust optimization method can reduce the risk of load shedding and improve the reliability. For co-planning generation and energy storage, a novel multi-objective planning approach for coordinated offshore wind farms and battery storage has been proposed [11]. For co-planning transmission and energy storage, a robust optimization model for joint planning has been established to minimize the total cost [12]. Overall, a stochastic programming model with expansion alternatives including renewable energy, transmission, energy storage, and flexibly combined cycled gas turbines has been proposed [13]. In general, central planners consider the security operation constraints to minimize the total investment cost and operation cost within the planning horizon.

In the deregulated market mechanism, merchants seek to maximize their profits through the strategic investment and operation of assets by participating in competitive electricity markets [14]. For strategic investment in generation and transmission, a joint investment model of wind farms and transmission has been proposed, in which merchant investors invest in transmission lines to obtain congestion rents in deregulated electricity markets [15]. A structure consisting of generation companies as merchant investors that participate in transmission projects has been proposed, in which long-term contracts are used to recover investment costs [16]. On the contrary, generation planning is decided by merchants trying to maximize their profits, while transmission-line investments aim to minimize the total cost [17]. Moreover, merchants prefer to invest in energy storage to carry out arbitrage in the energy and ancillary service market. For energy storage, a coordinated operation framework between price makers and energy storage has been proposed, whose objective is to maximize the total profit of energy storage [18]. A stochastic bilevel model that determines the optimal size of energy storage from a merchant investor's perspective is presented in [19]. Moreover, we note that a joint planning model of transmission and energy storage has been proposed. A joint investment model is proposed to coordinate the regulation of transmission and merchant energy storage, in which regulators consider anticipating merchant decisions [20]. Likewise, the joint investment of transmission and merchant energy storage has been proposed, but the merchant predicts the regulatory decisions [21]. A deregulation mechanism allows a merchant to participate in the expansion planning of power system, which provides an environment for the merchant to carry out arbitrage.

Most of the existing literature focuses on the minimization of the total costs of candidate assets in a centralized market. To the best of our knowledge, there are few studies on joint investment in candidate assets to maximize profits in deregulated markets. The vast majority of power systems today are transitioning from centralized to deregulated [22]. The preferential use of renewable energy with zero marginal cost leads to transmission congestion or variation of the locational marginal price (LMP). Therefore, joint investment in renewable energy, transmission, and energy storage is an effective measure for the construction of power systems [23]. A higher degree of risk is involved in the investment in transmission and energy storage, and a long time is required to return the capital cost [24]. This further increases the possibility of congestion in renewable energy systems.

With the deregulation of the electricity market, it is necessary to attract investment by merchants to participate in the expansion projects predetermined by a central planner. The investment in renewable energy to promote the transformation of the energy system includes the responsibility and obligation of central planners in renewable portfolio standards. To reduce the capital burden of central planners, a merchant is allowed to invest in transmission lines to improve the accommodation of renewable energy. Energy storage can smoothen the output of renewable energy and delay upgrades of transmission lines, which are favored by central planners and merchants [25]. The dispatch of merchant assets is deregulated, which means that merchants control the operation of transmission lines and energy storage to maximize profits [26]. Further, the investment and operational decisions by the merchant must account for the consequences of potential investments in the power system by central planners.

In this paper, a novel coordinated investment framework based on the Stackelberg game is proposed for merchants and central planners. The main work and contributions of this paper are summarized as follows.

1) In contrast to existing studies, a merchant invests in deregulated transmission lines (DTLs) and deregulated energy storage (DES) to maximize their net revenue, while central planners invest in centralized renewable energy (CRE) and centralized energy storage (CES) to minimize their total costs. This framework validates and illustrates the interaction between merchants and central planners.

2) The lifetime profit of the merchant's candidate assets from the liberalized energy and ancillary service market is expressed as an explicit function of the LMPs and their operation strategies. The expected lifetime profit collected by the DTLs and DES is related to their investment costs to enforce a predetermined rate of return on investments.

3) The impact of financial incentives, regulatory requirements, and the expected rate of return on the investment strategies of the merchant and central planners are studied. Numerical simulation illustrates the optimal trade-off between the investment by the merchant and centralized decisions under different operating conditions and the investment scenarios.

4) This investment model should be useful to merchants and central planners in techno-economic analyses of investments in the power system and in understanding the interactions between renewable energy, transmission, and energy storage decisions.

The remainder of this paper is organized as follows. The coordinated investment framework and model assumptions are described in Section II. The Stackelberg game model involving the merchants and central planners is presented in Section III. The solution method is discussed in Section IV. Case studies based on the modified IEEE 30-bus and IEEE 118-bus test systems are developed in Section V, where the results of the model applied to a case study are reported and discussed. Finally, conclusions are presented in Section VI.

## II. Coordinated Investment Framework and Model Assumption

This paper proposes a Stackelberg game model to explore the competing investments between a merchant and a central planner in a liberalized market environment. The merchant is the leader, and the central planner is the follower, which agrees with previous research in this subject area. In the presented competition investment structure, merchants are allowed to participate in specific transmission expansion projects, which is an attractive measure to ease the budget constraints of a transmission system operator (TSO). DTLs can only benefit from the energy market with transmission congestion, and DES has difficulty coping with the load demand and large-scale renewable energy integration. Therefore, a merchant can maximize the profit with joint investment in DTLs and DES in deregulated energy and ancillary service markets. The coordinated investment framework is formulated as a trilevel optimization problem, as shown in Fig. 1.

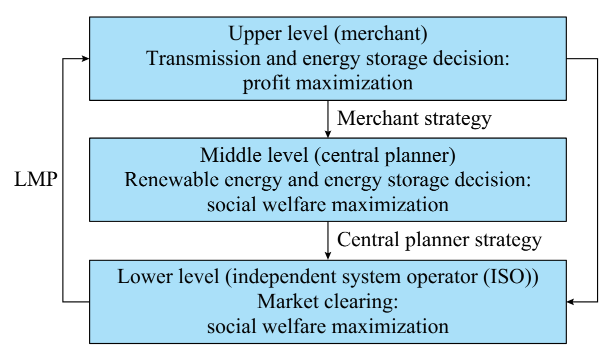


Fig. 1. Competition between merchants and central planners.

Figure 1 illustrates the game structure and shows the interfaces between the different levels of the optimization model. The upper-level problem implements the merchant's perspective, i.e., maximize the expected profit from the deregulated energy and ancillary service markets. The capital costs of the DTLs and DES are recovered through a financial right, which is settled using the LMPs produced by the lower-level problem. The merchant decides the investment and operation decisions of the DTLs and DES at the same time and in one stage in an open-loop manner. At the middle level, central planners seek to maximize the social welfare by investing in CRE and CES. The expansion decisions made by the central planners are fixed in the lower-level problem. At the lower level, the ISO carries out day-ahead market clearing. The economic dispatch problem with transmission constraints is solved to derive the LMPs. These LMPs can generate useful price signals that assist the merchant in identifying the suitable siting and sizing for building DTLs and DES. The merchant strategy from the upper level aims to increase the fluctuation of LMPs and maximize profit, which will affect social welfare and thus affect the central planners' strategy at the middle level. In turn, the central planners' decisions tend to increase renewable energy generation and social welfare, which influence the LMPs and thus may affect the merchant's strategies. The trilevel optimization framework can clearly describe the three processes of merchants, central planners, and market clearing.

As discussed in previous studies, the necessary model assumptions are as follows. The game model consists of one leader and one follower. The equilibrium problem with equilibrium constraints (EPEC) framework can be considered in the game model with multiple merchants as leaders. A leader (merchant) anticipates a follower's (central planner) decisions before making his own investment decisions. The life span cost of candidate assets is amortized to each day in proportion. Note that the theory of marginal pricing relies on the assumption of convexity of the optimization problem. The lower-level problem assumes that the day-ahead market is a fully competitive environment and has hourly time intervals, and the unit commitment is ignored during market clearing. The standard DC power flow model is used to represent the transmission network. The capacity of renewable energy and energy storage is relaxed to a continuous variable instead of an integer one.

## III. Stackelberg Game Model

In this section, the models for the merchant and central planner are introduced. A trilevel optimization framework considering the game between the merchant and the central planner is customized. Without loss of generality, a power system with an unidentified number of buses and linked through undetermined transmission lines is considered.

### A. Upper-level Problem

In the upper-level problem, the merchant makes decisions on the DTLs and DES to maximize net profits. The DTLs are paid for by the ISO according to the hourly values of their financial rights. Financial transmission rights (FTRs) provide a merchant with financial support to pay the congestion price that they are charged in the day-ahead energy market for their transaction [27]. The investment in transmission by the merchant is supposed to be recovered by an investment tax credit (ITC) and daily profit. The ITC takes a certain proportion of the capital cost as a financial subsidy, while the daily profit is the congestion rent collected through FTRs. The total profit of the DTLs is determined by the market price, transmission capacity, ITC policy, and investment costs. The problem for the strategic investment of DTLs is formulated as:

$$\max\left(R_{line}^{em}+R_{line}^{fs}-C_{line}\right) \tag{1}$$

$$R_{line}^{em}=\sum_{t\in T}\sum_{i\in N}\lambda_i^t\left(p_{inj,i}^{s,t}-p_{out,i}^{s,t}\right) \tag{2}$$

$$R_{line}^{fs}=\rho_{line}^{fs}C_{line} \tag{3}$$

$$C_{line}=\sum_{(i,j)\in LC}\sum_{l\in H}c_{ij}^l x_{ij}^l \tag{4}$$

$$C_{line}\le C_{\max}^{line} \tag{5}$$

$$p_{inj,i}^{s,t}=\sum_{j\in LC|+i}\sum_{l\in H}p_{l,ij}^{s,t} \tag{6}$$

$$p_{out,i}^{s,t}=\sum_{j\in LC|-i}\sum_{l\in H}p_{l,ij}^{s,t} \tag{7}$$

$$-\left(1-x_{ij}^l\right)M\le p_{l,ij}^{s,t}-b_{l,ij}^s\left(\theta_i^t-\theta_j^t\right)\le\left(1-x_{ij}^l\right)M \quad \forall (i,j)\in LC, l\in H, t\in T \tag{8}$$

$$-x_{ij}^l p_{\max}^{l,ij}\le p_{l,ij}^{s,t}\le x_{ij}^l p_{\max}^{l,ij} \quad \forall (i,j)\in LC, l\in H, t\in T \tag{9}$$

$$x_{ij}^l\in\{0,1\} \quad \forall (i,j)\in LC, l\in H \tag{10}$$

The objective function in (1) maximizes the difference between the profit of the DTLs over the representative days and investment cost. Equation (2) expresses the FTR revenue from the deregulated electricity market. The FTRs are defined as an obligation under which the owner is remunerated if the LMP difference is positive and pays if the LMP difference is negative. After regrouping the term, the transmission revenue is expressed as the sum of the difference between the input and output power flows at the end of the line, both of which are calculated according to the LMPs of their respective buses. Equation (3) is the financial subsidy of investment in DTLs under the ITC policy. Equation (4) expresses the daily prorated cost, which is calculated by the net present value approach. Note that multiple discrete standard capacity blocks with the corresponding susceptance are considered for the expansion of transmission. Equation (5) constrains the investment budget. Equations (6) and (7) express the block structure of the receiving power and sending power of each node. Formulas (8) and (9) are the power flow constraints for each candidate DTL formulated by disjunctive inequalities. Formula (10) defines the integer decision variables for the DTLs.

Energy storage is crucial for renewable energy integration, which can significantly enhance the efficiency and reliability of the power system. Broadly speaking, the short-term value of energy storage lies in the ability to carry out arbitrage over time and space. That is, energy storage can absorb excess energy within a short time and reshape the relationship between supply and demand over a long time. The concept of financial storage rights (FSRs) is proposed to explain the financial property rights of energy storage capacity [28], which is similar to FTRs. Moreover, the flexibility of energy storage can provide reserve auxiliary service for the ISO, and the dual variable of the reserve capacity constraint is used for the reserve capacity price. Therefore, energy storage can benefit from the energy and reserve markets. The strategic investment problem of DES is formulated as:

$$\max\left(R_{es}^{em}+R_{es}^{fs}-C_{es}^{s}-C_{es}^{s,o}\right) \tag{11}$$

$$R_{es}^{em}=\sum_{t\in T}\sum_{i\in N_{es}^{s}}\left(\lambda_i^t p_{es,d,i}^{s,t}-\lambda_i^t p_{es,c,i}^{s,t}+\lambda_{ru}^t r_{es,u,i}^{s,t}+\lambda_{rd}^t r_{es,d,i}^{s,t}\right) \tag{12}$$

$$R_{es}^{fs}=\rho_{es}^{fs}C_{es}^{s} \tag{13}$$

$$C_{es}^{s}=\sum_{i\in N_{es}^{s}}c_{es}^{s}n_{es,i}^{s} \tag{14}$$

$$C_{es}^{s}\le C_{\max}^{s,es} \tag{15}$$

$$C_{es}^{s,o}=\sum_{t\in T}\sum_{i\in N_{es}^{s}}\left(c_{es}^{o}p_{es,c,i}^{s,t}\eta_c+c_{es}^{o}p_{es,d,i}^{s,t}/\eta_d\right)+\sum_{i\in N_{es}^{s}}\left(c_{es}^{r}r_{es,u,i}^{s,t}+c_{es}^{r}r_{es,d,i}^{s,t}\right) \tag{16}$$

$$0\le p_{es,d,i}^{s,t}\le n_{es,i}^{s}\quad \forall i\in N_{es}^{s},t\in T \tag{17}$$

$$0\le p_{es,c,i}^{s,t}\le n_{es,i}^{s}\quad \forall i\in N_{es}^{s},t\in T \tag{18}$$

$$0\le r_{es,u,i}^{s,t}\le n_{es,i}^{s}\quad \forall i\in N_{es}^{s},t\in T \tag{19}$$

$$0\le r_{es,d,i}^{s,t}\le n_{es,i}^{s}\quad \forall i\in N_{es}^{s},t\in T \tag{20}$$

$$0\le p_{es,d,i}^{s,t}/\eta_d+r_{es,u,i}^{s,t}\le n_{es,i}^{s}\quad \forall i\in N_{es}^{s},t\in T \tag{21}$$

$$0\le p_{es,c,i}^{s,t}\eta_c+r_{es,d,i}^{s,t}\le n_{es,i}^{s}\quad \forall i\in N_{es}^{s},t\in T \tag{22}$$

$$r_{es,u,i}^{s,t}\le e_{es,i}^{s,t}\le n_{es,i}^{s}\tau_{es}^{s}-r_{es,d,i}^{s,t}\quad \forall i\in N_{es}^{s},t\in T \tag{23}$$

$$e_{es,i}^{s,t}=e_{es,i}^{s,t-1}+p_{es,c,i}^{s,t}\eta_c-p_{es,d,i}^{s,t}/\eta_d\quad \forall i\in N_{es}^{s},t\in T \tag{24}$$

$$\sum_{t\in T}\left(p_{es,c,i}^{s,t}\eta_c-p_{es,d,i}^{s,t}/\eta_d\right)=0\quad \forall i\in N_{es}^{s},t\in T \tag{25}$$

The objective function in (11) maximizes the difference between the total profit of DES and the total cost. Equation (12) is the DES revenue collected from the energy market and ancillary service market. Equation (13) expresses the financial subsidy for DES under the ITC policy. Equation (14) is the capital cost. Note that we assume fixed energy-to-power ratios; then, the investment cost of DES is a function of the power. Equation (15) represents the investment budget. Equation (16) limits the degradation cost and reserve cost. Equations (17) and (18) express the maximum discharging and charging powers of the DES. Formulas (19) and (20) are the upward and downward regulation capacities of the DES. Formulas (21) and (22) are the coupling constraints between the charging and discharging powers and the regulation capacity. In (23), the stored energy is bound by the state of charge (SOC). Equation (24) expresses the dynamic process of storing energy in the bank of energy storage. Equation (25) connects the initial and final SOC levels of energy in a representative day.

A merchant can invest in DTLs and DES, and the upper-level problem is expressed by (26) and (27), subject to (2)-(10) and (12)-(25):

$$\max\left(R_{line}^{em}+R_{line}^{fs}+R_{es}^{em}+R_{es}^{fs}-C_{line}-C_{es}^{s}-C_{es}^{s,o}\right) \tag{26}$$

$$R_{line}^{em}+R_{line}^{fs}+R_{es}^{em}+R_{es}^{fs}\ge\rho\left(C_{line}+C_{es}^{s}+C_{es}^{s,o}\right) \tag{27}$$

Formula (26) maximizes the net profits of DTLs and DES. Formula (27) relates the total profit and capital cost by setting a predetermined parameter to implement the expected rate of return. An LMP can reflect the degree of energy scarcity at each node in the power system. A high LMP indicates that a node has no access to cheap generation or is excessive. Conversely, a low LMP implies that the node accesses too much cheap generation or has no access to sufficient demand. Hence, a new transmission line is built between two buses with low and high LMPs to distribute the excess cheap power to the excessive load demand. Consequently, the constructed DTL should be paid for by the FTRs, which is the congestion profit caused by the potential price difference. Further, the merchant's storage provides market participants with the ability to hedge hourly LMP fluctuations at specific nodes in the power grid. As in (12), the profits of FSRs related to the DES are calculated according to the sequence of hourly LMPs at a specific node and the corresponding sequence of hourly injection/withdrawal flow. The investment in DTLs aiming to maximize financial rights is established. DES investments seek to maximize profits from the energy and ancillary service market.

## B. Middle-level Problem

In the middle-level problem, central planners make investment decisions related to CRE and CES to minimize the total cost of the power system. Investment in CRE is an attractive measure to reduce carbon dioxide emissions and achieve carbon neutrality. However, the uncertainty of renewable energy will cause extra costs and potentially high risks during the planning and operation of the power system. Energy storage provides an opportunity for large-scale renewable energy integration into the power system. From the perspective of central planners, a joint investment model for CRE and CES is expressed as:

$$\min\left(C_{res}+C_g^o+C_{es}^c+C_{es}^{c,o}+C_{res}^{cut}\right) \tag{28}$$

$$C_{res}=\sum_{i\in N_{res}}c_{res}n_{res,i} \tag{29}$$

$$C_g^o=\sum_{t\in T}\sum_{i\in N_g}\left(c_g^o p_{g,i}^t+c_g^r r_{g,u,i}^t+c_g^r r_{g,d,i}^t\right) \tag{30}$$

$$C_{es}^{c}=\sum_{i\in N_{es}^{c}}c_{es}^{c}n_{es,i}^{c} \tag{31}$$

$$C_{es}^{c,o}=\sum_{t\in T}\sum_{i\in N_{es}^{c}}\left(c_{es}^{o}p_{es,c,i}^{c,t}\eta_c+c_{es}^{o}p_{es,d,i}^{c,t}/\eta_d\right)+\sum_{t\in T}\sum_{i\in N_{es}^{c}}\left(c_{es}^{r}r_{es,u,i}^{c,t}+c_{es}^{r}r_{es,d,i}^{c,t}\right) \tag{32}$$

$$C_{res}^{cut}=\sum_{t\in T}\sum_{i\in N_{res}}c_{res}^{cut}\left(n_{res,i}\hat{P}_{res}^{t}-p_{res,i}^{t}\right) \tag{33}$$

The objective function in (28) minimizes the total system cost. Equation (29) expresses the investment cost of CRE. Equation (30) expresses the operation cost of the thermal generators (TGs), which is composed of production and regulation costs. Equation (31) is the investment cost of energy storage. Equation (32) is the degradation and regulation costs of CES. Equation (33) is the penalty cost caused by renewable energy spillage. The central planner aims to maximize social welfare, which means that they will invest in CRE and CES only if the resulting improvement in social welfare is higher than the investment cost. Note that the operation of CRE and CES is determined by the ISO.

### C. Lower-level Problem

In the lower-level problem, the energy and reserve markets are jointly cleared, and the LMPs and marginal regulation prices are derived. It is usual for ISOs to employ optimizations to minimize the total operating costs according to a predetermined merchant strategy and central planner strategy. The economic dispatch problem is expressed as:

$$\min\left(C_g^o + C_{es}^{c,o} + C_{res}^{cut}\right) \tag{34}$$

$$p_{g,i}^t + p_{res,i}^t - p_{e,ij}^t + p_{es,d,i}^{c,t} - p_{es,c,i}^{c,t} + p_{inj,i}^{s,t} - p_{out,i}^{s,t} + p_{es,d,i}^{s,t} - p_{es,c,i}^{s,t} = p_{d,i}^t \quad :\left(\lambda_i^t\right) \quad \forall i \in N, t \in T \tag{35}$$

$$P_{i,\min}^g + r_{g,d,i}^t \le p_{g,i}^t \le P_{i,\max}^g - r_{g,u,i}^t \quad :\left(\underline{\alpha}_{g,i}^t, \bar{\alpha}_{g,i}^t\right) \quad \forall i \in N_g, t \in T \tag{36}$$

$$-rd_{i,\max}^g \le p_{g,i}^t - p_{g,i}^{t-1} \le ru_{i,\max}^g \quad :\left(\underline{\beta}_{g,i}^t, \bar{\beta}_{g,i}^t\right) \quad \forall i \in N_g, t \in T \tag{37}$$

$$0 \le r_{g,u,i}^t \le rc_{i,\max}^{g,u} \quad :\left(\underline{\delta}_{g,i}^t, \bar{\delta}_{g,i}^t\right) \quad \forall i \in N_g, t \in T \tag{38}$$

$$0 \le r_{g,d,i}^t \le rc_{i,\max}^{g,d} \quad :\left(\underline{\varepsilon}_{g,i}^t, \bar{\varepsilon}_{g,i}^t\right) \quad \forall i \in N_g, t \in T \tag{39}$$

$$0 \le p_{res,i}^t \le n_{res,i} \hat{P}_{res}^t \quad :\left(\underline{\mu}_{res,i}^t, \bar{\mu}_{res,i}^t\right) \quad \forall i \in N_{res}, t \in T \tag{40}$$

$$0 \le n_{res,i} \le N_{i,\max}^{res} \quad :\left(\underline{\chi}_i, \bar{\chi}_i\right) \quad \forall i \in N_{res} \tag{41}$$

$$\sum_{t \in T} \sum_{i \in N_{res}} p_{res,i}^t \ge R_{rps} \sum_{t \in T} \sum_{i \in N_d} p_{d,i}^t \quad :\left(\phi_{rps}^t\right) \tag{42}$$

$$\sum_{i \in N_g} r_{g,u,i}^t + \sum_{i \in N_{es}^c} r_{es,u,i}^{c,t} + \sum_{i \in N_{es}^s} r_{es,u,i}^{s,t} \ge R_{rc}^u \sum_{i \in N_d} p_{d,i}^t \quad :\left(\lambda_{rc,u}^t\right) \quad \forall t \in T \tag{43}$$

$$\sum_{i \in N_g} r_{g,d,i}^t + \sum_{i \in N_{es}^c} r_{es,d,i}^{c,t} + \sum_{i \in N_{es}^s} r_{es,d,i}^{s,t} \ge R_{rc}^d \sum_{i \in N_d} p_{d,i}^t \quad :\left(\lambda_{rc,d}^t\right) \quad \forall t \in T \tag{44}$$

$$p_{e,ij}^t - b_{ij}^e\left(\theta_i^t - \theta_j^t\right) = 0 \quad :\left(v_{e,ij}^t\right) \quad \forall (i,j) \in LE, t \in T \tag{45}$$

$$-p_{\max}^{e,ij} \le p_{e,ij}^t \le p_{\max}^{e,ij} \quad :\left(\bar{\pi}_{e,ij}^t, \underline{\pi}_{e,ij}^t\right) \quad \forall (i,j) \in LE, t \in T \tag{46}$$

$$\theta_{i,\min} \le \theta_i^t \le \theta_{i,\max} \quad :\left(\bar{\varsigma}_i^t, \underline{\varsigma}_i^t\right) \quad \forall i \in N, t \in T \tag{47}$$

$$0 \le p_{es,d,i}^{c,t} \le n_{es,i}^c \quad :\left(\underline{\sigma}_{es,d,i}^t, \bar{\sigma}_{es,d,i}^t\right) \quad \forall i \in N_{es}^c, t \in T \tag{48}$$

$$0 \le p_{es,c,i}^{c,t} \le n_{es,i}^c \quad :\left(\underline{\sigma}_{es,c,i}^t, \bar{\sigma}_{es,c,i}^t\right) \quad \forall i \in N_{es}^c, t \in T \tag{49}$$

$$0 \le r_{es,u,i}^{c,t} \le n_{es,i}^c \quad :\left(\underline{\omega}_{es,ru,i}^t, \bar{\omega}_{es,ru,i}^t\right) \quad \forall i \in N_{es}^c, t \in T \tag{50}$$

$$0 \le r_{es,d,i}^{c,t} \le n_{es,i}^c \quad :\left(\underline{\omega}_{es,rd,i}^t, \bar{\omega}_{es,rd,i}^t\right) \quad \forall i \in N_{es}^c, t \in T \tag{51}$$

$$0 \le p_{es,d,i}^{c,t}/\eta_d + r_{es,u,i}^{c,t} \le n_{es,i}^c \quad :\left(\underline{\vartheta}_{es,i}^t, \bar{\vartheta}_{es,i}^t\right) \quad \forall i \in N_{es}^c, t \in T \tag{52}$$

$$0 \le p_{es,c,i}^{c,t}\eta_c + r_{es,d,i}^{c,t} \le n_{es,i}^c \quad :\left(\underline{\upsilon}_{es,i}^t, \bar{\upsilon}_{es,i}^t\right) \quad \forall i \in N_{es}^c, t \in T \tag{53}$$

$$e_{es,i}^{c,t} = e_{es,i}^{c,t-1} + p_{es,c,i}^{c,t}\eta_c - p_{es,d,i}^{c,t}/\eta_d \quad :\left(\phi_{soc,i}^t\right) \quad \forall i \in N_{es}^c, t \in T \tag{54}$$

$$r_{es,u,i}^{c,t} \le e_{es,i}^{c,t} \le n_{es,i}^c \tau_{es}^c - r_{es,d,i}^{c,t} \quad :\left(\underline{\psi}_{es,i}^t, \bar{\psi}_{es,i}^t\right) \quad \forall i \in N_{es}^c, t \in T \tag{55}$$

$$\sum_{t \in T}\left(p_{es,c,i}^{c,t}\eta_c - p_{es,d,i}^{c,t}/\eta_d\right) = 0 \quad :\left(\varepsilon_{soc,i}^t\right) \quad \forall i \in N_{es}^c, t \in T \tag{56}$$

$$0 \le n_{es,i}^c \le N_{i,\max}^{c,es} \quad :\left(\underline{\varphi}_{es,i}^c, \bar{\varphi}_{es,i}^c\right) \quad \forall i \in N_{es}^c, t \in T \tag{57}$$

The objective function in (34) minimizes the total operating cost. Equation (35) expresses the balance of node powers in each period. Formula (36) restricts the production of power by TGs. Formula (37) confines the ramp rate of the TGs. Formulas (38) and (39) limit the upward and downward regulation capacities of TGs. Formula (40) ensures that renewable energy production does not exceed the predicted value. Formula (41) limits the maximum installed capacity of renewable energy at each node. Formula (42) sets a requirement on the proportion of renewable energy production during load demand. Formulas (43) and (44) express the hourly upward and downward regulatory requirements. Formulas (45) and (46) are used to model the DC power flow of existing lines. Formula (47) bounds the phase angles of all nodes in each period. Formulas (48) and (49) restrict the charge and discharge powers of the CES. Formulas (50) and (51) model the upward and downward regulatory capacities for the CES. Formula (52) states the constraint between the discharge power and the upward regulatory capacity for the CES. The constraint between the charge power and downward regulatory capacity is given in (53). Formulas (54) and (55) express the dynamic operation and reservoir capacity of the CES at each node. Formula (56) connects the initial and final SOCs. Formula (57) defines the maximum installed capacity of the CES. The Lagrange multipliers of the lower-level problem are specified after the colons in (35)-(57). Note that the Lagrange multiplier corresponding to (36) denotes the LMP. The Lagrange multipliers of (43) and (44) are the upward and downward regulatory prices, respectively.

## IV. Solution Method

To solve the trilevel optimization problem, the middle- and lower-level problems are first converted into a single-level equivalent. Note that both central planners and the ISO seek to minimize the total cost. Therefore, the middle- and lower-level problems are replaced by an equivalent optimization problem (EOP), as shown in (58), subject to (30)-(34) and (36)-(58).

$$\min\left(C_{res} + C_g^o + C_{es}^c + C_{es}^{c,o} + C_{res}^{cut}\right) \tag{58}$$

Then, the Stackelberg game model is formulated as a bi-level optimization problem [29]. Furthermore, the problem can be recast as mathematical programming with equilibrium constraints by the Karush-Kuhn-Tucker (KKT) condition.

Firstly, the first-order optimal conditions of the EOP are given as:

$$c^g_{g,i} - \lambda^t_i + \bar{\alpha}^t_{g,i} - \underline{\alpha}^t_{g,i} + \bar{\beta}^t_{g,r,i} - \underline{\beta}^t_{g,r,i} - \bar{\beta}^{t+1}_{g,r,i} + \underline{\beta}^{t+1}_{g,r,i} = 0 \quad \forall i \in N_g, t = 1,2..., T-1 \tag{59}$$

$$c^g_{g,i} - \lambda^t_i + \bar{\alpha}^t_{g,i} - \underline{\alpha}^t_{g,i} + \bar{\beta}^t_{g,r,i} - \underline{\beta}^t_{g,r,i} = 0 \quad \forall i \in N_g, t = T \tag{60}$$

$$c^g_{r,i} + \bar{\alpha}^t_{g,i} + \bar{\delta}^t_{g,i} - \underline{\delta}^t_{g,i} - \lambda^t_{rc,u} = 0 \quad \forall i \in N_g, t \in T \tag{61}$$

$$c^g_{r,i} + \underline{\alpha}^t_{g,i} + \bar{\varepsilon}^t_{g,i} - \underline{\varepsilon}^t_{g,i} - \lambda^t_{rc,d} = 0 \quad \forall i \in N_g, t \in T \tag{62}$$

$$-c^{res}_{cut} - \lambda^t_i + \bar{\mu}^t_{res,i} - \underline{\mu}^t_{res,i} - \phi^t_{rps} = 0 \quad \forall i \in N_{res}, t \in T \tag{63}$$

$$c_{res} + \sum_{t \in T}\left(c^{res}_{cut}\hat{P}^t_{res} - \bar{\mu}^t_{res,i}\hat{P}^t_{res}\right) + \bar{\chi}_{res,i} - \underline{\chi}_{res,i} = 0 \quad \forall i \in N_{res} \tag{64}$$

$$\lambda^t_i - \lambda^t_j + v^t_{e,ij} - \underline{\pi}^t_{e,ij} + \bar{\pi}^t_{e,ij} = 0 \quad \forall (i,j) \in LE, t \in T \tag{65}$$

$$-b^e_{ij} v^t_{e,ij} - \underline{\varsigma}^t_i + \bar{\varsigma}^t_i = 0 \quad \forall (i,j) \in LE, t \in T \tag{66}$$

$$c^o_{es}/\eta_d + \bar{\vartheta}^t_{es,i}/\eta_d - \underline{\vartheta}^t_{es,i}/\eta_d - \phi^t_{soc,i}/\eta_d - \lambda^t_i + \bar{\sigma}^t_{es,d,i} - \underline{\sigma}^t_{es,d,i} = 0 \quad \forall i \in N^c_{es}, t \in T \tag{67}$$

$$c^o_{es}\eta_c + \bar{\upsilon}^t_{es,i}\eta_c - \underline{\upsilon}^t_{es,i}\eta_c + \phi^t_{soc,i}\eta_c + \lambda^t_i + \bar{\sigma}^t_{es,c,i} - \underline{\sigma}^t_{es,c,i} = 0 \quad \forall i \in N^c_{es}, t \in T \tag{68}$$

$$c^r_{es} + \bar{\omega}^t_{es,ru,i} - \underline{\omega}^t_{es,ru,i} + \bar{\vartheta}^t_{es,i} - \underline{\vartheta}^t_{es,i} + \underline{\psi}^t_{es,i} - \lambda^t_{rc,u} = 0 \quad \forall i \in N^c_{es}, t \in T \tag{69}$$

$$c^r_{es} + \bar{\omega}^t_{es,rd,i} - \underline{\omega}^t_{es,rd,i} + \bar{\upsilon}^t_{es,i} - \underline{\upsilon}^t_{es,i} + \bar{\psi}^t_{es,i} - \lambda^t_{rc,d} = 0 \quad \forall i \in N^c_{es}, t \in T \tag{70}$$

$$-\phi^t_{soc,i} + \phi^{t+1}_{soc,i} + \bar{\psi}^t_{es,i} - \underline{\psi}^t_{es,i} = 0 \quad \forall i \in N^c_{es}, t \in 1,2,...T-1 \tag{71}$$

$$-\phi^t_{soc,i} + \bar{\psi}^t_{es,i} - \underline{\psi}^t_{es,i} = 0 \quad \forall i \in N^c_{es}, t = T \tag{72}$$

$$c^c_{es} - \sum_{t \in T}\left(\bar{\sigma}^t_{es,d,i} + \bar{\sigma}^t_{es,c,i} + \bar{\omega}^t_{es,ru,i} + \bar{\omega}^t_{es,rd,i} + \bar{\vartheta}^t_{es,i}\right) + \sum_{t \in T}\left(\bar{\upsilon}^t_{es,i} + \bar{\psi}^t_{es,i}\tau^c_{es}\right) + \bar{\varphi}^c_{es,i} - \underline{\varphi}^c_{es,i} = 0 \quad \forall i \in N^c_{es} \tag{73}$$

Note that $t$ in (59) and (71) ranges from 1 to $T$–1, while $t$ in (60) and (72) is equal to $T$.

Secondly, the complementary slackness conditions for each inequality constraint in the EOP are given as:

$$\bar{\alpha}^t_{g,i}\left(p^t_{g,i} + r^t_{g,u,i} - P^g_{i,\max}\right) = 0 \quad \forall i \in N_g, t \in T \tag{74}$$

$$\underline{\alpha}^t_{g,i}\left(P^g_{i,\min} + r^t_{g,d,i} - p^t_{g,i}\right) = 0 \quad \forall i \in N_g, t \in T \tag{75}$$

$$\bar{\beta}^t_{g,r,i}\left(p^t_{g,i} - p^{t-1}_{g,i} - ru^g_{i,\max}\right) = 0 \quad \forall i \in N_g, t \in T \tag{76}$$

$$\underline{\beta}^t_{g,r,i}\left(p^{t-1}_{g,i} - p^t_{g,i} - rd^g_{i,\max}\right) = 0 \quad \forall i \in N_g, t \in T \tag{77}$$

$$\bar{\delta}^t_{g,i}\left(r^t_{g,u,i} - rc^{g,u}_{i,\max}\right) = 0 \quad \forall i \in N_g, t \in T \tag{78}$$

$$\underline{\delta}^t_{g,i} r^t_{g,u,i} = 0 \quad \forall i \in N_g, t \in T \tag{79}$$

$$\bar{\varepsilon}^t_{g,i}\left(r^t_{g,d,i} - rc^{g,d}_{i,\max}\right) = 0 \quad \forall i \in N_g, t \in T \tag{80}$$

$$\underline{\varepsilon}^t_{g,i} r^t_{g,d,i} = 0 \quad \forall i \in N_g, t \in T \tag{81}$$

$$\bar{\mu}^t_{res,i}\left(p^t_{res,i} - n^{res}_i \hat{P}^t_{res}\right) = 0 \quad \forall i \in N_{res}, t \in T \tag{82}$$

$$\underline{\mu}^t_{res,i} p^t_{res,i} = 0 \quad \forall i \in N_{res}, t \in T \tag{83}$$

$$\bar{\chi}_i\left(n^{res}_i - N^{res}_{i,\max}\right) = 0 \quad \forall i \in N_{res} \tag{84}$$

$$\underline{\chi}_i n^{res}_i = 0 \quad \forall i \in N_{res} \tag{85}$$

$$\phi^t_{rps} R_{rps} \sum_{t \in T}\sum_{i \in N} p^t_{d,i} - \phi^t_{rps} \sum_{t \in T}\sum_{i \in N_{res}} p^t_{res,i} = 0 \tag{86}$$

$$\lambda^t_{rc,u} R^u_{rc} \sum_{i \in N_d} p^t_{d,i} - \lambda^t_{rc,u} \sum_{i \in N_g} r^t_{g,u,i} - \lambda^t_{rc,u} \sum_{i \in N^c_{es}} r^{c,t}_{es,u,i} - \lambda^t_{rc,u} \sum_{i \in N^s_{es}} r^{s,t}_{es,u,i} = 0 \quad \forall t \in T \tag{87}$$

$$\lambda^t_{rc,d} R^d_{rc} \sum_{i \in N_d} p^t_{d,i} - \lambda^t_{rc,d} \sum_{i \in N_g} r^t_{g,d,i} - \lambda^t_{rc,d} \sum_{i \in N^c_{es}} r^{c,t}_{es,d,i} - \lambda^t_{rc,d} \sum_{i \in N^s_{es}} r^{s,t}_{es,d,i} = 0 \quad \forall t \in T \tag{88}$$

$$\underline{\pi}^t_{e,ij}\left(p^t_{e,ij} + p^{e,ij}_{\max}\right) = 0 \quad \forall (i,j) \in LE, t \in T \tag{89}$$

$$\bar{\pi}^t_{e,ij}\left(p^t_{e,ij} - p^{e,ij}_{\max}\right) = 0 \quad \forall (i,j) \in LE, t \in T \tag{90}$$

$$\underline{\varsigma}^t_i\left(\theta_{i,\min} - \theta^t_i\right) = 0 \quad \forall i \in N, t \in T \tag{91}$$

$$\bar{\varsigma}^t_i\left(\theta^t_i - \theta_{i,\max}\right) = 0 \quad \forall i \in N, t \in T \tag{92}$$

$$\bar{\sigma}^t_{es,d,i}\left(p^{c,t}_{es,d,i} - n^c_{es,i}\right) = 0 \quad \forall i \in N^c_{es}, t \in T \tag{93}$$

$$\underline{\sigma}^t_{es,d,i} p^{c,t}_{es,d,i} = 0 \quad \forall i \in N^c_{es}, t \in T \tag{94}$$

$$\bar{\sigma}^t_{es,c,i}\left(p^{c,t}_{es,c,i} - n^c_{es,i}\right) = 0 \quad \forall i \in N^c_{es}, t \in T \tag{95}$$

$$\underline{\sigma}^t_{es,c,i} p^{c,t}_{es,c,i} = 0 \quad \forall i \in N^c_{es}, t \in T \tag{96}$$

$$\bar{\omega}^t_{es,ru,i}\left(r^{c,t}_{es,u,i} - n^c_{es,i}\right) = 0 \quad \forall i \in N^c_{es}, t \in T \tag{97}$$

$$\underline{\omega}^t_{es,ru,i} r^{c,t}_{es,u,i} = 0 \quad \forall i \in N^c_{es}, t \in T \tag{98}$$

$$\bar{\omega}^t_{es,rd,i}\left(r^{c,t}_{es,d,i} - n^c_{es,i}\right) = 0 \quad \forall i \in N^c_{es}, t \in T \tag{99}$$

$$\underline{\omega}^t_{es,rd,i} r^{c,t}_{es,d,i} = 0 \quad \forall i \in N^c_{es}, t \in T \tag{100}$$

$$\bar{\vartheta}^t_{es,i}\left(p^{c,t}_{es,d,i}/\eta_d + r^{c,t}_{es,u,i} - n^c_{es,i}\right) = 0 \quad \forall i \in N^c_{es}, t \in T \tag{101}$$

$$\underline{\vartheta}^t_{es,i}\left(p^{c,t}_{es,d,i}/\eta_d + r^{c,t}_{es,u,i}\right) = 0 \quad \forall i \in N^c_{es}, t \in T \tag{102}$$

$$\bar{\upsilon}^t_{es,i}\left(p^{c,t}_{es,c,i}\eta_c + r^{c,t}_{es,d,i} - n^c_{es,i}\right) = 0 \quad \forall i \in N^c_{es}, t \in T \tag{103}$$

$$\underline{\upsilon}^t_{es,i}\left(p^{c,t}_{es,c,i}\eta_c + r^{c,t}_{es,d,i}\right) = 0 \quad \forall i \in N^c_{es}, t \in T \tag{104}$$

$$\bar{\psi}^t_{es,i}\left(e^{c,t}_{es,i} - n^c_{es,i}\tau^c_{es} + r^{c,t}_{es,d,i}\right) = 0 \quad \forall i \in N^c_{es}, t \in T \tag{105}$$

$$\underline{\psi}^t_{es,i}\left(r^{c,t}_{es,u,i} - e^{c,t}_{es,i}\right) = 0 \quad \forall i \in N^c_{es}, t \in T \tag{106}$$

$$\bar{\varphi}^c_{es,i}\left(n^c_{es,i} - N^{c,es}_{i,\max}\right) = 0 \quad \forall i \in N^c_{es} \tag{107}$$

$$\underline{\varphi}^c_{es,i} n^c_{es,i} = 0 \quad \forall i \in N^c_{es} \tag{108}$$

Note that solving the EOP is equivalent to solving (35)-(57) and (59)-(108). The set of (74)-(108) is nonconvex; the nonlinear problem can be tackled by using disjunctive inequalities [30]. As the EOP is a substitute for a set of linear equations, the bilevel optimization is formulated into a single-level optimization problem. However, the profits of DTLs and DES are determined using the LMPs, which lead to a nonconvex objective function in the upper-level problem. Fortunately, the EOP is linear, and Slater's condition is satisfied [31]. Strong duality theory is used to linearize the objective function.

$$\begin{aligned}&C_{res}+C_g^o+C_{es}^c+C_{es}^{c,o}+C_{res}^{cut}=-\sum_{t\in T}\sum_{i\in N}\lambda_i^t\left(p_{inj,i}^{c,t}-p_{out,i}^{c,t}\right)-\\&\sum_{t\in T}\sum_{i\in N_{es}^s}\lambda_i^t\left(p_{es,d,i}^{s,t}-p_{es,c,i}^{s,t}\right)-\sum_{t\in T}\sum_{i\in N_{es}^s}\left(\lambda_{ru}^t r_{es,u,i}^{s,t}+\lambda_{rd}^t r_{es,d,i}^{s,t}\right)+\\&\sum_{t\in T}\sum_{i\in N_g}\left(P_{i,\min}^g\underline{\alpha}_{g,i}^t-P_{i,\max}^g\bar{\alpha}_{g,i}^t-ru_{i,\max}^g\bar{\beta}_{g,i}^t-rd_{i,\max}^g\underline{\beta}_{g,i}^t\right)-\\&\sum_{t\in T}\sum_{i\in N_g}\left(rc_{i,\max}^{g,u}\bar{\delta}_{g,i}^t+rc_{i,\max}^{g,d}\bar{\varepsilon}_{g,i}^t\right)-\sum_{i\in N_{res}}N_{i,\max}^{res}\bar{\chi}_{res,i}+\\&\sum_{t\in T}\sum_{i\in N_d}p_{d,i}^t\left(\lambda_i^t+R_{rps}\phi_{rps}^t-R_{rc}^u\lambda_{rc,u}^t-R_{rc}^d\lambda_{rc,d}^t\right)-\\&\sum_{(i,j)\in LC}p_{\max}^{e,ij}\left(\underline{\pi}_{e,ij}^t+\bar{\pi}_{e,ij}^t\right)+\sum_{i\in N}\left(\theta_{i,\min}\underline{\varsigma}_i^t-\theta_{i,\max}\bar{\varsigma}_i^t\right)-\sum_{i\in N_{es}^c}N_{i,\max}^{c,es}\bar{\chi}_{es,i}\end{aligned}\tag{109}$$

After reordering the terms, the revenue from the market for DTLs and DES is rewritten as:

$$\begin{aligned}&R_{line}^m+R_{es}^m=-\sum_{i\in N_{es}^c}N_{i,\max}^{c,es}\bar{\chi}_{es,i}-C_{res}-C_g^o-C_{es}^c-C_{es}^{c,o}-C_{res}^{cut}+\\&\sum_{t\in T}\sum_{i\in N_g}\left(P_{i,\min}^g\underline{\alpha}_{g,i}^t-P_{i,\max}^g\bar{\alpha}_{g,i}^t-ru_{i,\max}^g\bar{\beta}_{g,i}^t-rd_{i,\max}^g\underline{\beta}_{g,i}^t\right)-\\&\sum_{t\in T}\sum_{i\in N_g}\left(rc_{i,\max}^{g,u}\bar{\delta}_{g,i}^t+rc_{i,\max}^{g,d}\bar{\varepsilon}_{g,i}^t\right)-\sum_{i\in N_{res}}N_{i,\max}^{res}\bar{\chi}_{res,i}+\\&\sum_{t\in T}\sum_{i\in N_d}p_{d,i}^t\left(\lambda_i^t+R_{rps}\phi_{rps}^t-R_{rc}^u\lambda_{rc,u}^t-R_{rc}^d\lambda_{rc,d}^t\right)-\\&\sum_{(i,j)\in LC}p_{\max}^{e,ij}\left(\underline{\pi}_{e,ij}^t+\bar{\pi}_{e,ij}^t\right)+\sum_{i\in N}\left(\theta_{i,\min}\underline{\varsigma}_i^t-\theta_{i,\max}\bar{\varsigma}_i^t\right)\end{aligned}\tag{110}$$

The FTR and FSR profits are represented by the dual variable and the boundary of the primal variable. The nonconvexity and nonlinearity of the objective function in (26) and the complementary slackness conditions in (74)-(108) are linearized. To this end, the joint planning framework considering the game between the merchant and the central planner is customized as mixed-integer linear programming (MILP) problem, which can be solved by a commercial package.

The variability of renewable energy and the load is integrated into the market clearing in the lower-level problem. Suppose that $Q$ denotes the number of generation and demand scenarios. Accordingly, a scenario-based stochastic optimization model is proposed, and its compact form is given as:

$$\max\left(AX+B\sum_{q\in Q}\varpi_q Y_q+C\sum_{q\in Q}\varpi_q Z_q\right)\tag{111}$$

$$DX+E_qY_q\le F_q\tag{112}$$

$$G_qY_q+H_qZ_q\le I_q\tag{113}$$

$$\sum_{q\in Q}\varpi_q=1\tag{114}$$

Formula (111) maximizes the net profit. Formula (112) expresses the primal constraint corresponding to (2)-(10), (12)-(25), (27), (29)-(33), and (35)-(57). Formula (113) expresses the first-order optimal conditions and the complementary slackness conditions corresponding to Equations (59)-(108). Equation (114) limits the sum of all scenario probabilities. It is worth mentioning that an equality constraint can be rewritten as two inequality constraints. The deterministic model can be extended to the case of uncertainty in the supply and demand in the electricity market. The number of scenarios increases the computational burden. However, this model of maximum expected profit can be efficiently solved by a software package.

## V. Case Studies

In this section, we present numerical experiments to validate the presented methodology. All numerical studies have been run using the CPLEX solver within the MATLAB environment on a 64-bit Windows-based server.

### *A. Data and Experimental Setup*

The framework is implemented in a modified IEEE 30-bus test system, and the original data are given in [32]. The maximum load and capacity of the units and transmission lines are three times their original values. The hourly ramp-down and ramp-up limits of the TGs are 30% of their capacity. The minimum output of a TG is set as 10% of their capacity. The operating costs of the TGs range from 50 $/MWh to 350 $/MWh, and the regulation cost is set as 5 $/MWh. The transmission expansion projects in which merchants can participate are lines 29, 30, and 35. Three kinds of discrete capacity levels (20, 40, and 60 MW) with the corresponding susceptance of the lines are considered, and the daily cost of the candidate lines is set as 240 $/MWh. DES can be installed on buses 6, 22, 23, and 27. CES can be installed on buses 11 and 27. The daily capital costs of DES and CES are 450 $/MWh and 500 $/MWh, respectively. The degradation and regulation costs are set as 0.5 $/MWh and 0.5 $/MWh, respectively. The charging and discharging efficiencies of all energy storage are set to be 0.95. The energy-to-power ratios for DES and CES are set as 3 and 5 hours, respectively. The installation capacities of DES and CES on each bus are limited to 50 and 30 MW, respectively. The parameters are feasible for performing spatial and temporal arbitrage. Wind turbines (WTs) and photovoltaics (PVs) can be installed on buses 22, 23, and 27. The installation capacities of WTs and PVs on each bus are limited to 150 and 100 MW, respectively. The daily capital costs of PVs and WTs are set to be 80 and 70 $/MW, and their operating cost is zero. The penalty cost of renewable energy spillage is set to be 500 $/MWh. A day is divided into hourly time slots with $T=24$. The curves of renewable energy and the load [33] are shown in Appendix A Fig. A1. Unless stipulated otherwise, the rate of return on investment by the merchant is set to be 1 to ensure that the investment can be accurately recovered. The regulatory requirement is set to be 10% of the total system load in each period. The ITC subsidy is set to be 10%.

A numerical analysis is performed for the spatiotemporal arbitrage of DTLs and DES in a liberalized day-ahead electricity market. Economic results such as the merchant's profit and total social cost are analyzed. The planning and operation strategies of the merchants and central planners are given. Specifically, an example of investment by a merchant without a central planner is given in Section V-B. The coordinated investment results of the merchant and central planners are given in Section V-C. Finally, a stochastic version of the analysis is given in Section V-D.

### B. Investment by a Merchant Without a Center Planner

As a benchmark, an example of investment by a merchant and an operation strategy without a central planner is given in this subsection. The advantage of joint investment in DTLs and DES is demonstrated with the following three cases: ① Case 1: investment in DTLs without DES; ② Case 2: investment in DES without DTL; and ③ Case 3: joint investment in DTLs and DES. Firstly, the results obtained by investment plans by a merchant are summarized in Table I.

TABLE I
INVESTMENT PLANS BY A MERCHANT WITHOUT A CENTRAL PLANNER

| Case | DTL (MW) | | | DES (MW/MWh) | | | |
|---|---|---|---|---|---|---|---|
| | No. 29 | No. 30 | No. 35 | No. 6 | No. 22 | No. 23 | No. 27 |
| Case 1 | 60 | 60 | | | | | |
| Case 2 | | | | 50/150 | | | |
| Case 3 | 80 | 60 | | 31/93 | 14/42 | 0 | 22/66 |

Note that the DES capacity is rounded. The results in Table I show that the expansion capacity of the DTLs and DES is the largest in Case 3. Without a central planner, the system load is supplied by TGs. The operating costs of the TGs in these three cases are \$1347600, \$1460300, and \$1298200, respectively. Obviously, joint investment in DTLs and DES can significantly reduce the operation cost of the TGs. Secondly, the investment and profit in the three cases are shown in Fig. 2.

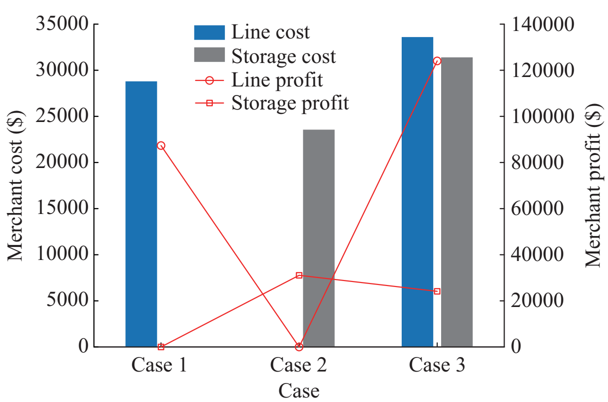


Fig. 2. Investment and profit of merchant in three cases.

The total investment costs of the merchant in the three cases are \$28800, \$23600, and \$65000, respectively. The total profits of the merchant in the three cases are \$87300, \$31100, and \$148200, respectively. It is not difficult to determine that the net profit in Case 3 is the highest, which demonstrates the advantage of joint investment. The DTLs can alleviate congestion, while the DES can reduce regulation costs. Thus, joint investment in DTLs and DES can effectively reduce the operation cost of the TGs and increase the profit of the merchant.

In contrast to the above example, the financial subsidy and regulatory requirements are fixed at 10%. Here, the effects of regulatory requirements and financial subsidies on the profit of the merchant in Case 3 are shown in Fig. 3.

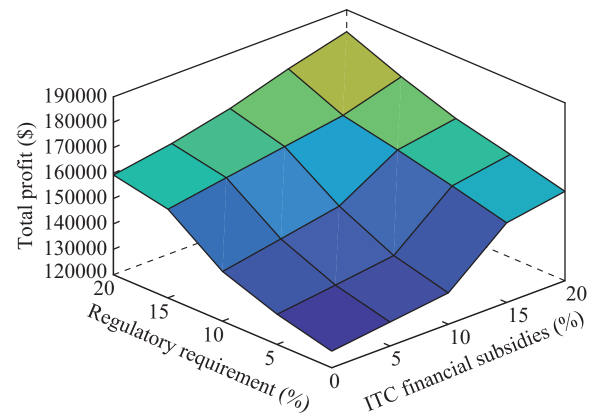


Fig. 3. Total profit with different regulatory requirements and ITCs.

The regulatory requirements and ITC financial subsidies are gradually increased from 0% to 20% in steps of 5%. In Case 3, the merchant profits with each regulatory requirement, and the ITC financial subsidies are calculated. The total profit is proportional to the regulatory requirements and ITC financial subsidies. The regulatory requirements will increase congestion and reserve costs, which provides arbitrage opportunities for DTLs and DES. The ITC financial policy is equivalent to reducing investment costs and promoting the installation capacity of DTLs and DES. However, it is important for policy-makers to design reasonable ITC financial subsidies according to regulatory requirements.

### C. Game Between Merchant and Central Planners

In this subsection, a numerical example of joint investment considering a game between the merchant and the central planners is given. Similarly, the interaction between the merchant and the central planners is illustrated in two cases: ① Case 4: joint investment by the merchant and central planners; and ② Case 5: the central planners invest without the merchant. Firstly, the results for planning by the merchant and central planners in the two cases are summarized in Table II.

Note that the installed capacity for CRE and CES is rounded. The results in Table II show that the investment by the merchant can promote investment in renewable energy by the central planners and reduce their capital burden. Node 22 is installed with large-scale WTs and PVs, which increases the transmission congestion cost of line 29 and necessitates the expansion of transmission. Moreover, the central planners prefer to reduce the investment in CES to avoid high social costs. The investment and operation costs in Cases 4 and 5 are summarized in Table III.

The investment by the merchant reduces the operation cost of the system, which lowers the operation cost of the TGs in Case 4. The energies consumed by renewables in Cases 4 and 5 are 5691 and 4323 MWh, respectively. Renewable energy has zero marginal cost, which can reduce the operation cost of the power system. Secondly, the investment by the merchant increases the risk of peak LMPs. The LMP for each period for the two cases is shown in Fig. 4.

TABLE II
INVESTMENT SOLUTIONS FOR MERCHANT AND CENTRAL PLANNERS

| Case | Merchant | | | | | | | Central planner | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Transmission lines (MW) | | | Energy storage (MW/MWh) | | | | WT (MW) | | | PV (MW) | | | Energy storage (MW/MWh) | |
| | No. 29 | No. 30 | No. 35 | No. 6 | No. 22 | No. 23 | No. 27 | No. 22 | No. 23 | No. 27 | No. 22 | No. 23 | No. 27 | No. 11 | No. 27 |
| Case 4 | 120 | | | 50/150 | 38/114 | 41/123 | 31/93 | 150 | 42 | 133 | 100 | 35 | 100 | 30/150 | 0/0 |
| Case 5 | | | | | | | | 95 | 27 | 136 | 36 | 35 | 89 | 30/150 | 30/150 |

TABLE III
INVESTMENT AND OPERATION COSTS IN CASES 4 AND 5

| Case | Investment and operation cost ($) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Deregulated lines | Deregulated storage | Thermal units | Centralized WT | Centralized PV | CES | Penalty |
| Case 4 | 28800 | 73939 | 893556 | 22750 | 18800 | 15568 | 0 |
| Case 5 | 0 | 0 | 1163082 | 18060 | 12800 | 31244 | 5913 |

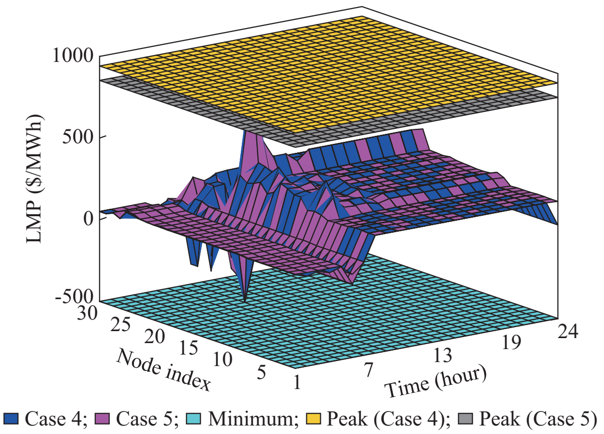


Fig. 4. LMP for each period for Cases 4 and 5.

The minimum LMP for the two cases is −500 \$/MWh, which appears in node 22 in the 9th period. The maximum LMPs for the two cases are 940.5 and 852.3 \$/MWh, which occur in node 21 in the 9th period. The WTs and PVs integrated into node 22 lead to a negative LMP and transmission congestion in line 29. Large-scale renewable energy is installed in Case 4, and the uncertainty of production leads to drastic fluctuation of the LMP. Further, as a result of their investment and operation strategy, the merchant expects a higher fluctuation of the LMP, which is beneficial for the arbitrage of DTLs and DES. For Case 4, the profits of the DTLs and DES are \$180000 and \$103500, respectively. The dispatch power of a unit in Case 4 is shown in Fig. 5.

The anti-peak shaving of wind leads to the production of energy by TGs fixed at a forced output. The reduction of renewable energy generation and the increase of load demand lead to a large value of LMP. The arbitrage of DES in liberalized energy and reserve markets uses electricity prices as an arbitrage signal. Therefore, the DES is continuously discharging without charging during the period of 14:00-24:00. The difference is that the CES has a lower installed capacity and is inactive. Thirdly, the effect of the rate of return on the investment by the merchant is studied. The cost and profit of investment with different rates of return are shown in Fig. 6. This figure shows that it is difficult to achieve high rates of return, which can reduce the merchant's profits and social welfare. Note that a profit-unconstrained situation ($\rho<3$) leads to a large installed capacity of DES. The profit-unconstrained case overestimates the market demand for energy storage capacity and reduces the value of energy storage for the whole system [26]. A large transmission flow power and LMP diversity between nodes are conducive to arbitrage of DTLs, which means that the merchant prefers to invest in DTLs.

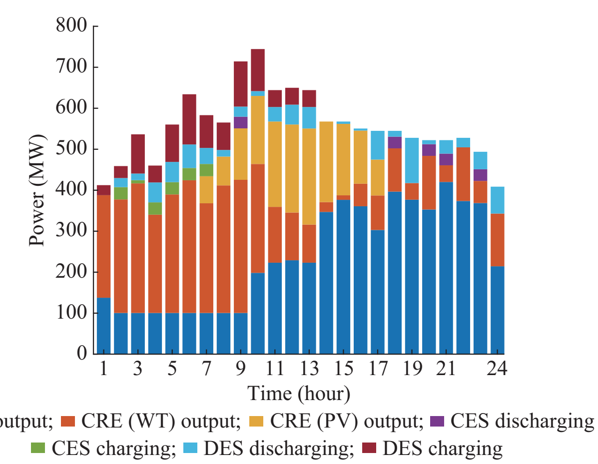


Fig. 5. Day-ahead dispatch power of a unit in Case 4.

Profit-constrained decisions result in a larger CES capacity and operation costs. This change between the profit-constrained and unconstrained cases can be attributed to modeling priorities. As a leader, merchants aim to maximize their net profit instead of the expected rate of return. As a follower, the central planners seek to minimize the social cost. The profit-constrained case will reduce the investment in DTLs and DES, which will lead to additional CES and operation costs.

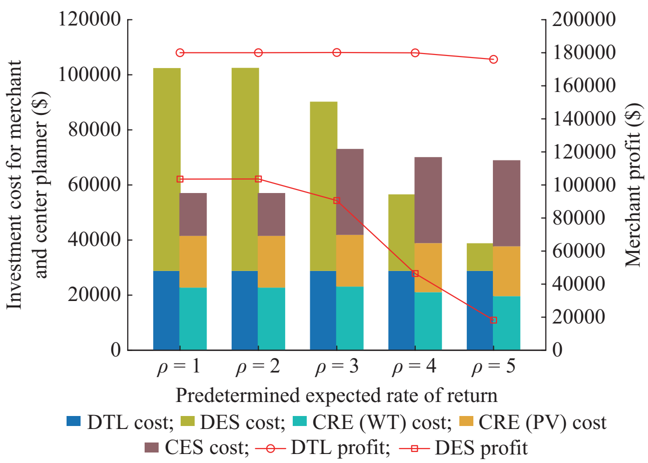


Fig. 6. Influence of rate of return on investment cost and profit in Case 4.

In summary, the investment by the merchant shares the capital burden of central planners and improves social welfare. The investment in CRE by the central planners offers arbitrage opportunities for merchants.

### *D. Numerical Analysis of Stochastic Scenarios*

In this subsection, a stochastic analysis based on the modified IEEE 118-bus test system is presented to verify the effectiveness of the framework. The original data are given in [32]. The operating costs of TGs range from 50 to 500 $/MWh. DES can be installed on buses 56 and 59. CES can be installed on bus 56. The expansion lines are lines 84, 85, and 87, and the capacity of these lines is set to be 30 MW. WTs can be installed on buses 56 and 59. PVs can be installed on buses 54 and 56. The remaining parameter settings are given in Section V-A. Owing to the seasonal characteristics of renewable energy and the load, the annual scenario set is reduced to four typical scenarios (spring, summer, autumn, and winter). These scenarios and probabilities can be obtained using the *K*-means clustering algorithm [34], as shown in Appendix A Figs. A2-A4. The results for planning by the merchants and central planners in different scenarios are summarized in Table IV.

TABLE IV
INVESTMENT BY MERCHANTS AND CENTRAL PLANNERS IN VARIOUS SCENARIOS

| Scenario | DTL (MW) | | | DES (MW/MWh) | | Centralized WT (MW) | | Centralized PV (MW) | | CES (MW/MWh) |
|---|---|---|---|---|---|---|---|---|---|---|
| | No. 84 | No. 85 | No. 87 | No. 56 | No. 59 | No. 56 | No. 59 | No. 54 | No. 56 | No. 56 |
| Scene 1 | 20 | | | 3/9 | | 120 | 150 | 100 | 70 | 26/130 |
| Scene 2 | 20 | | | 20/60 | 18/54 | 150 | 150 | 100 | 68 | 30/150 |
| Scene 3 | | | 20 | 19/57 | 22/66 | 150 | 150 | 100 | 100 | 30/150 |
| Scene 4 | | | | | 23/69 | 150 | 150 | 100 | 100 | |
| Multi-scene | 20 | | | 16/48 | 15/45 | 129 | 150 | 100 | 76 | 30/150 |

The weight in each scenario is set to be 1. The weights of the four typical scenarios are 0.26, 0.17, 0.29, and 0.28 in the multi-scene scenario, respectively. An economic analysis of the merchants and central planners in various scenarios is shown in Fig. 7.

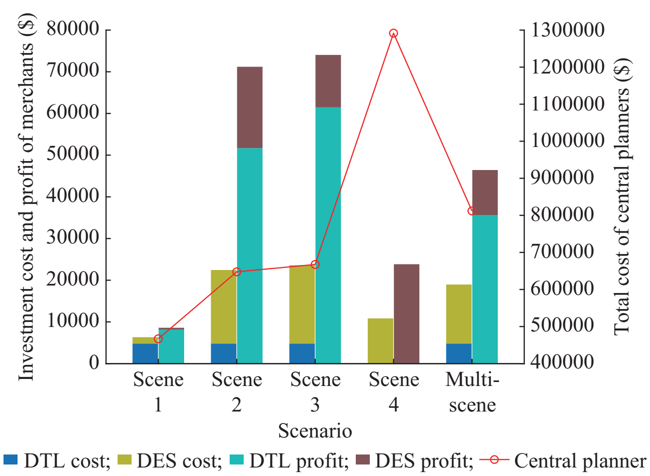


Fig. 7. Costs and profits of investors in various scenarios.

Diversified renewable energy and load curves lead to large differences in the planning results corresponding to each typical scenario. For the individual scenarios, the highest net profit is $50437 in Scene 3, and the lowest net profit is $2261 in Scene 1. The expected net profit in the multi-scene scenario is $27468. The degree of transmission congestion in each scenario is different, and the large differences in LMPs and power flows lead to a high yield of DTLs. The merchants did not invest in DTLs (Scene 4), which indicates that the merchants prefer to invest in DES. Transmission lines will reduce the fluctuation of the LMPs, but arbitrage is difficult for both DTLs and DES in a power system without transmission congestion. Finally, the renewable energy and load scenarios affect the rate of return of the merchant. The risk to the merchants can be mitigated by using the multi-scene scenario and setting weight coefficients.

Financial rights can promote merchants to invest in DTLs and DES and reduce the financial burden of transmission service providers. The merchants can strategically invest in the deregulated electricity market to maximize their profits. The behavior is more pronounced with increased renewable energy penetration and deregulation of the market, which offer an opportunity for intertemporal arbitrage in energy and ancillary service markets.

The number of scenes in a scenario will greatly increase the computational burden. The results for planning a single scene are obtained in 10 min. The results for planning multiple scenes are obtained within 6 hours, which is acceptable for offline simulation.

## VI. Conclusion

In this paper, a novel coordinated investment framework for merchants and central planners using the Stackelberg game is proposed. Examples utilizing the modified IEEE 30-bus and 118-bus test systems illustrate the interactions between the profit-maximizing merchants and the cost-minimizing central planners. The following conclusions are drawn from the results.

1) For the merchants, joint investment in DTLs and DES has higher market profits. The DTLs and DES become remunerated on the basis of the difference in the LMPs of different nodes and periods. Merchants tend to invest in transmission and energy storage in a power system with a fluctuating LMP. Assigning a weight coefficient to each scenario can reduce the risk to the merchant.

2) For the central planners, CRE can reduce the operation cost of the system and increase the risk of peak LMPs. This can attract investment by the merchants and promote the production of renewable energy. The investment by the merchants allows the capital burden of the central planners to be shared and improves social welfare.

3) From the perspective of the system, joint investment by the merchants and central planners can help merchants obtain higher profits and help central planners achieve greater cost savings than deployment alone.

Future work will extend this framework to include an investment model, e.g., improve the computational tractability of the multistage investment framework with a decomposition algorithm. Moreover, the application of deep learning for portfolio optimization is worthy of attention.

## Appendix A

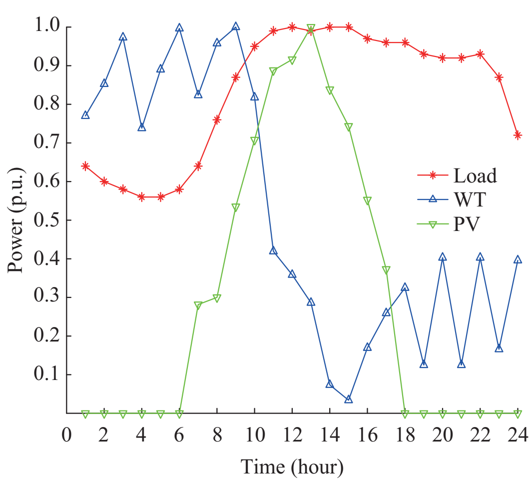


Fig. A1. Forecasting power of renewable energy and load.

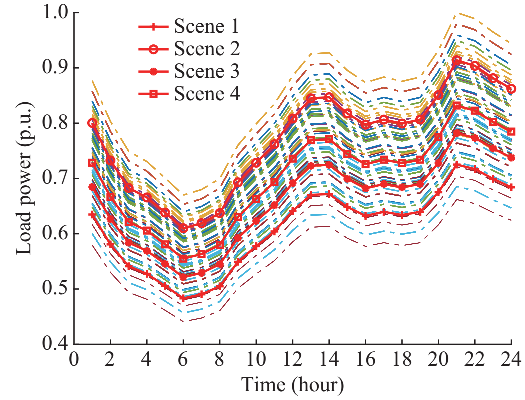


Fig. A2. Original scene set and typical scenes of load.

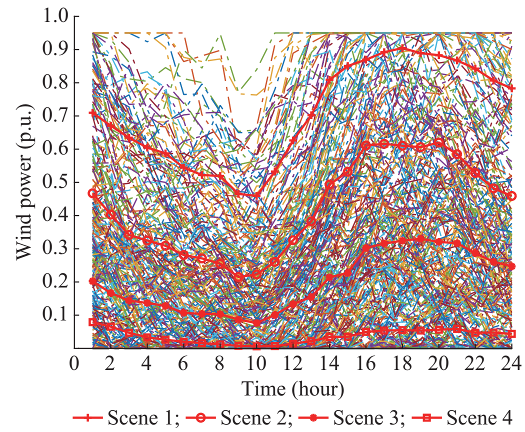


Fig. A3. Original scene set and typical scenes of wind.

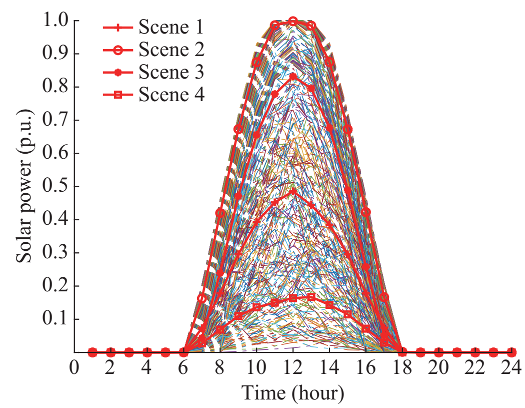


Fig. A4. Original scene set and typical scenes of solar.

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