Optimal Planning of Community Integrated Energy Station Considering Frequency Regulation Service

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***Abstract*—With the extensive integration of high-penetration renewable energy resources, more fast-response frequency regulation (FR) providers are required to eliminate the impact of uncertainties from loads and distributed generators (DGs) on system security and stability. As a high-quality FR resource, community integrated energy station (CIES) can effectively respond to frequency deviation caused by renewable energy generation, helping to solve the frequency problem of power system. This paper proposes an optimal planning model of CIES considering FR service. First, the model of FR service is established to unify the time scale of FR service and economic operation. Then, an optimal planning model of CIES considering FR service is proposed, with which the revenue of participating in the FR service is obtained under market mechanism. The flexible electricity pricing model is introduced to flatten the peak tie-line power of CIES. Case studies are conducted to analyze the annual cost and the revenue of CIES participating in FR service, which suggest that providing ancillary services can bring potential revenue.**

***Index Terms*—Community integrated energy station (CIES), frequency regulation (FR), flexible pricing model, optimal configuration.**

I. Introduction

WITH the increasing penetration of distributed generators (DGs) at the user side, large-scale intermittent and random power generation of DGs aggravate frequency deviation and bring stability problem to power system [1]. Subjected to the ramp-up/down rate constraints with slower response, it is difficult to keep the frequency balance by relying on traditional generators [2]. Additional fast-response frequency regulation (FR) capabilities are required [3], and have become challenging tasks that should be considered. Thus, researchers have to resort to user-side resources, which are flexible to schedule. Community integrated energy station (CIES) is regarded as an effective approach to address the issue [4].

The application of combined heat and power (CHP) technology brings heating, natural gas, and electric power systems together [5], [6]. The coupling and complementary characteristics among diverse energy resources and devices have prompted the emergence of CIES. A CIES integrates and supplies various forms of energy such as cooling, heat and electricity to the end users [7]. The CIES can efficiently utilize multiple energies and reliably supply energy. Complementary energy supplies ensure an optimized operation of CIES, and energy storage equipment within the system can provide fast response capabilities [8]. The features of complementarity and fast response make CIES a promising approach not only to meet the energy requirements of local communities, but also to provide ancillary services. Meanwhile, ancillary services will become important revenue sources for CIES. The efficiency and quality of ancillary services depend significantly on the configuration of the CIES. However, the generation, delivery and consumption of the CIES are highly coupled, suggesting higher requirements for system planning and design. Instead of the traditional independent planning of electricity, gas, heating and cooling systems, joint planning with multi-form energies should be considered for CIES.

A number of studies have investigated CIES planning. In [9], a mixed-integer linear programming (MILP) model was developed to find an optimized combination of candidate equipment and operation strategies, with a minimal annual cost of investment and operation. Reference [10] developed a convex programming method for optimal capacity and energy management of smart home with electrical energy storage and photovoltaic (PV) power generation. In [11], based on the energy hub model, a two-stage MILP model of CIES was proposed, which modeled the devices as energy converters, distributed generators and energy storage. Reference [12] proposed a multi-objective optimization algorithm, which is to minimize the overall economic cost, the unsatisfied load and fuel emissions simultaneously. In [13], an approach was proposed for optimal designing of CIES. Economic cost, carbon dioxide emission, and the probability of

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load loss were considered. The equivalent cost of pollution and power supply reliability were converted into operation constraints by the ε-constraint method. For the issues of CIES planning and design, objective functions of economics, operation reliability and environmental concern are usually considered on the premise of satisfying internal diverse demands. The ability of CIES participating in the ancillary service market needs to be further studied.

With the development of the ancillary service market, CIES can participate in the FR market competition as a fast-response load. Previous works have been proposed to consider FR demand in the planning stage. In [14], a strategy for sizing energy storage systems to provide primary FR service was proposed. Considering the slow response of generators, coordinated planning of energy storage and generators was proposed to provide FR power [15]. Reference [16] investigated the participation of an aggregator with energy storage and electric vehicles in both regulation and energy markets, and determined the optimal bidding capacity of the aggregator. These works usually considered the planning of a single type device to provide FR service. In a CIES, the planning and operation of FR equipment such as electric energy storage should be involved in the co-planning with other devices. In addition, because of participating in ancillary services, two or multiple different goals of power balance and ancillary service are required to be considered in the planning model simultaneously, which are in different time scales. The rapid variation of FR power needs to be considered in the planning model.

Thus, an optimal planning model of CIES considering FR service is proposed in this paper. First, the mechanism and simplified transaction procedure of the FR market are presented. An optimal planning model of CIES considering FR service is proposed with a minimal annual cost. Conversion devices, energy storage and distributed generators are considered in the model. In addition, flexible electricity pricing model is introduced to mitigate the fluctuation of tie-line power. Taking a real industrial park as the example, the optimal configuration of equipment and annual comprehensive cost are compared.

The main contributions are summarized as follows.

1) An optimal planning model of CIES considering FR is established. First, the model of FR service is established to unify the time scale of FR service and economic operation of CIES. Then, considering FR service and operation constraints, the planning model of CIES is proposed, with the objective function of minimizing annual cost. CIES can provide FR service, while efficiently satisfying its internal cooling, heating and electric demands. Both equipment capacity and FR bidding strategy can be optimized. Case study on real load data is conducted to analyze the benefit of the CIES participating in the FR market.

2) Given that the participation of CIES in the FR market and concentrated power purchasing may lead to power fluctuation in distribution network, a flexible electricity pricing model is introduced to flatten the peak power demand of the CIES. The simulation results indicate that the pricing model can effectively mitigate the tie-line power fluctuation and over-limit problem.

The remainder of this paper is organized as follows. In Section II, the mechanism and simplified transaction procedure of the FR market are introduced. In Section III, a planning model of CIES participating in the FR market is established. In Section IV, taking a practical demand of an industrial park as the example, numerical results and comparisons demonstrate the effectiveness of the proposed method. Finally, conclusions are drawn in Section V.

II. Modeling of FR Demand

FR service is an important part of the ancillary service market. The main function of FR service is to track the load change, maintain the real-time balance of electric power, and keep the system frequency stable [17]. In the ancillary service market, FR service providers are required to respond to regulation signals rapidly and accurately. Referring to the U.S. Pennsylvania-New Jersey-Maryland (PJM) market, the mechanism and simplified procedure of FR market are presented [18].

In the bidding process, each FR service provider reports the information such as available capacity, response speed, callable time and price [19]. Then the ancillary service provider is selected according to the market rules. For the regional power system of PJM, which covers the power supply of 13 states in the U.S., the required capacity of the FR market is between 500 MW and 800 MW [20]. The CIES as a high-quality FR resource can only provide a small fraction of the total regulation capacity that the market requires. Thus, we assume that the CIES is a price taker that accepts the market clearing prices [21]. Therefore, this work focuses only on determining the reported capacity and assumes that the assigned capacity is equal to the reported capacity. In addition, to avoid excessive fluctuations of tie-line power [22], the CIES specifies the maximum FR capacity. When the CIES participates in FR service, the regulation power is determined by the frequency adjustment signal and usually won't exceed its regulation capacity.

Figure 1 shows a typical FR signal in the PJM market [18]. The signal ranges from −1 to 1, and changes with time. The absolute value of signal represents the ratio of actual required regulation power to the assigned capacity. Positive signal indicates that the system frequency needs to be regulated upwards, while negative signal indicates that the frequency is required to be adjusted downward. RegUp and RegDown capacities are the FR capacities provided by FR service operator. RegUp power is the signal of required power when the grid frequency declines, while RegDown power is the signal of additional power absorbed by FR servicer when the system frequency rises.

The bidding interval is 5 min in PJM market [23]. In a planning problem, we assume that CIES reports the same FR capacity every 5 min in one-hour period [24]. Thus, only the assigned capacity in each hour is required to be optimized. Considering that the FR power is directly determined by the FR signal, the relationship between FR power and FR capacity is formulated as:

$$P_{\tau}^{\mathrm{REG}} = \gamma_{\tau}^{\mathrm{REG}} S_{t}^{\mathrm{REG}} \tag{1}$$

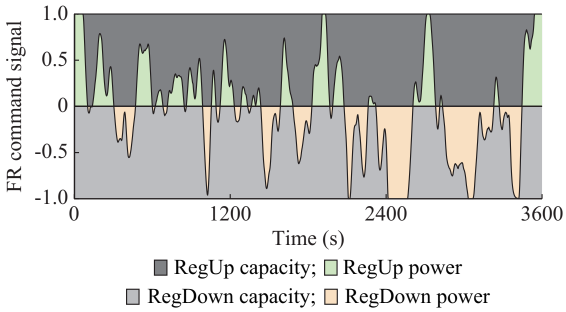

Fig. 1. PJM FR signal.

$$S_t^{\text{REG}} \leq S_{\max}^{\text{REG}} \tag{2}$$

where P_τ^{REG} is the FR power at time τ; γ_τ^{REG} is the value of the FR signal at time τ; S_t^{REG} is the FR capacity at period t; and $S_{\max}^{\text{REG}}$ is the upper limit of the FR capacity.

The other variable to be optimized in FR service is the corresponding electric power adjustment value. To quantify the FR power adjustment, the RegUp efficiency and RegDown efficiency are defined, which represent the fractions of the assigned capacity actually deployed for RegUp and RegDown, respectively, and are calculated as follows:

$$\eta_t^{\text{RU}} = \sum_{\tau=t}^{t+3600} \frac{\gamma_\tau^{\text{RU}}}{3600} \tag{3}$$

$$\eta_t^{\text{RD}} = \sum_{\tau=t}^{t+3600} \frac{\gamma_\tau^{\text{RD}}}{3600} \tag{4}$$

where η_t^{RU} and η_t^{RD} are the RegUp and RegDown efficiencies at period t, respectively; and γ_τ^{RU} and γ_τ^{RD} are the RegUp and RegDown signals, respectively.

In the planning problem, we concentrate on the power consumption related to FR service in each hour, without consideration on the dynamic FR power change in time scale of several seconds. The electric power adjustment at period t corresponding to the FR service can be calculated as follows:

$$\int_t^{t+3600} P_\tau^{\text{REG}} \mathrm{d}\tau = \left(\eta_t^{\text{RD}} - \eta_t^{\text{RU}}\right) S_t^{\text{REG}} \tag{5}$$

In PJM ancillary service market, FR revenue R^{REG} is settled according to the actual contributions of each participant [23]. The payback is based on the capability offered as well as the performance provided in (6). The capacity revenue R^{CAP} is included in (7) and the performance revenue R^{PER} is obtained as (8) indicates.

$$R^{\text{REG}} = R^{\text{CAP}} + R^{\text{PER}} \tag{6}$$

$$R^{\text{CAP}} = \sum_t S_t^{\text{REG}} \lambda_t c_t^{\text{RMCCP}} \tag{7}$$

$$R^{\text{PER}} = \sum_t S_t^{\text{REG}} \lambda_t \beta_t^{\text{M}} c_t^{\text{RMPCP}} \tag{8}$$

where c_t^{RMCCP} and c_t^{RMPCP} are the capacity clearing price and the performance clearing price at period t, respectively; λ_t is the performance score [25] at period t; and β_t^{M} is the PJM mileage ratio of the two signals, Regulation D (RegD) and Regulation A (RegA). Considering that CIES participates in the day-ahead market, the historical data of performance score from the PJM FR market are used as a reference in this paper.

RegD is a fast and dynamic signal that requires the resources to respond nearly instantaneously, such as electric energy storage equipment. RegA is a slower signal for the resources such as a gas turbine. It is used to compensate larger and longer fluctuations in system conditions. For a RegD system, the mileage ratio β_t^{M} is defined as [18]:

$$\beta_t^{\text{M}} = \frac{M^{\text{RegD}}}{M^{\text{RegA}}} \tag{9}$$

where M^{RegD} and M^{RegA} are the mileages of RegD and RegA signals, respectively.

Mileage is defined as the accumulated movement requested by the regulation control signal in a period. For example, the RegD mileage over a one-hour period is defined as [18]:

$$M^{\text{RegD}} = \sum_{\tau=1}^{N} \left| D_\tau - D_{\tau-1} \right| \tag{10}$$

where D_τ is the value of RegD signal at time τ.

Similarly, the RegA mileage is calculated as follows:

$$M^{\text{RegA}} = \sum_{\tau=1}^{N} \left| A_\tau - A_{\tau-1} \right| \tag{11}$$

where A_τ is the value of RegA signal at time τ.

III. Planning Model of CIES

In this section, a planning model of a CIES is established considering its participation in the FR market.

A. Structure of CIES

The structure of CIES is shown in Fig. 2.

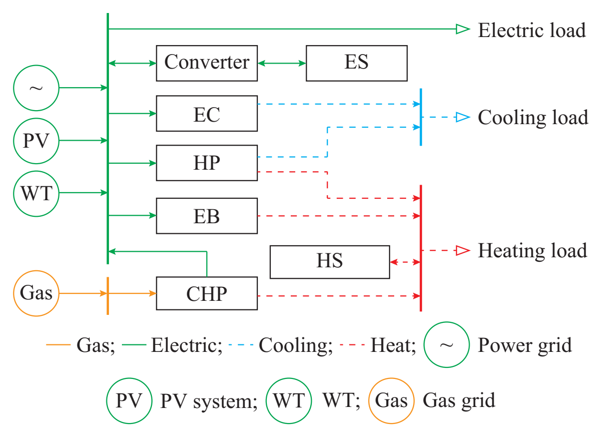

Fig. 2. Structure of CIES with candidate devices.

The loads consist of electric load, cooling load and heating load (includes hot water load and steam load), which cover the general needs of users. For a CIES to be constructed, the main energy resources are electricity, gas and renewable energy. Typical electric energy conversion equipments such as the electric boiler (EB) and electric chiller (EC) are considered to supply the cooling and heating loads. CHP is chosen as the coupling equipment between power and natural gas. Ground source heat pump (HP) transfers the heat from the ground for space heating or cooling, which can effectively reduce annual maintenance costs and carbon emissions. Moreover, DGs such as PV and wind turbine (WT), electrical storage (ES), and heat storage (HS) are considered to achieve better economy and sustainability [26]. The above equipment covers common devices in most CIES scenarios. The above candidate equipment set ensures that all types of energy demands can be satisfied.

B. Flexible Electricity Pricing Model

Time-of-use electricity price is widely adopted in distribution system. It provides an incentive to charge the CIES during off-peak periods in order to achieve the lowest operation cost [27]. But if the charging of CIES is completely driven by wholesale prices, it may lead to serious tie-line power fluctuation and congestion in distribution network [28].

A real-time electricity pricing model is introduced to mitigate the power fluctuation and over-limit at the tie-line [29]-[31]. In the real-time market environment, the loads in different locations are composed of fixed and flexible loads (CIES, electric vehicles, etc.), and the electricity price differs from locations and changes with the total power consumption. Therefore, the price, e.g., locational marginal price (LMP), is influenced by both fixed and flexible loads. When the power demand of CIES has a significant market share, it will influence the wholesale electricity price. The relationship between electricity price and flexible load is as follows:

$$c_t^{\mathrm{E}} = \alpha_t^{\mathrm{E}} + \gamma_t P_t \tag{12}$$

where c_t^{E} is the price of electricity affected by both fixed and flexible loads at period t; α_t^{E} is the basic electricity price at period t; γ_t is the price sensitivity coefficient at period t; and P_t is the flexible load at period t. This approximation allows for using quadratic programming to solve the CIES planning problem, while it includes the feedback of purchased power on the electricity prices. By considering this feedback mechanism, the power demand of CIES will not be supplied in a short time interval at the lowest prices. This paper introduces the flexible electricity pricing model to mitigate the power fluctuation at tie-line. CIES can regulate its power purchase and respond to the distribution network based on market pricing mechanism. When the purchased power does not exceed the limit, the electricity purchase price is equal to the system basic electricity price. When the purchased power exceeds the limit, the electricity purchase price will be exactly relevant to the power demand, which is higher than the system basic electricity price. For the CIES, the electricity price and purchased power can be expressed as follows:

$$c_t^{\mathrm{E}} = \begin{cases} \alpha_t^{\mathrm{E}} & 0 \le P_t^{\mathrm{GRID}} \le P^{\mathrm{LIMIT}} \\ \alpha_t^{\mathrm{E}} + \gamma_t P_t^{\mathrm{GRID}} & P_t^{\mathrm{GRID}} > P^{\mathrm{LIMIT}} \end{cases} \tag{13}$$

where P_t^{GRID} is the purchased power at period t; and P^{LIMIT} is the upper limit of purchased power.

C. Objective Function of CIES Planning

The minimum annual cost C^{COS} is taken as the objective function, which consists of investment cost C^{I}, maintenance cost C^{M}, operation cost C^{O}, and FR revenue R^{REG}.

$$\min C^{\mathrm{COS}} = C^{\mathrm{I}} + C^{\mathrm{M}} + C^{\mathrm{O}} - R^{\mathrm{REG}} \tag{14}$$

1) Investment Cost

$$C^{\mathrm{I}} = \frac{r(1+r)^y}{(1+r)^y - 1} \sum_{i \in \Omega} c_i^{\mathrm{I}} p_i x_i \tag{15}$$

where r is the discount rate; y is the service life; Ω is the set of candidate devices; c_i^{I} is the investment cost of per unit capacity of facility i; p_i is the minimum configuration unit of facility i; and x_i is the amount of p_i which is an integer variable.

2) Maintenance Cost

$$C^{\mathrm{M}} = \sum_{i \in \Omega} \sum_{m,d,t \in D} c_i^{\mathrm{M}} P_{i,m,d,t}^{\mathrm{OUT}} \tag{16}$$

where c_i^{M} is the maintenance cost of per-unit power of facility i; D is the set of typical day data; and $P_{i,m,d,t}^{\mathrm{OUT}}$ is the output power of facility i at period t of day d in month m.

3) Operation Cost

The operation cost C^{O} consists of the electricity purchase cost C^{E} and gas purchase cost C^{F}. The electricity purchase cost related to FR service is included in (18).

$$C^{\mathrm{O}} = C^{\mathrm{E}} + C^{\mathrm{F}} \tag{17}$$

$$C^{\mathrm{E}} = \sum_{m,d,t \in D} c_t^{\mathrm{E}} \left[P_{m,d,t}^{\mathrm{GRID}} + \left(\eta_{m,d,t}^{\mathrm{RD}} - \eta_{m,d,t}^{\mathrm{RU}} \right) S_{m,d,t}^{\mathrm{REG}} \right] \tag{18}$$

$$C^{\mathrm{F}} = c^{\mathrm{F}} \sum_{m,d,t \in D} G_{m,d,t}^{\mathrm{CHP}} q \tag{19}$$

where $P_{m,d,t}^{\mathrm{GRID}}$ is the purchased power of the CIES at period t of day d in month m; $\eta_{m,d,t}^{\mathrm{RD}}$ and $\eta_{m,d,t}^{\mathrm{RU}}$ are the RegUp and RegUp efficiencies, respectively; $S_{m,d,t}^{\mathrm{REG}}$ is the FR capacity; $c_t^{\mathrm{E}}\left(\eta_{m,d,t}^{\mathrm{RD}} - \eta_{m,d,t}^{\mathrm{RU}} \right) S_{m,d,t}^{\mathrm{REG}}$ is the electricity purchase cost of FR service at period t; c^{F} is the gas price at period t; $G_{m,d,t}^{\mathrm{CHP}}$ is the input gas volume of CHP; and q is the calorific value of natural gas.

4) Frequency Regulation Revenue

The FR revenue R^{REG} consists of capacity revenue R^{CAP} and performance revenue R^{PER}. The specific formulas are shown in (1)-(11).

D. Operation Constraints of Candidate Devices

1) Operation Constraints of EB

$$H_t^{\mathrm{EB}} = P_t^{\mathrm{EB}} \eta^{\mathrm{EB}} \tag{20}$$

$$0 \le P_t^{\mathrm{EB}} \le p^{\mathrm{EB}} x^{\mathrm{EB}} \tag{21}$$

where P_t^{EB} and H_t^{EB} are the electric and heating power of the EB at period t, respectively; η^{EB} is the efficiency of the EB; p^{EB} is the minimum planning unit of the EB; and x^{EB} is the amount of p^{EB}.

2) Operation Constraints of EC

$$C_t^{\mathrm{EC}} = P_t^{\mathrm{EC}} \eta^{\mathrm{EC}} \tag{22}$$

$$0 \le P_t^{\mathrm{EC}} \le p^{\mathrm{EC}} x^{\mathrm{EC}} \tag{23}$$

where P_t^{EC} and C_t^{EC} are the electric and cooling power of the EC at period t, respectively; η^{EC} is the coefficient of performance (COP) of the EC; p^{EC} is the minimum planning unit of the EC; and x^{EC} is the amount of p^{EC}.

3) Operation Constraints of CHP

In this planning model, we consider CHP supplies heating and electric power at a fixed ratio.

$$H_t^{\text{CHP}} = G_t^{\text{CHP}} q \eta_{\text{H}}^{\text{CHP}} \tag{24}$$

$$P_t^{\text{CHP}} = G_t^{\text{CHP}} q \eta_{\text{P}}^{\text{CHP}} \tag{25}$$

$$0 \le G_t^{\text{CHP}} q \le p^{\text{CHP}} x^{\text{CHP}} \tag{26}$$

where H_t^{CHP} and P_t^{CHP} are the heating and electric power of CHP at period t, respectively; G_t^{CHP} is the input gas volume of CHP at period t; $\eta_{\text{H}}^{\text{CHP}}$ and $\eta_{\text{P}}^{\text{CHP}}$ are the efficiencies of heating and electricity of CHP, respectively; p^{CHP} is the minimum planning unit of CHP; and x^{CHP} is the amount of p^{CHP}.

4) Operation Constraints of HP

Unlike CHP, the HP can only produce either heating or cooling power in a given time interval. This paper assumes that the HP supplies cooling power in summer and heating power in winter.

$$H_t^{\text{HP}} = P_t^{\text{HP}} \eta_{\text{H}}^{\text{HP}} \tag{27}$$

$$C_t^{\text{HP}} = P_t^{\text{HP}} \eta_{\text{C}}^{\text{HP}} \tag{28}$$

$$0 \le P_t^{\text{HP}} \le p^{\text{HP}} x^{\text{HP}} \tag{29}$$

where H_t^{HP} and C_t^{HP} are the heating and cooling power of the HP at period t, respectively; P_t^{HP} is the electric power of the HP at period t; $\eta_{\text{H}}^{\text{HP}}$ and $\eta_{\text{C}}^{\text{HP}}$ are the COPs of heating and cooling of HP, respectively; p^{HP} is the minimum planning unit of HP; and x^{HP} is the amount of p^{HP}.

5) Operation Constraints of HS

$$E_t^{\text{HS}} = E_{t-1}^{\text{HS}}\left(1-\eta^{\text{HS}}\right) + \left(H_{\text{CH},t}^{\text{HS}} \eta_{\text{CH}}^{\text{HS}} - \frac{H_{\text{DIS},t}^{\text{HS}}}{\eta_{\text{DIS}}^{\text{HS}}}\right)\Delta t \tag{30}$$

$$E_0^{\text{HS}} = E_T^{\text{HS}} \tag{31}$$

$$0 \le E_t^{\text{HS}} \le p^{\text{HS}} x^{\text{HS}} \tag{32}$$

where E_t^{HS} is the heat energy stored in HS at period t; T is the number of periods in one planning cycle; η^{HS} is the heat loss coefficient of HS; $H_{\text{CH},t}^{\text{HS}}$ and $H_{\text{DIS},t}^{\text{HS}}$ are the charging and discharging power of HS at period t, respectively; $\eta_{\text{CH}}^{\text{HS}}$ and $\eta_{\text{DIS}}^{\text{HS}}$ are the charging and discharging efficiencies of HS, respectively; Δt is the time interval; p^{HS} is the minimum planning unit of HS; and x^{HS} is the amount of p^{HS}.

6) Operation Constraints of ES

To ensure the long life-time of ES, the upper and lower limits of state of charge (SOC) are used to constrain the ES from being fully charged or discharged [32]. Considering that the CIES participates in the FR market, the fast response characteristics are derived from ES. The electricity quantity of FR is added to the model. Equation (33) shows that the electricity corresponding to the FR service is charged/discharged by the ES.

$$E_{t+1}^{\text{ES}} = E_t^{\text{ES}}\left(1-\eta^{\text{ES}}\right) + \left(P_{\text{CH},t}^{\text{ES}} \eta_{\text{CH}}^{\text{ES}} - \frac{P_{\text{DIS},t}^{\text{ES}}}{\eta_{\text{DIS}}^{\text{ES}}}\right)\Delta t + \left(\eta_t^{\text{RD}} \eta_{\text{CH}}^{\text{ES}} - \frac{\eta_t^{\text{RU}}}{\eta_{\text{DIS}}^{\text{ES}}}\right) S_t^{\text{REG}} \tag{33}$$

$$E_0^{\text{ES}} = E_T^{\text{ES}} \tag{34}$$

$$0 \le E_t^{\text{ES}} \le p^{\text{ES}} x^{\text{ES}} \tag{35}$$

$$SOC_{\min} \le SOC_t \le SOC_{\max} \tag{36}$$

$$0 \le P_{\text{CH},t}^{\text{ES}} \le z_{\text{CH}}^{\text{ES}} \bar{P}_{\text{CH}}^{\text{ES}} \tag{37}$$

$$0 \le P_{\text{DIS},t}^{\text{ES}} \le z_{\text{DIS}}^{\text{ES}} \bar{P}_{\text{DIS}}^{\text{ES}} \tag{38}$$

$$0 \le z_{\text{CH}}^{\text{ES}} + z_{\text{DIS}}^{\text{ES}} \le 1 \tag{39}$$

where E_t^{ES} is the electricity stored in ES at period t; η^{ES} is the heat loss coefficient of ES; $P_{\text{CH},t}^{\text{ES}}$ and $P_{\text{DIS},t}^{\text{ES}}$ are the charging and discharging power at period t, respectively; $\eta_{\text{CH}}^{\text{ES}}$ and $\eta_{\text{DIS}}^{\text{ES}}$ are the charging and discharging efficiencies of ES, respectively; p^{ES} is the minimum planning unit of ES; x^{ES} is the amount of p^{ES}; SOC_t is the SOC of ES at period t; $SOC_{\min}$ and $SOC_{\max}$ are the lower and upper limit of SOC, respectively; $\bar{P}_{\text{CH}}^{\text{ES}}$ and $\bar{P}_{\text{DIS}}^{\text{ES}}$ are the upper limits of charging and discharging power, respectively; and $z_{\text{CH}}^{\text{ES}}$ and $z_{\text{DIS}}^{\text{ES}}$ are Boolean variables of charging and discharging modes, respectively.

7) Operation Constraints of Converter

When the ES is charged or discharged, the energy conversion is realized through the converter. The capacity of the converter should be larger than the charging/discharging power and the FR capacity.

$$0 \le P_{\text{CH},t}^{\text{ES}} + S_t^{\text{REG}} \le p^{\text{CON}} x^{\text{CON}} \tag{40}$$

$$0 \le P_{\text{DIS},t}^{\text{ES}} + S_t^{\text{REG}} \le p^{\text{CON}} x^{\text{CON}} \tag{41}$$

where p^{CON} is the minimum planning unit of converter; and x^{CON} is the amount of p^{CON}.

8) Operation Constraints of PV

The electric power of PV depends on many factors such as solar irradiance and temperature. However, to reduce the complexity, the electric power of PV is regarded to be directly determined by the capacity and the solar irradiance [33].

$$P_t^{\text{PV}} = \begin{cases} \dfrac{I_t}{I^{\text{R}}} p^{\text{PV}} x^{\text{PV}} & 0 \le I_t < I^{\text{R}} \\ p^{\text{PV}} x^{\text{PV}} & I^{\text{R}} \le I_t \end{cases} \tag{42}$$

where I_t is the solar irradiance at period t; I^{R} is the standard solar irradiance; p^{PV} is the minimum planning unit of PV; and x^{PV} is the amount of p^{PV}.

9) Operation Constraints of WT

The electric power of WT is directly determined by the capacity and the wind speed.

$$P_t^{\text{WT}} = \begin{cases} 0 & v_t < v^{\text{in}} \text{ or } v_t \ge v^{\text{out}} \\ p^{\text{WT}} x^{\text{WT}} \dfrac{v_t - v^{\text{in}}}{v^{\text{r}} - v^{\text{in}}} & v^{\text{in}} \le v_t < v^{\text{r}} \\ p^{\text{WT}} x^{\text{WT}} & v^{\text{r}} \le v_t < v^{\text{out}} \end{cases} \tag{43}$$

where v_t is the wind speed at period t; v^{in}, v^{r} and v^{out} are the cut-in, rated and cut-off wind speeds, respectively; p^{WT} is the minimum planning unit of WT; and x^{WT} is the amount of p^{WT}.

10) Operation Constraints of FR

Equation (2) is the upper limit of the FR capacity. Considering the tie-line power limitation, FR capacity is also limited by the current tie-line power. The FR capacity constraint is as follows:

$$S_t^{\text{REG}} \le (1-z) S_{\max}^{\text{REG}} \tag{44}$$

$$z = \begin{cases} 1 & P_t^{\text{GRID}} > P^{\text{LIMIT}} \\ 0 & P_t^{\text{GRID}} \le P^{\text{LIMIT}} \end{cases} \tag{45}$$

where z is a decision variable. When $z = 1$, the purchased power exceeds the limit, and CIES cannot provide FR service. In the optimization model, (45) indicates whether the purchased power exceeds the limit.

11) Operation Constraints of Tie-line

For the planning of the CIES, it is generally considered that the electric, heating, and cooling loads remain constant in one-hour period. Thus, the tie-line power is also considered to be a constant value. However, while participating in the FR service, the CIES is required to provide power that can track the rapid change of the FR signal. Therefore, the tie-line power can be divided into two parts: the constant purchased power and the dynamic FR power.

$$P_\tau^{\mathrm{TL}} = P_t^{\mathrm{GRID}} + P_\tau^{\mathrm{REG}} \tag{46}$$

where P_τ^{TL} is the tie-line power at period t; and P_τ^{REG} is the FR power at time τ.

The FR power P_τ^{REG} is not larger than the FR capacity S_t^{REG}, so the maximum power of the tie-line is as follows:

$$P_t^{\mathrm{TL,MAX}} = S_t^{\mathrm{REG}} + P_t^{\mathrm{GRID}} \tag{47}$$

$$P_t^{\mathrm{TL,MAX}} \le (1-z)\,P^{\mathrm{LIMIT}} + zP^{\mathrm{MAX}} \tag{48}$$

where $P_t^{\mathrm{TL,MAX}}$ is the upper limit of the tie-line power; and P^{MAX} is the maximum power transfer limit of the tie-line. Equation (48) gives the constraint of the tie-line power under two opposite conditions: the purchased power exceeds the limit or does not reach it.

12) Power Balance Constraints

1) Electric load balance

$$P_t^{\mathrm{LD}} = P_t^{\mathrm{GRID}} + P_t^{\mathrm{CHP}} + P_{\mathrm{DIS},t}^{\mathrm{ES}} + P_t^{\mathrm{PV}} + P_t^{\mathrm{WT}} - P_t^{\mathrm{EB}} - P_t^{\mathrm{EC}} - P_t^{\mathrm{HP}} - P_{\mathrm{CH},t}^{\mathrm{ES}} \tag{49}$$

where P_t^{LD} is the electric load at period t.

2) Heating load balance

$$H_t^{\mathrm{LD}} = H_t^{\mathrm{EB}} + H_t^{\mathrm{CHP}} + H_t^{\mathrm{HP}} + H_{\mathrm{DIS},t}^{\mathrm{HS}} - H_{\mathrm{CH},t}^{\mathrm{HS}} \tag{50}$$

where H_t^{LD} is the heating load at period t.

3) Cooling load balance

$$C_t^{\mathrm{LD}} = C_t^{\mathrm{EC}} + C_t^{\mathrm{HP}} \tag{51}$$

where C_t^{LD} is the cooling load at period t.

The decision variables mainly include amounts of equipment planning unit, FR capacity, purchased power, gas volume purchased at period t, output power of each equipment, SOC, and charging and discharging modes of ES. The planning model of the CIES can be described as follows:

$$\begin{cases} \min C^{\mathrm{COS}} \\ \text{s.t. } (1)\text{-}(5), (20)\text{-}(51) \end{cases} \tag{52}$$

Formulae (1)-(5) and (44)-(45) are the FR constraints; (20)-(43) are the operational constraints of equipment; (46)-(48) are the tie-line power constraints; and (49)-(51) are the power balance constraints.

IV. Case Study and Analysis

In this paper, a practical demand of an industrial park [7] is chosen to demonstrate the proposed model. To reduce the computation and obtain a higher solution efficiency, the data of typical days (2 days in each month, 24 days in total) rather than a whole year are selected. Figures 3 and 4 show typical daily loads in June and November, respectively. The upper limit of the purchased power is 4 MW. The upper limit of the FR capacity is set to be 2 MW to reduce the impact of FR service on distribution network operation, and the parameters of the equipment and the price of electricity and natural gas [33], [11] are listed in Tables I and II.

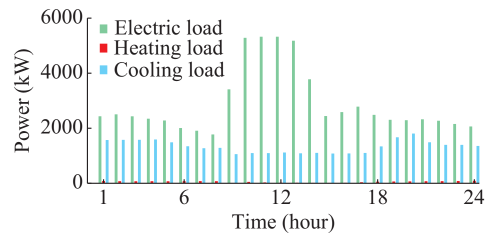

Fig. 3. Typical daily load in June.

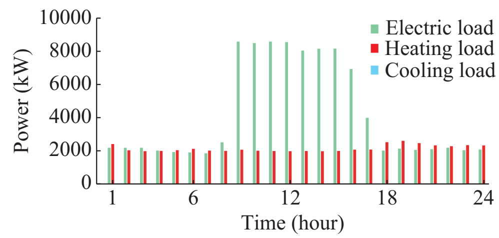

Fig. 4. Typical daily load in November.

TABLE I
PLANNING PARAMETERS OF CANDIDATE DEVICES [11], [33]

Equipment	Parameter	Value
EB	Investment cost	1000 CNY/kW
	Maintenance cost	0.03 CNY/kWh
	Efficiency	0.95
EC	Initial investment	1500 CNY/kW
	Maintenance cost	0.02 CNY/kWh
	COP	4
CHP	Initial investment	7900 CNY/kW
	Maintenance cost	0.015 CNY/kWh
	Gas-heat efficiency	0.45
	Gas-electricity efficiency	0.3
HP	Initial investment	7000 CNY/kW
	Maintenance cost	0.015 CNY/kWh
	COP of heating/cooling	4.5/5.8
HS	Initial investment	500 CNY/kWh
	Maintenance cost	0.03 CNY/kWh
	Coefficient of heat loss	0.01
	Efficiency of charging	0.9
	Efficiency of discharging	0.9
ES	Initial investment	2000 CNY/kWh
	Maintenance cost	0.03 CNY/kWh
	Coefficient of power loss	0.01
	Charging efficiency	0.95
	Discharging efficiency	0.95
	Maximum SOC	0.9
	Minimum SOC	0.1
Converter	Initial investment	300 CNY/kW
PV	Initial investment	7500 CNY/kW
	Maintenance cost	0.02 CNY/kWh
WT	Initial investment	7500 CNY/kW
	Maintenance cost	0.02 CNY/kWh

TABLE II
COMMON PLANNING AND OPERATION PARAMETERS OF CIES [11]

Parameter	Value
Service life of equipment	20 years
Minimum capacity of planning unit	100 kVA
Discount rate	0.04
Electricity valley price Electricity average price Electricity peak price	0.4744 CNY/kWh 0.8999 CNY/kWh 1.3454 CNY/kWh
Gas price	3 CNY/m^3
Price sensitive	10^{-4} CNY/kWh

The proposed planning model belongs to mixed-integer quadratic programming (MIQP) model. The model is implemented in the OPTI optimization toolbox using MATLAB R2016a and solved by IBM ILOG CPLEX 12.6 [34].

A. Planning Result Analysis

To analyze the influence of FR service and the flexible electricity pricing model on the planning results, three scenarios are selected and shown as follows.

Scenario 1: the CIES does not participate in the FR market, and the flexible electricity pricing model and tie-line constraints are not considered.

Scenario 2: the CIES participates in the FR market, but the flexible electricity pricing model and tie-line constraints are not considered.

Scenario 3: the CIES participates in the FR market, and the flexible electricity pricing model and tie-line constraints are both considered.

The optimal configurations in the three scenarios are shown in Table III. The CHP capacity optimization result is 0, indicating that although CHP can cover part of the electric load, but its current investment price and efficiency are not economic in the CIES system. The total capacity of installed DGs is greater than the electric load in most periods, which means that CIES has a high self-sufficient rate.

TABLE III
PLANNING RESULTS OF THREE SCENARIOS

Scenario	Power (kW)							Capacity (kWh)	
	EB	EC	CHP	HP	Converter	PV	WT	ES	HS
Scenario 1	1100	100	0	600	4400	3500	6200	10500	7500
Scenario 2	1100	100	0	600	5900	3400	6200	10300	7800
Scenario 3	1500	100	0	600	4500	3800	6400	9600	10000

Comparing Scenarios 1 and 2, since the CIES in Scenario 2 provides FR service, the power exchanged between the ES and the electric bus increases, so the capacity of the converter increases from 4400 kW to 5900 kW. However, the electric power adjustment values of charging and discharging corresponding to the FR service are almost balanced in each time period, so nearly no additional ES capacity is needed.

It can be observed that ES capacity in Scenario 3 is reduced by 700 kWh compared with Scenario 2, which proves that the power purchase congestion problem has been mitigated due to the introduction of flexible electricity pricing model. Meanwhile, the capacity of converter is reduced by 1400 kW, indicating that the maximum value of charging/discharging decreases and the FR capacity of the CIES is reduced compared with Scenario 2. Because of the input electric power limitation of EB and HP, HS is required to supply more heating power, so its capacity increases by 2200 kWh. In addition, the capacities of PV and WT increase by 400 kW and 200 kW, respectively, indicating that CIES can accommodate higher DG penetration.

In Table IV, the optimization results including the annual cost and consumption of electricity and gas are presented to analyze the economic impact of CIES participation in the FR market and the flexible electricity pricing model. In Scenario 1, in the economic operation mode, the CIES obtains the optimal configuration on the premise of the lowest annual cost and system operation constraints through reasonable planning.

TABLE IV
OPTIMIZATION RESULTS OF THREE SCENARIOS

Scenario	Annual cost (10^4 CNY)	Investment cost (10^4 CNY)	Maintenance cost (10^4 CNY)	Operation cost (10^4 CNY)	FR revenue (10^4 CNY)	Electricity (10^4 kWh)	Gas (10^4 m^3)
Scenario 1	1304.36	755.06	84.96	464.34		700.23	0
Scenario 2	637.30	750.46	85.07	372.54	570.77	684.41	0
Scenario 3	697.83	777.76	88.01	372.88	540.82	651.88	0

It is obvious that CIES participation in the FR market can effectively reduce the annual cost. Through CIES participation in the ancillary service market, additional revenue is obtained while other costs change very little.

The annual cost increases by 605300 CNY in Scenario 3 with an increase of 9.50% compared with the optimization result of Scenario 2. Due to the influence of the flexible electricity pricing model, additional capacities of DGs and

HS are required, so the investment cost increases by 273000 CNY. Considering that less electricity is purchased when the loads are at the valley periods, the electricity consumption is reduced by 325300 kWh. In addition, as the tie-line constraints are considered, when the purchased power reaches the limit, the CIES cannot provide FR service, so the FR revenue decreases by 295500 CNY.

B. Trading Power Analysis

In Scenario 1, due to the time-of-use electricity price, the CIES concentrates on purchasing electricity when the prices are low through ES and stops purchasing electricity when the loads are at the peak periods.

In Scenario 2, because the CIES provides the FR service, the tie-line power is a combination of the purchased power and FR power. The power fluctuation and over-limit conditions are not alleviated. In contrast, the maximum tie-line power further increases. Thus, the flexible electricity pricing model is introduced in Scenario 3 to mitigate the tie-line power fluctuation and prevent the purchased power from exceeding the limit. A comparison of the optimal operation strategies between Scenarios 2 and 3 is presented in Fig. 5 to illustrate the impact of the flexible electricity pricing model.

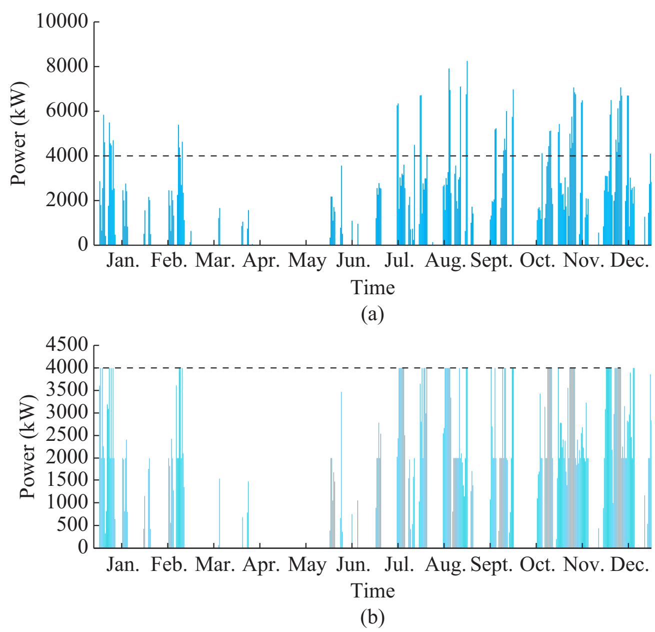

Fig. 5. Annual purchased power in Scenarios 2 and 3. (a) Scenario 2. (b) Scenario 3.

The introduction of DGs results in reduced electricity purchase. The power of the DGs can cover the electric load when the demand is low. However, when the load demands are high or the electricity prices are low, the purchased power in Scenario 2 exceeds the limit, while in Scenario 3 CIES can adjust the power purchasing strategy and energy storage operation mode so that the purchased power reaches but does not exceed the limit. The comparison suggests that the flexible electricity pricing model adopted in this paper can effectively mitigate the tie-line power fluctuation and prevent the power from exceeding the limit.

The rates of the purchased power exceeding the limit in Scenarios 2 and 3 are shown in Table V.

TABLE V
PROBABILITY OF EXCEEDING LIMIT

Scenario	Probability (%)
Scenario 2	9.55
Scenario 3	0

The power purchasing strategies of the CIES on the typical day in June are compared in Fig. 6(a), suggesting that due to the low electricity demand and the high COPs of the HP, the purchased power of the CIES does not exceed the limit. Therefore, the purchased power in the two scenarios is basically the same.

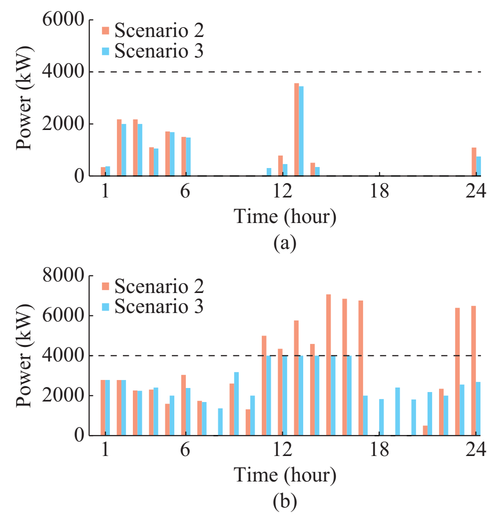

Fig. 6. Comparison of purchased power on typical days in June and November. (a) June. (b) November.

In Fig. 6(b), the purchased power is over the limit due to the peak load in periods of the 11th-17th hours. In periods of the 23rd-24th hours, the incentive of the lowest electricity price causes CIES fully purchased electricity, which leads to very high peaks. As the flexible electricity pricing model is applied in Scenario 3, CIES adjusts the power purchasing strategy to avoid the over-limit problem, which will increase the operation cost.

Based on the previous power purchase plan in Fig. 6(b), if the flexible electricity pricing model is implemented in Scenario 2, additional operation costs are required at some periods. The electricity price in Scenario 3 is equal to the system basic price. The comparison of the electricity prices in Scenarios 2 and 3 is shown in Fig. 7.

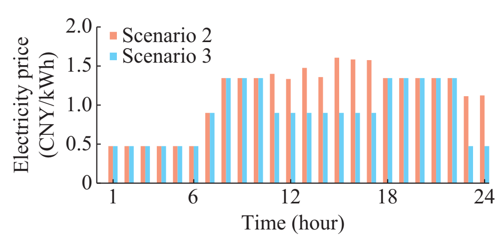

Fig. 7. Comparison of electricity prices in Scenarios 2 and 3.

Since the CIES also provides FR service, the instantaneous tie-line power is equal to the sum of the purchased power and the real-time FR power. When the CIES provides the RegDown service (absorbing the excess power), the tie-line power may exceed the limit while the purchased power does not exceed the limit. These short-duration peaks will affect the secure operation of the distribution network. Figure 8 shows the maximum tie-line power values of the two scenarios on the typical day in June. In Scenario 2, the purchased power is not over limited. But in periods of the 2nd, 3rd, and 13th hours, the FR service is provided, so the tie-line power exceeds the limit. However, when considering the tie-line constraints, both the purchased power and the tie-line power do not exceed the limit.

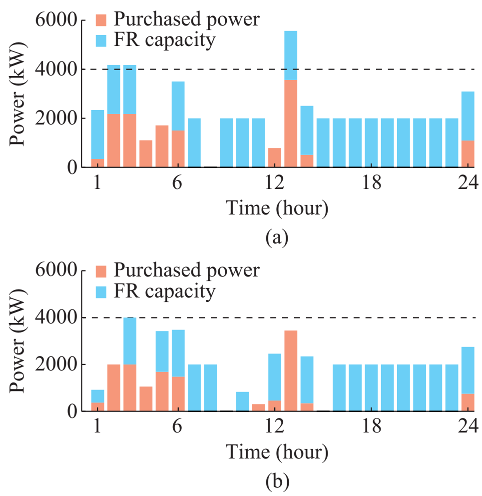

Fig. 8. Maximum tie-line power in Scenarios 2 and 3 in June. (a) Scenario 2. (b) Scenario 3.

The maximum tie-line power of the typical day in November is compared in Fig. 9.

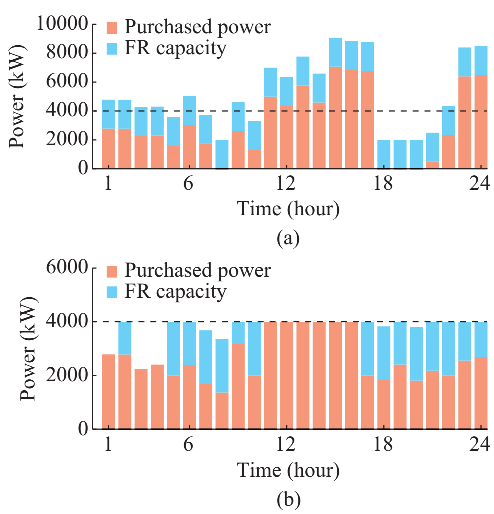

Fig. 9. Maximum tie-line power in Scenarios 2 and 3 in November. (a) Scenario 2. (b) Scenario 3.

Due to the large heating and electricity loads of CIES, the purchased power is at the peak in periods of the 11th-17th and 23rd-24th hours, as shown in Fig. 9(a). In Scenario 3, the increase in the capacities of the DGs and the adjustment of operation mode of ES ease the over-limit problem of both purchasing and tie-line power. The peak demand reaches but does not exceed the limit in periods of the 11th-17th hours, when CIES does not provide FR service during these time periods to avoid exceeding the limit.

V. Conclusion

This paper proposes an optimal planning model of CIES considering FR service. After modeling the FR service, an optimal planning model of CIES considering FR service is established to optimize the type and capacity of candidate devices. With the minimum annual comprehensive cost as the objective function, it is considered that the CIES can participate in the FR market to obtain revenue. The flexible electricity pricing model is introduced to mitigate the power fluctuation problem of tie-line. Using practical demand of an industrial park, case study is conducted to verify the effectiveness of the proposed model. The result shows that the participation in FR service can provide fast-response regulation capacity as well as effectively reduce the annual cost of CIES. Additionally, the feedback mechanism of electricity price can also mitigate the power fluctuation of tie-line and prevent power over-limit. In the further work, several notable issues are worth studying. The siting of CIES can be considered in the planning model, which will affect the configuration of device and trading strategy. In FR market, it can be investigated that slow-response equipment in CIES participates in the traditional regulation market.

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