Capacity Allocation of Hybrid Power System with Hot Dry Rock Geothermal Energy, Thermal Storage, and PV Based on Game Approaches

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***Abstract*—This study utilizes hot dry rock (HDR) geothermal energy, which is not affected by climate, to address the capacity allocation of photovoltaic (PV)-storage hybrid power systems (HPSs) in frigid plateau regions. The study replaces the conventional electrochemical energy storage system with a stable HDR plant assisted by a flexible thermal storage (TS) plant. An HPS consisting of an HDR plant, a TS plant, and a PV plant is proposed. Game approaches are introduced to establish the game pattern model of the proposed HPS as the players. The annualized income of each player is used as the payoff function. Furthermore, non-cooperative game and cooperative game approaches for capacity allocation are proposed according to the interests of each player in the proposed HPS. Finally, the proposed model and approaches are validated by performing calculations for an HPS in the Gonghe Basin, Qinghai, China as a case study. The results show that in the proposed non-cooperative game approach, the players focus only on the individual payoff and neglect the overall system optimality. The proposed cooperative game approach for capacity allocation improves the flexibility of the HPS as well as the payoff of each game player. Thereby, the HPS can better satisfy the power fluctuation rate requirements of the grid and increase the equivalent firm capacity (EFC) of PV plants, which in turn indirectly guarantees the reliability of grid operation.**

***Index Terms*—Capacity allocation, equivalent firm capacity, game theory, hot dry rock, hybrid power system.**

I. INTRODUCTION

WITH the concept of clean energy utilization gaining acceptance worldwide, the clean energy industry represented by photovoltaic (PV) power systems has developed rapidly [1]. The proportion of installed capacity of PV plants in the power grid has been increasing. Simultaneously, considering the need to fulfill stringent environmental protection and carbon emission reduction, the proportion of non-renewable energy generators decreases [2]. The reliable connection of PV power systems to the power grid has become an urgent problem for further developing large-scale PV plants in various countries.

The reliable grid connection of PV plants has gained the attention of scholars worldwide. There have been a few studies on the optimal access capacity of renewable power sources from the perspective of passive grid consumption [3]. Theories such as effective load carrying capacity (ELCC) [4] and equivalent firm capacity (EFC) have been conceptualized [5]. In [6], EFC theory was applied to the capacity assessment of an urban virtual energy storage system of the electric vehicle, and a method for assessing the equivalent energy storage capacity of a grid-connected parking lot was proposed. Taking EFC as an index, a calculation method of market capacity value oriented to large-scale investment dispatching was proposed in [7], and the contribution of wind plant capacity to power supply security was discussed.

There have also been studies on the critical role of PV-storage hybrid power systems (HPSs) in enhancing the reliable connection of PV plants from the perspective of the active configuration of energy storage systems [8]. At present, PV-storage HPSs have become a vital research field for the reliabile connection of PV plants. These HPSs constitute an essential means to achieve multi-energy complementation and improve the reliability and economics of PV plants. In [9], a bi-level capacity allocation method was proposed for the HPS composed of wind, PV, and battery systems to maximize the annual income and return on investment. Furthermore, an adaptive distributionally robust method for residential PV-battery HPSs was established in [10], optimizing the system capacity while minimizing the operation cost.

However, the performance of the electrochemical energy storage system (EESS) such as cycle life and system self-

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consumption of electricity is substantially affected by environmental factors, which hinders its large-scale application in frigid plateau regions. Owing to climatic characteristics of severe cold and significant temperature differences, the present EESSs cannot effectively satisfy the demand for further development of the PV power industry in these regions. As a result, the power systems with high proportion of renewable power plants in plateau regions are deprived of reliable power supply [11]. Therefore, new techology routes are required urgently to improve the grid-connection reliability of large-scale PV plants.

Compared with battery systems, high-quality hot dry rock (HDR) geothermal energy resources [12], which are not affected by environmental and climatic factors, show substantial potential for replacing EESSs. The advantages include stable underground thermal reservoirs, long heat mining cycle life, and large annual utilization hours [13]. It can be seen that HDR geothermal energy resources provide a new technological approach to constituting a PV-storage HPS and improving the grid-connection reliability of PV plants. In [13], a thermal cycle for comprehensive utilization of HDR geothermal energy was addressed. In [14], a multi-energy cogeneration enhanced geothermal system was proposed. In [15], an HPS composed of a heat storage power station with HDR power station was further proposed and the cooperative game (CG) dispatching model was addressed.

The above literature shows that the capacity allocation problem is a hot topic in the research of HPSs, which is an optimization problem to obtain the optimal value of capacity allocation of HPSs considering the grid parameters and the characteristics of each plant, so as to achieve the best matching between the plants and resources. The existing research on the capacity allocation of PV-storage HPSs mainly adopts the multi-objective optimization method to solve the capacity allocation model. However, this method does not adequately explain the interaction mechanism among multiple energy subjects and cannot reveal the inherent physical significance of the capacity allocation results. Therefore, a few scholars extensively explored the capacity allocation of HPSs from game theory among multiple energy subjects [16]. In [17], a general framework for power system flexibility analysis was proposed based on CG theory for risk design and energy policy design. In [18], the CG theory was used to solve the conflict problem among multiple wind/solar/hydro stakeholders and the application of kernel and Shapley value in solving the payoff allocation problem was discussed. In [19], a multi-agent capacity optimization method based on the CG theory was proposed to analyze the benefit interactions among independent operators in decision-making processes. The results showed that the complete CG model yielded better economic performance for the whole and individuals.

In conclusion, the existing research on the capacity allocation of HPSs is based mainly on HPSs comprising PV and EESS, and has not been carried out on the capacity allocation of HPSs containing HDR plants and PV plants. HDR is different from other forms of energy storage due to its stable and continuous physical characteristics. Game theory approaches can fully reflect the physical characteristics of each player in the HPS, effectively reveal the mechanism of interaction, and clarify the physical and practical significance of the capacity allocation. This paper intends to adopt the game theory approaches to analyze the capacity allocation of the HPS with HDR geothermal energy, thermal storage (TS), and PV, and explore the competitive and cooperative relationship between the stable geothermal from the HDR plant and the fluctuating power from the PV plant.

In our previous research [15], we applied game theory to analyze the dispatching of the HPS with HDR geothermal energy, TS, and PV in specific scenarios. The capacity of each player is based on the local renewable energy capacity matching policy, which is not guaranteed to be optimal. As a follow-up of [15], the main contribution of this paper is as follows: ① establish a more detailed structure between the HDR plant and TS plant, and improve the heat exchange and electrothermal conversion models; ② from the perspective of investors, the optimal capacity allocation models of the HPS are obtained considering the annual investment cost and average annual operation cost; ③ the non-cooperative cooperative game (NCG) and CG approaches for capacity allocation with the minimum annual cost as the payoff are established by taking the installed capacity as the strategy sets; ④ the influence of grid parameters and electricity price policy on the investment strategy is analyzed in detail by using a case study constructed by actual weather condition scenario and the policy boundaries of investing in the HPS are obtained, guiding the investors in future.

II. COMPOSITION OF HPS AND CHARACTERISTICS OF HDR PLANT

A. Architecture of HPS

The HPS proposed in this paper consists of an HDR plant, a TS plant, a PV plant, and a substation [15], as shown in Fig. 1, where Q_{cur}^{t} is the curtailed heat power; Q_{β}^{t} is the geothermal power input to exchanger; Q_{dc}^{t} is the exothermic power; Q_{ec}^{t} is the electric heating power; Q_{hc}^{t} is the geothermal power; P_{G}^{t} is the electrical power purchased from the grid; P_{T}^{t} is the output power of the TS plant; P_{P}^{t} is the output power of the PV plant; and P_{H}^{t} is the output power of the HDR plant. The HDR plant includes the geothermal mining cycle (GMC) and the organic Rankine cycle (ORC) generators. The brines are used as the working fluid of the GMC.

The HDR plant has a very high annual utilization and can guarantee continuous and steady output power, because it is unaffected by climate conditions. However, the flexibility of conventional HDR plants is insufficient to fully utilize the large thermal reservoirs to provide reserves for PV plants due to the long dynamic response time of GMC [20]. Therefore, there is a need to build TS plants that coordinate with HDR plants, thereby improving the operational flexibility. The TS plant consists of an exchanger, two thermal energy storage tanks (TESTs), an ORC generator, and an electric heater that uses heat transfer oil (HTO) as the working fluid. The exchanger can be used to store the heat discarded from the HDR plant. The electric heater can convert the surplus PV power into stored thermal energy. The TS plant is not affected by the climatic environment, thereby overcoming the disadvantages of EESSs. Therefore, the TS plant is highly suitable to combine an HDR plant to form an HPS.

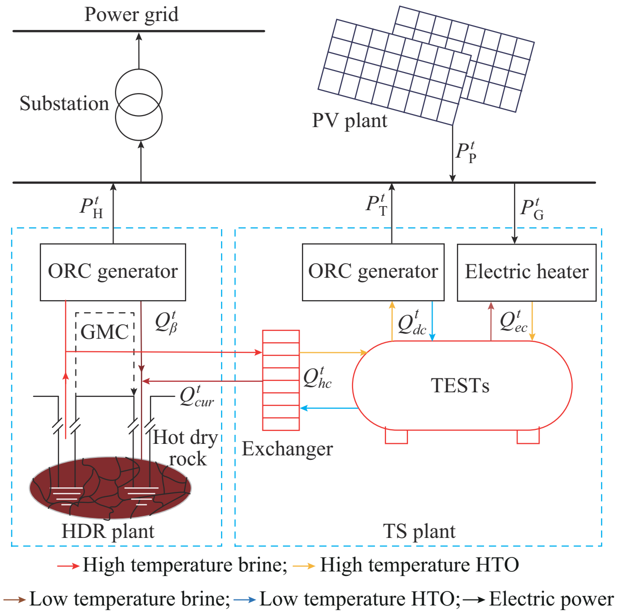

Fig. 1. Architecture of proposed HPS.

B. Output Characteristics of HDR Plants

Owing to the continuous characteristic of the GMC, the ORC generator of a conventional HDR plant must maintain continuous power output to prevent residual heat loss. By contrast, under the architecture shown in Fig. 1, part of the geothermal energy generated by the GMC can be stored in the TESTs of the TS plant. Therefore, without losing geothermal energy, the HDR plant can completely utilize the fast regulation speed and wide working conditions of the ORC generator to flexibly provide reserve service for the power grid. The continuous output model and flexible output model of the HDR plant [21] are expressed as:

$$P_{hc}^t = \eta_P m_r^t c_{pr} (T_{HDR} - T_{well}^t) \tag{1}$$

$$m_\alpha^t + m_\beta^t = m_r^t \tag{2}$$

$$Q_\beta^t = m_\beta^t c_{pr} (T_{HDR} - T_\beta^t) \tag{3}$$

$$P_{hf}^t = \eta_P m_\alpha^t c_{pr} (T_{HDR} - T_{well}^t) \tag{4}$$

where t denotes the current moment; P_{hc}^t is the output power of the conventional HDR plant; m_r^t is the mass flow rate of brine; c_{pr} is the specific heat capacity of brine; η_P is the efficiency of the ORC generator; T_{HDR} is the outlet temperature of HDR production wells; T_{well}^t is the reinjection temperature; m_α^t and m_β^t are the mass flow rates of brine used for power generation and thermal energy storage, respectively; Q_β^t is the geothermal input to the exchanger; T_β^t is the residual heat temperature of the brine after heat exchange; and P_{hf}^t is the output power of the flexible HDR plant.

Equation (1) represents the continuous output model of the HDR plant. Equations (2)-(4) represent the flexible model of the HDR plant. Generally, ORC generators have the ability to make full use of the input brine for generation by controlling the mass flow. Therefore, in this paper, it is assumed that the geothermal energy allocated to ORC generators can be fully utilized, i.e., $T_{well}^t = T_{well}^{\min}$, where $T_{well}^{\min}$ is the minimum reinjection temperature to maintain a stable HDR reservoir.

III. GAME PATTERN FOR CAPACITY ALLOCATION OF HPS

Compared with conventional multi-objective optimization methods, game theory can further reveal the relationships between allocation outcomes through the studies of competition and cooperation among rational decision-makers [22]. The players, strategy, and payoff function are the fundamental elements that constitute a game pattern, which are described separately in this section.

A. Elements of Gaming

1) Players

The HDR, TS, and PV plants (denoted by H, T, and P, respectively) are the three players.

2) Strategy

The strategies of players are their installed capacity values, which are denoted as P_{H}, P_{T}, and P_{P}, respectively. Ω_{H}, Ω_{T}, and Ω_{P} represent the strategy sets corresponding to each player. $P_i^{\max}$ and $P_i^{\min}$ $(i \in \{\mathrm{H}, \mathrm{T}, \mathrm{P}\})$ are the upper and lower limits of installed capacity, respectively. Subject to environmental, technological, and policy factors, the strategy spaces of the players are denoted as: $P_{\mathrm{H}} \in \{\Omega_{\mathrm{H}} = [P_{\mathrm{H}}^{\min}, P_{\mathrm{H}}^{\max}]\}$, $P_{\mathrm{T}} \in \{\Omega_{\mathrm{T}} = [P_{\mathrm{T}}^{\min}, P_{\mathrm{T}}^{\max}]\}$, $P_{\mathrm{P}} \in \{\Omega_{\mathrm{P}} = [P_{\mathrm{P}}^{\min}, P_{\mathrm{P}}^{\max}]\}$.

3) Payoff Function

The objective of each player is to gain the payoff by selling electricity to the power grid: the larger the installed capacity, the higher the payoff from generation. However, the cost incurred by the game players is also proportional to the installed capacity. Thus, the payoff function of each player in the game pattern can be expressed as:

$$f_i = V_i - C_i \quad i \in \{\mathrm{H}, \mathrm{T}, \mathrm{P}\} \tag{5}$$

where V_i is the income of the players from electricity sales; and C_i is the cost incurred by the players.

To focus on the physical characteristics, the labor maintenance cost is excluded from calculating the operation cost.

B. Payoff Function of Each Player

Owing to different cycle lifes, to unify the basis of the study, the annualized incomes and annualized costs constitute the payoff function of each player. Herein, the annualized costs are composed of the annualized investment cost C_i^{inv} and average annual operation cost C_i^{opt}. That is, C_i in (5) can be expressed as:

$$C_i = C_i^{inv} + C_i^{opt} \quad i \in \{\mathrm{H}, \mathrm{T}, \mathrm{P}\} \tag{6}$$

Since each player has different operation characteristics, its annualized income and average annual operation cost vary accordingly. Therefore, the payoff of each player is detailed separately as follows.

1) HDR Plant

The output models of the HDR plant are given by (1) and (4). According to the two models of the HDR plant, the annualized income of the HDR plant when participating in an NCG can be expressed as:

$$V_{\mathrm{H}}^{\mathrm{NCG}}=\sum_{t\in T}c_e^t P_{hc}^t \tag{7}$$

where c_e^t is the time-of-use (TOU) electricity price; and T is the set of annual generation hours.

When the HDR plant forms a coalition in CG, the annualized income of the HDR plant can be expressed as:

$$V_{\mathrm{H}}^{\mathrm{CG}}=\sum_{t\in T}c_e^t P_{hf}^t \tag{8}$$

The annualized investment cost of an HDR plant mainly consists of the investment cost of the GMC and the cost of the power generation system. The former is determined by the HDR resource and the level of underground engineering technology. It is a fixed cost in this paper. The latter can be determined by the capacity of the ORC generator. Thus, the annualized investment cost of an HDR plant can be expressed as:

$$C_{\mathrm{H}}^{inv}=c_{ORC}P_{\mathrm{H}}+C_{GMC} \tag{9}$$

where c_{ORC} is the annualized cost factor per unit capacity of the ORC generator; and C_{GMC} is the fixed cost of GMC. The P_{H} in the NCG is the maximum of P_{hc}^t, while it is the maximum of P_{hf}^t in the CG.

The main operation cost of an HDR plant is the residual heat loss owing to flexible operation. Thus, the average annual operation cost of an HDR plant can be expressed as:

$$C_{\mathrm{H}}^{opt}=\sum_{t\in T}c_Q Q_{cur}^t \tag{10}$$

where c_Q is the geothermal price coefficient. The curtailed heat power Q_{cur}^t is modeled as:

$$Q_{cur}^t=m_\beta^t c_{pr}(T_\beta^t-T_{well}^{\min}) \tag{11}$$

From (7)-(10), the payoff functions of the HDR plant in the NCG and CG are expressed as:

$$f_{\mathrm{H}}^{\mathrm{NCG}}=V_{\mathrm{H}}^{\mathrm{NCG}}-C_{\mathrm{H}}^{inv}-C_{\mathrm{H}}^{opt} \tag{12}$$

$$f_{\mathrm{H}}^{\mathrm{CG}}=V_{\mathrm{H}}^{\mathrm{CG}}-C_{\mathrm{H}}^{inv}-C_{\mathrm{H}}^{opt} \tag{13}$$

2) *TS Plant*

TS plant achieves arbitrage by converting electrical or geothermal energy into thermal energy during low-electricity-price periods and converting the stored thermal energy into electrical energy during high-electricity-price periods. The annualized income of the TS plant can be expressed as:

$$V_{\mathrm{T}}=\sum_{t\in T}c_e^t(P_{\mathrm{T}}^t-P_{\mathrm{G}}^t)-c_Q Q_\beta^t \tag{14}$$

where P_{G}^t is the electrical power purchased from the power grid. The annualized investment cost of the TS plant is mainly composed of the cost of the generation system and that of the TEST. These can be calculated from the capacity of the ORC generator and the mass of the required HTO, respectively, i.e.,

$$C_{\mathrm{T}}^{inv}=c_{ORC}P_{\mathrm{T}}+c_{TS}M_{all} \tag{15}$$

where c_{TS} is the annualized cost factor of the TEST; M_{all} is the total mass of the HTO required by the TEST; and P_{T} is the maximum of P_{T}^t.

The cost during the TS plant operation is reflected mainly in the heat loss of the TEST and the cost of replenishing the HTO. Herein, the heat loss is negligible owing to the improved insulation technology. The annual average HTO replenishment is obtained according to the practical engineering experience. Therefore, the average annual operation cost of the TS plant can be expressed as:

$$C_{\mathrm{T}}^{opt}=\eta_{HTO}c_{HTO}M_{all} \tag{16}$$

where η_{HTO} is the annual HTO replenishment factor; and c_{HTO} is the HTO price.

The rectification of (14)-(16) yields the payoff function for the TS plant as:

$$f_{\mathrm{T}}=V_{\mathrm{T}}-C_{\mathrm{T}}^{inv}-C_{\mathrm{T}}^{opt} \tag{17}$$

3) *PV Plant*

PV plant profits by selling electricity to the power grid. Due to solar irradiance uncertainty, the power fluctuation of PV plants causes curtailment losses and load-shedding penalties during operation. The annualized income, annualized investment cost, and average annual operation cost of PV plants are calculated as:

$$V_{\mathrm{P}}=\sum_{t\in T}c_e^t P_{\mathrm{P}}^t \tag{18}$$

$$C_{\mathrm{P}}^{inv}=c_{\mathrm{P}}P_{\mathrm{P}} \tag{19}$$

$$C_{\mathrm{P}}^{opt}=\sum_{t\in T}c_e^t P_{Pcur}^t+pc_e^t P_{Pal}^t \tag{20}$$

where c_{P} is the annualized investment cost factor of the PV plant; P_{Pcur}^t is the power under curtailment; P_{Pal}^t is the power under load shedding; and p is the penalty coefficient.

The rectification of (18)-(20) yields the payoff function for the PV plant as:

$$f_{\mathrm{P}}=V_{\mathrm{P}}-C_{\mathrm{P}}^{inv}-C_{\mathrm{P}}^{opt} \tag{21}$$

IV. GAME APPROACHES FOR CAPACITY ALLOCATION OF HPS WITH HDR GEOTHERMAL ENERGY, TS, AND PV

The three players independent of each other in the proposed HPS pursue their individual interests and naturally constitute an NCG with the mutual competition. Besides, the three players are willing to cooperate due to the complementarity between the fluctuating solar energy and the stable geothermal energy. The NCG and CG approaches for capacity allocation are presented next.

A. *NCG Approach*

In the NCG, the decision of each player focuses only on the maximization of the individual payoff while neglecting the overall optimality of the HPS. The NCG pattern that constitutes capacity allocation is as follows.

1) Player: H, T, and P.
2) Strategy set: Ω_{H}, Ω_{T}, and Ω_{P}.
3) Payoff: $f_{\mathrm{H}}^{\mathrm{NCG}}$, f_{T}, and f_{P}.

The equilibrium solution of the NCG approach for capacity allocation of the HPS is as follows:

$$\begin{cases} P_{\mathrm{H}}^*=\arg\max\limits_{P_{\mathrm{H}}} f_{\mathrm{H}}^{\mathrm{NCG}} \\ P_{\mathrm{T}}^*=\arg\max\limits_{P_{\mathrm{T}}} f_{\mathrm{T}} \\ P_{\mathrm{P}}^*=\arg\max\limits_{P_{\mathrm{P}}} f_{\mathrm{P}} \end{cases} \tag{22}$$

where P_i^* $(i\in\{\mathrm{H},\mathrm{T},\mathrm{P}\})$ is the optimal installed capacity of plant i.

TS plants are also required to satisfy operational constraints while operating non-cooperatively:

$$P_{\mathrm{T}}^t=\eta_{\mathrm{P}} m_{dc}^t c_{po}(T_h-T_l) \tag{23}$$

$$S_h^t=\eta_h S_h^{t-1}+(Q_c^t-Q_{dc}^t/\eta_{dc})\Delta\tau \tag{24}$$

$$Q_c^t=Q_{ec}^t+Q_{hc}^t \tag{25}$$

$$Q_{ec}^t=\eta_e P_G^t \tag{26}$$

$$Q_{hc}^t=\eta_{ex} Q_\beta^t \tag{27}$$

$$Q_{dc}^t=m_{dc}^t c_{po}(T_h-T_l) \tag{28}$$

where m_{dc}^t is the mass flow rate of the HTO in exothermic power generation; c_{po} is the specific heat capacity of the HTO; T_h and T_l are the temperatures of HTO used for power generation and after power generation, respectively; S_h^t is the amount of heat storage; Q_c^t is the thermal power input to the TS plant for storage, which consists of electric heating power Q_{ec}^t and geothermal power Q_{hc}^t; η_h is the insulation factor of tanks; η_{dc} is the exothermic exchanger efficiency; η_e is the electric heater efficiency; η_{ex} is the efficiency of the exchanger; and $\Delta\tau$ is the time interval.

The TEST is the critical equipment for realizing energy storage in the TS plant. The masses of HTO in the high-temperature tank and low-temperature tank should be maintained in dynamic balance during operation. Meanwhile, the total mass of HTO should be maintained constant. The mass balance constraints of the TEST are given as:

$$M_h^{t+1}=M_h^t+m_c^t\Delta\tau-m_{dc}^t\Delta\tau \tag{29}$$

$$M_l^{t+1}=M_l^t-m_c^t\Delta\tau+m_{dc}^t\Delta\tau \tag{30}$$

$$M_{all}=M_h^t+M_l^t \tag{31}$$

where M_h^t and M_l^t are the masses of the HTO in the high-temperature and low-temperature tanks, respectively; and m_c^t is the mass flow rate of the HTO during TS.

The PV plant model can be established by considering the quantity of solar irradiance and capacity of the plant [23]. Owing to the fluctuation rate of solar irradiance, the uncertainty of the PV plant can generally be described by a Bayesian game model [24]: the two sides of the game are the PV plant and nature. The PV plant makes decisions based on the predicted values, and the nature determines the joint probability of the type of practical solar irradiance that occurs. After describing the power uncertainty of the PV plant using the Bayesian game model, (20) can be expressed as:

$$C_{\mathrm{P}}^{opt}=\pi_s\sum_{s\in S}\sum_{t\in T}(c_e^t P_{Pcur}^{s,t}+pc_e^t P_{Pal}^{s,t}) \tag{32}$$

where s is the solar irradiance type provided by the nature; S is the type set; $P_{Pcur}^{s,t}$ and $P_{Pal}^{s,t}$ are the power under curtailment and load shedding of solar irradiance type s, respectively; and π_s is the probability of occurrence of each type.

Based on this, the output power, curtailment loss, and load shedding penalty constraints of the PV plant can be obtained as:

$$P_{\mathrm{P}}^t=\lambda_{\mathrm{P}}^t P_{\mathrm{P}} \tag{33}$$

$$P_{Pcur}^{s,t}=\max\{\xi_{\mathrm{P}}^{s,t}-P_{\mathrm{P}}^t,0\} \tag{34}$$

$$P_{Pal}^{s,t}=\max\{P_{\mathrm{P}}^t-\xi_{\mathrm{P}}^{s,t},0\} \tag{35}$$

where λ_P^t is the power generation coefficient of the PV plant [23]; and $\xi_P^{k,t}$ is the practical power output of the PV plant.

In conclusion, the constraints of NCG approach for capacity allocation (22) include (1), (23)-(31), and (33)-(35).

B. CG Approach

Unlike the NCG, the HDR plant seeks to enhance geothermal energy value through the cooperation in an HPS. The TS plant seeks to achieve profitability through cooperation, and the PV plant seeks to satisfy the power fluctuation requirement of the power grid through cooperation. Therefore, all the players are willing to form a coalition, thereby constituting a CG pattern. The three players can form four coalitions: {{H, T}, {P}}, {{H, P}, {T}}, {{T, P}, {H}}, and {H, T, P}. The CG pattern for capacity allocation of each coalition is analyzed further here.

1) Capacity Allocation for {{H, T}, P}

In the HDR-TS coalition, the HDR plant and TS plant maintain the minimum output, and the geothermal energy is stored in the TESTs during low electricity price hours. During high electricity price hours, the TS plant utilizes heat to generate electricity. This increases the value of geothermal energy generation. Thus, the CG pattern for the capacity allocation of the HDR-TS coalition is described as follows.

1) Player: {H, T} and {P}.
2) Strategy set: $\Omega_{\mathrm{H}}\times\Omega_{\mathrm{T}}$ and Ω_{P}, where × represents the Cartesian product.
3) Payoff: coalition payoff $f_{\mathrm{HT}}=f_{\mathrm{H}}^{\mathrm{CG}}+f_{\mathrm{T}}$ and f_{P}.

Since the TS plant can directly store and utilize the geothermal energy as denoting in operational constraint (27), the outlet thermal power of the TS exchanger can be described as:

$$Q_{Hc}^t=m_c^t c_{po}(T_h-T_l) \tag{36}$$

The equilibrium solution of the capacity allocation for the HDR-TS coalition is expressed as:

$$\begin{cases}(P_{\mathrm{H}}^*,P_{\mathrm{T}}^*)=\arg\max\limits_{P_{\mathrm{H}},P_{\mathrm{T}}} f_{\mathrm{HT}}\\ P_{\mathrm{P}}^*=\arg\max\limits_{P_{\mathrm{P}}} f_{\mathrm{P}}\end{cases} \tag{37}$$

The constraints of $(P_{\mathrm{H}}^*,P_{\mathrm{T}}^*)$ include (2)-(4), (23)-(31), and (36). The constraints of P_{P}^* include (33)-(35).

2) Capacity Allocation for {{H, P}, T}

In the HDR-PV coalition, the HDR plant can provide reserves for the PV plant, which reduces the curtailment losses and load shedding penalties of the PV plant and increases the total coalition payoff. Therefore, the CG pattern for the capacity allocation of the HDR-PV coalition is described as follows.

1) Player: {H, P} and {T}.
2) Strategy set: $\Omega_{\mathrm{H}}\times\Omega_{\mathrm{P}}$ and Ω_{T}.
3) Payoff: coalition payoff $f_{\mathrm{HP}}=f_{\mathrm{H}}^{\mathrm{CG}}+f_{\mathrm{P}}$ and f_{T}.

The purpose of an HPS consisting of an HDR plant, a TS plant, and a PV plant is to rely on a stable HDR plant to provide reserves for the PV plant. This equates the PV plant to a dispatchable plant and satisfies the requirements of the power grid with regard to the power fluctuation rate. Therefore, the HDR-PV coalition should also satisfy the EFC constraints during operation:

$$|\xi_{\mathrm{P}}^{s,t} - R_{\mathrm{H}}^{s,t} - P_{\mathrm{P}}^{t}| \leq \sigma P_{\mathrm{P}}^{t} \tag{38}$$

where σ is the allowed fluctuation rate; and $R_{\mathrm{H}}^{s,t}$ is the reserves provided by the HDR plant to the PV plant, which is modeled as:

$$R_{\mathrm{H}}^{s,t} = \Delta m_{\alpha}^{s,t} \eta_{\mathrm{P}} c_{pr} (T_{HDR} - T_{well}^{s,t}) \tag{39}$$

where $\Delta m_{\alpha}^{s,t}$ is the mass flow rate of the brine to be adjusted when the reserves are called.

The equilibrium solution of the capacity allocation for the HDR-PV coalition is expressed as:

$$\begin{cases} (P_{\mathrm{H}}^{*}, P_{\mathrm{P}}^{*}) = \underset{P_{\mathrm{H}}, P_{\mathrm{P}}}{\arg\max}\ f_{\mathrm{HP}} \\ P_{\mathrm{T}}^{*} = \underset{P_{\mathrm{T}}}{\arg\max}\ f_{\mathrm{T}} \end{cases} \tag{40}$$

The constraints of (P_{H}^{*}, P_{P}^{*}) include (2) - (4), (33) - (35), (38), and (39). The constraints of P_{T}^{*} include (23)-(31).

3) Capacity Allocation for {{T, P}, H}

In the TS-PV coalition, on the one hand, the TS plant can absorb excess PV power. On the other hand, it can provide up reserves for the PV plant. This reduces the curtailment losses and load shedding penalties of the PV plant and increases the coalition payoff. The CG pattern for the capacity allocation of the TS-PV coalition is described as follows.

1) Player: {T, P} and {H}.

2) Strategy set: $\Omega_{\mathrm{T}} \times \Omega_{\mathrm{P}}$ and Ω_{H}.

3) Payoff: coalition payoff $f_{\mathrm{TP}} = f_{\mathrm{T}} + f_{\mathrm{P}}$ and $f_{\mathrm{H}}^{\mathrm{NCG}}$.

Similar to the HDR-PV coalition, the TS-PV coalition is subject to the EFC constraint in its operation:

$$|\xi_{P}^{s,t} - R_{T}^{s,t} - P_{\mathrm{P}}^{t}| \leq \sigma P_{\mathrm{P}}^{t} \tag{41}$$

where $R_{\mathrm{T}}^{s,t}$ is the reserve provided by the dry storage thermal power plant to the PV plant, which is modeled as:

$$R_{T}^{s,t} = \Delta m_{dc}^{s,t} \eta_{\mathrm{P}} c_{po} (T_c - T_l) - P_{Pcur}^{s,t} \tag{42}$$

where $\Delta m_{dc}^{s,t}$ is the mass flow rate of the HTO.

The equilibrium solution of the capacity allocation for the TS-PV coalition is expressed as:

$$\begin{cases} (P_{\mathrm{T}}^{*}, P_{\mathrm{P}}^{*}) = \underset{P_{\mathrm{T}}, P_{\mathrm{P}}}{\arg\max}\ f_{\mathrm{TP}} \\ P_{\mathrm{H}}^{*} = \underset{P_{\mathrm{H}}}{\arg\max}\ f_{\mathrm{H}}^{\mathrm{NCG}} \end{cases} \tag{43}$$

The constraints of (P_{T}^{*}, P_{P}^{*}) include (23) - (31), (33) - (35), (41), and (42). The constraint of P_{H}^{*} includes (1).

4) Capacity Allocation for {{H, T, P}}

In the HDR-TS-PV coalition, the TS plant can absorb the surplus PV power and geothermal power to achieve profitability. The HDR plan increases the geothermal energy value through the TS plant, and the PV plant reduces the curtailment losses and load shedding penalties through the reserves provided by the HDR plant and the TS plant. This increases the total payoff. The CG pattern for the capacity allocation of the HDR-TS-PV coalition is described as follows.

1) Player: {H, T, P}.

2) Strategy set: $\Omega_{\mathrm{H}} \times \Omega_{\mathrm{T}} \times \Omega_{\mathrm{P}}$.

3) Payoff: coalition payoff $f_{\mathrm{HTP}} = f_{\mathrm{H}}^{\mathrm{CG}} + f_{\mathrm{T}} + f_{\mathrm{P}}$.

The EFC constraint of the HDR-TS-PV coalition is given as:

$$|\xi_{\mathrm{P}}^{s,t} - R_{\mathrm{H}}^{s,t} - R_{\mathrm{T}}^{s,t} - P_{\mathrm{P}}^{t}| \leq \sigma P_{\mathrm{P}}^{t} \tag{44}$$

The equilibrium solution of the capacity allocation for the HDR-TS-PV coalition is expressed as:

$$(P_{\mathrm{H}}^{*}, P_{\mathrm{T}}^{*}, P_{\mathrm{P}}^{*}) = \underset{P_{\mathrm{H}}, P_{\mathrm{T}}, P_{\mathrm{P}}}{\arg\max}\ f_{\mathrm{HTP}} \tag{45}$$

The constraints of (45) include (2) - (4), (23) - (31), (33) - (35), (39), (42), and (44).

The aforementioned NCG and CG approaches involve upper and lower bound constraints on each variable. These are not presented here individually, owing to space constraints.

5) Constraint Linearization

The product term of two decision variables in (4) and (39) causes the whole capacity allocation approach to be nonlinear. This paper addresses the Boolean expansion method [25] to transform the nonlinear problem into a mixed-integer linear planning problem.

Define K as the set of segments. T_{well}^{t} can be divided into 2^{K-1} segments as:

$$\hat{T}_{well}^{t} = T_{well}^{\min} + \sum_{k \in K} 2^{k-1} u_k^t \Delta T \tag{46}$$

where $\hat{T}_{well}^{t}$ is the discrete value of T_{well}^{t} after piecewise linearization; u_k^t is a 0-1 variable, indicating whether the current segment at time t is included in $\hat{T}_{well}^{t}$; and ΔT is the minimum temperature difference. Then $m_{\alpha}^{t} T_{well}^{t}$ in (4) can be changed to:

$$m_{\alpha}^{t} T_{well}^{t} \approx m_{\alpha}^{t} T_{well}^{\min} + \sum_{k \in K} 2^{k-1} v_k^t \Delta T \tag{47}$$

$$m_{\alpha}^{\min} \leq v_k^t \leq m_{\alpha}^{\max} u_k^t \tag{48}$$

$$m_{\alpha}^{\min} \leq m_{\alpha}^{t} - v_k^t \leq m_{\alpha}^{\max} (1 - u_k^t) \tag{49}$$

where $m_{\alpha}^{\min}$ and $m_{\alpha}^{\max}$ are the minimum and maximum values of m_{α}^{t}, respectively; and $v_k^t = m_{\alpha}^{t} u_k^t$.

It can be observed that (47) with v_k^t as the variable is linear. In the same way, (39) can also be transformed into a linear equation. Then, the proposed approaches can be solved using MATLAB2016b and CPLEX12.8 solvers.

V. CASE STUDY

A. System Parameters

The scenario is constructed based on practical data from the Gonghe Basin, Qinghai, China. The region has a plateau continental climate as one of the 10 GW level clean energy bases with abundant solar energy resources and is also the only high-quality HDR resource area in China. The operation parameters of the HDR plant are selected according to the local HDR resources [13]. The detailed parameters of the system are shown in Table I.

To focus more on the competition and cooperation among the three players, the simulation in this study satisfies the following assumptions:

1) HDR plants are double-well systems [26].

2) The effects of grid congestion and line capacity are neglected.

3) The installed capacity of the HPS is 100 MW.

TABLE I
SYSTEM PARAMETERS

Parameter	Value	Parameter	Value
Temperature of production well T_{HDR}	200 °C	Annual investment of ORC generator c_{ORC}	200 \$/(kW·year)
Mass flow range of production well m_r^t	50-75 kg/s [12]	Annual investment of TEST c_{TEST}	38.7 \$/(ton·year)
Minimum reinjection temperature $T_{well}^{\min}$	40 °C	Price of HTO c_{HTO}	3020 \$/ton
Initial temperature of HTO T_l	25 °C	Annual investment of PV plant c_{PV}	33 \$/(kW·year)
Specific heat capacity of HTO c_{po}	1.938 kJ/(kg·°C)	Price of thermal energy c_Q	0.07 \$/kWh
Specific heat capacity of brine c_{pr}	4.2 kJ/(kg·°C)	Efficiency of exchanger η_{ex}	90%
Efficiency of ORC generator η_P	13.2% [27]	Prediction error of PV plant α	20%
Insulation coefficient η_h	99%	Permitted fluctuation rate σ	≤10%
Efficiency of electric heater η_e	98%	Penalty coefficient p	2-10

In the proposed HPS, HDR geothermal energy is not affected by seasonal variations. Meanwhile, PV plants are susceptible to weather variations, and their day-ahead prediction accuracy is closely related to the weather state [27]. Therefore, this paper uses practical PV plant data under four weather conditions (rainy, sunny, cloudy, and overcast) to model typical days for capacity allocation. According to practical local meteorological statistics, the percentages of rainy, sunny, cloudy, and overcast days are 24%, 35%, 17%, and 24%, respectively. The solar irradiance and TOU electricity prices on typical days are shown in Fig. 2.

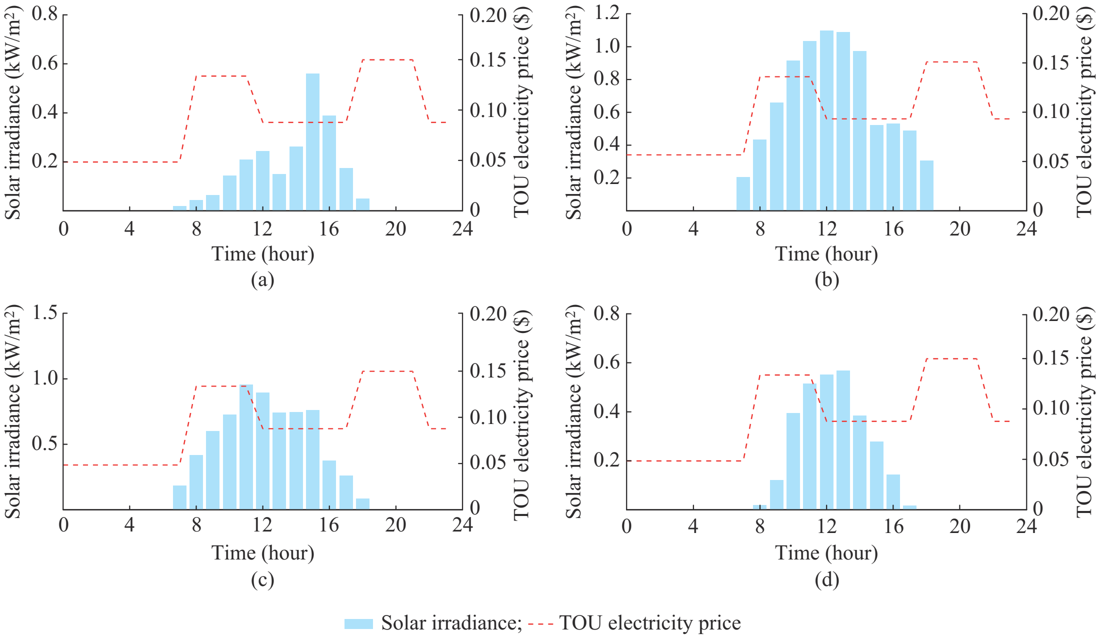

Fig. 2. Solar irradiance and TOU electricity price of typical days. (a) Rainy day. (b) Sunny day. (c) Cloudy day. (d) Overcast day.

The sample sets of data on various typical days are N_{rainy}, N_{sunny}, N_{cloudy}, and $N_{overcast}$, respectively. The corresponding probability sets of their samples are π_{rainy}, π_{sunny}, π_{cloudy}, and $\pi_{overcast}$, respectively. Assuming that the four weather conditions are mutually exclusive, the set of total samples N_S is $N_{rainy}N_{sunny}N_{cloudy}N_{overcast}$. Its corresponding probability π_s is obtained from the joint probability distribution of the probability sets of the four types of samples. This paper uses the Latin hypercube method [28] to sample the solar irradiance curve on each typical day. According to [27], the day-ahead prediction errors before each typical day are 20% for cloudy day, 8% for sunny day, 10% for overcast day, and 20% for rainy day to generate 10000 samples each. The sample space of each typical day is reduced to 10 samples using the scenario reduction method [29]. The obtained 10000 joint samples of typical days are again reduced to 100 samples using the same scenario reduction method.

B. Allocation Results of NCG

The NCG approach for capacity allocation of the proposed HPS is carried out using 3% as the allowed fluctuation rate. The capacity allocation results using the NCG approach are shown in Table II. Under the current TOU electricity price, the TS plant cannot obtain profits through arbitrage, whereby its capacity allocation result is zero. The capacity allocation of the HDR plant is 6.6 MW according to the mass flow rate of GMC [25]. The PV plant obtains 93.4% of the total capacity of the proposed HPS with its advantage of low investment cost. In the competition, the HDR plant always maintains full generation for maximizing its payoff. It will not reduce its output power by providing reserves for the PV plant or geothermal energy for the TS plant. By contrast, the PV plant cannot prevent the curtailment losses and load shedding penalties. Further calculations show that the percentage of time that the proposed HPS satisfies the allowed fluctuation rate is only 53.96% due to the fluctuation of the PV generation. The curtailment losses and load shedding penalties of the PV plant amount to 12.32% of its annualized payoff.

TABLE II
CAPACITY ALLOCATION RESULTS USING NCG APPROACH

Coalition form	P^*_{H} (MW)	P^*_{T} (MW)	P^*_{P} (MW)	Payoff of each player (M$/year)	Total payoff (M$/year)
{H}, {T}, {P}	6.6	0	93.4	$f_{\mathrm{H}}^{\mathrm{NCG}}=3.66, f_{\mathrm{T}}=0,$ $f_{\mathrm{P}}=13.34$	17.00

C. Allocation Results of CG

As shown in NCG, the TS plant is not profitable, the PV plant has a large amount of curtailment and load shedding losses, and the HDR plant is incapable of utilizing the TOU electricity price to increase its payoff. The capacity allocation results using the CG approach, where the three players are willing to cooperate to increase the total profits of the proposed HPS and their individual payoffs simultaneously, are shown in Table III.

TABLE III
CAPACITY ALLOCATION RESULTS USING CG APPROACH

Coalition form	P^*_{H} (MW)	P^*_{T} (MW)	P^*_{P} (MW)	Payoff of each player (M$/year)	Total payoff (M$/year)
{H, T, P}	6.6	4.49	88.91	$f_{\mathrm{HTP}}=18.45$	18.45
{H, T}, {P}	6.6	7.55	85.85	$f_{\mathrm{HT}}=4.61,$ $f_{\mathrm{P}}=12.37$	16.98
{H, P}, {T}	6.6	0	93.40	$f_{\mathrm{HP}}=17.35, f_{\mathrm{T}}=0$	17.35
{H}, {T, P}	6.6	5.18	88.22	$f_{\mathrm{H}}^{\mathrm{NCG}}=3.66,$ $f_{\mathrm{TP}}=12.26$	15.92

Table III reveals that the HDR plant is allocated the maximum installable capacity regardless of competition or cooperation. This result is owing to the stable output of the HDR plant, with annual utilization hours exceeding 8000. However, when the HDR plant forms a coalition with the PV plant, it can provide reserves and reduce part of the losses and penalties of the PV plant. Its residue heat losses also increase the operation cost. As a result, the total payoff of the corresponding HPS increases only by 2.05%. The final result is that the three players form a grand coalition. At this point, the total payoff of the corresponding HPS is increased by 8.52% relative to the NCG. In addition, the percentage of time that the PV plant satisfies the allowed fluctuation rate is increased to 95%. Therefore, the PV plant can be equated to a dispatchable power source. Figure 3 presents the operation results of each player in the HDR-TS-PV coalition on typical days, where P^t_{US} and P^t_{DS} represent the up and down reserves provided by the HDR plant and TS plant, respectively.

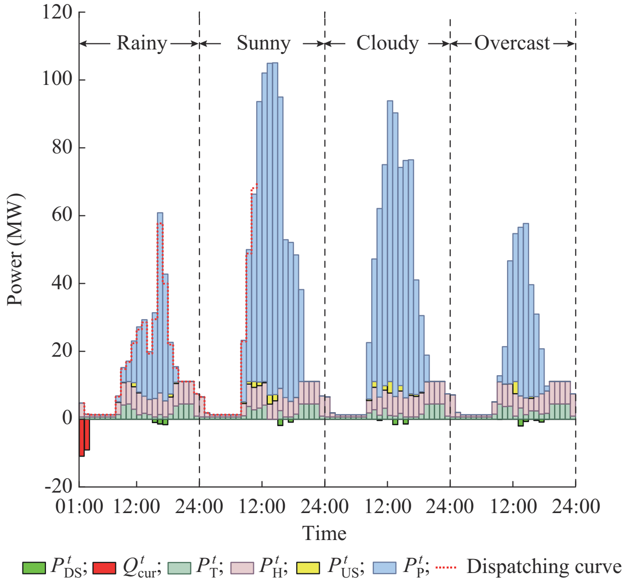

Fig. 3. Operation results of each player in HDR-TS-PV coalition on typical days.

No matter how the environmental conditions change, the TS plant permanently stores geothermal energy during the low-electricity-price periods and profits from the high-electricity-price periods to realize the peak shaving services. In terms of providing reserves to stabilize the fluctuation of the PV plant, Fig. 3 shows that the reserves provided by the HDR plant and TS plant under the cloudy condition are much more than those under other environmental conditions. This result indicates that the prediction error of the PV plant under cloudy condition increases and the power uncertainty intensifies, and the proposed HPS needs to prepare more reserve capacity to cope with more severe power fluctuations under the cloudy condition. Finally, the capacity allocation based on the complete CG strategy can meet the operation requirements of an HPS under four environmental conditions, which verifies the correctness and effectiveness of the proposed approaches and models.

D. Payoff Allocation of HDR-TS-PV Coalition

As mentioned above, the three players increase the total payoff of the proposed HPS in CG and meet the overall rationality. Then, the total payoff needs to be allocated to the coalition members reasonably and without bias to satisfy their individual rationality, thereby promoting the stability of the coalition. The stability of the HDR-TS-PV coalition is the premise for further analysis of the proposed HPS and the benefits of the players. We use the minimum core (ε-core) method to analyze the stability of the proposed HPS. The result of the stable core set is shown in the blue region in Fig. 4. The payoff distribution in the blue region can ensure that the three players are always willing to form a grand coalition, and the overall rationality of the corresponding HPS and the individual rationality of the players can be satisfied simultaneously.

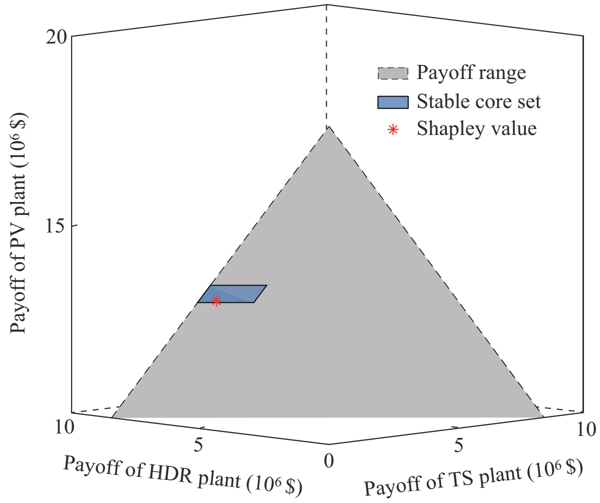

Fig. 4. Stable core set and Shapley value.

The Shapley value is the fairest and most reasonable value of the payoff allocation among game players. It is based on the marginal contribution and is widely used in the payoff allocation of the CG approach [30]. Table IV presents the payoff based on the Shapley value allocated to the players in the HDR-TS-PV coalition.

As shown in Table IV, the payoff of the HDR plant is increased by 28.87%, whereas the TS plant achieves the profitability through the zero marginal cost of geothermal energy and excess PV power. The PV plant increases its payoff by 0.3% through cooperation. However, its output power satisfies the grid assessment requirements during 95% of the generation hours in the example scenario of this paper, thereby improving the grid-connection reliability.

TABLE IV
PAYOFFS BASED ON SHAPLEY VALUE AND ADDITIONAL PROFIT

Player	Payoff ($/year)	Additional profit ($/year)
HDR plant	4717000	1057000
TS plant	349000	349000
PV plant	13384000	44000

Therefore, the cooperation is preferred over the competition in the proposed HPS. The capacity allocation using a CG approach in which the players form a grand coalition that can maximize the payoff of both the whole HPS and individual players. As can be observed from the payoff allocation result obtained from the Shapley value shown in Fig. 4, the HDR-TS-PV coalition is stable under the payoff allocation strategy based on the Shapley value. However, it should also be noted that this allocation result is close to the edge of the stable core set. The factors that affect the stable core set and allocation will be analyzed in detail below.

E. Sensitivity Analysis

In addition to the physical characteristics of power sources and environmental conditions, the electricity price, penalty coefficient, and allowed fluctuation rate are the primary power grid parameters involved in the paper. The profit of HPS all comes from the sales of electricity to the power grid. Therefore, the electricity price is the key factor that affects the coalition of all players in HPS and the capacity allocation strategy. Based on the TOU electricity price shown in Fig. 2, the influence of electricity price on the payoff and stability of the HDR-TS-PV coalition is studied, as shown in Fig. 5.

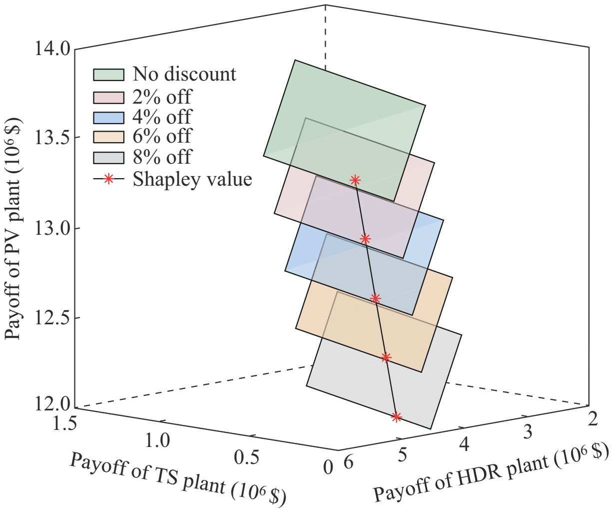

Fig. 5. Influence of electricity price on payoff and stability of HDR-TS-PV coalition.

In Fig. 5, the stable core set of the HDR-TS-PV coalition under different electricity price discounts and the payoff allocation based on the Shapley value is given. With the increase of the electricity price discount, the payoff of each player decreases, and the Shapley value gradually approaches the edge of the stable core set. When the discount is more than 8%, the payoff of the TS plant will be negative at first. Thus, the distribution based on the Shapley value will not keep the HDR-TS-PV coalition stable, which further shows that when the electricity price falls, the marginal benefit of the TS plant will decrease the fastest, and the importance of players in forming a coalition will no longer be equal. Therefore, the payoff allocation method based on the Shapley value is no longer applicable.

The load shedding penalty coefficient determines the price paid by the PV plant when it does not satisfy the fluctuation rate requirement and plays a decisive role in the willingness of the PV plant to participate in the cooperation. Therefore, it is necessary to analyze its impact on the HDR-TS-PV coalition. Under the assumption that the total capacity of the proposed HPS is 100 MW, the stability of the HDR-TS-PV coalition is analyzed by setting the penalty coefficient p as 5, 6, 7, 8, and 9, respectively, as shown in Fig. 6.

As shown in Fig. 6, the scope of the stability core set of the HDR-TS-PV coalition shrinks as the penalty coefficient decreases. When p is less than 4, the stable core set will be empty so that the HDR-TS-PV coalition is unstable. When p equals 5, the payoff allocation result based on the Shapley value is no longer in the stable core set, which shows that the equal relationship between players is broken. Unlike the reason for the influence of electricity price discount on payoff in Fig. 5, the main reason is that the PV plants cannot benefit through the cooperation. It is evident that the willingness of PV plants to participate in the HDR-TS-PV coalition decreases as the grid penalty for load-shedding of PV plants decreases.

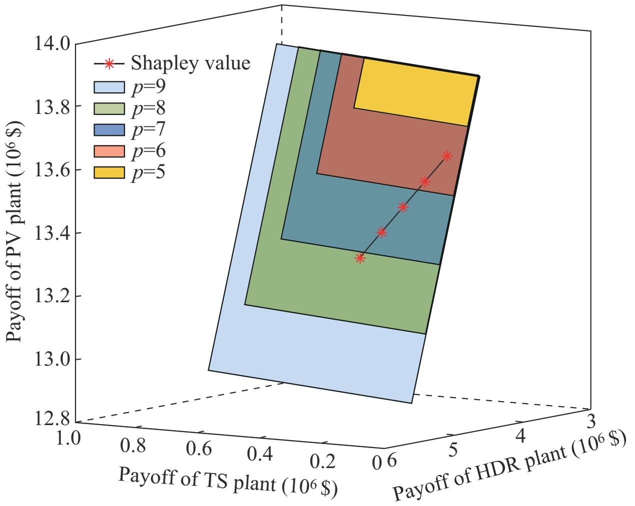

Fig. 6. Influence of penalty coefficient on stability of HDR-TS-PV coalition.

The previous simulations show that the three players would eventually form a stable coalition in the proposed HPS with a high penalty coefficient and electricity price. To further investigate the role of HDR plants and TS plants in smoothing out power fluctuations and improving the grid-connection reliablity of PV plants in the system, we relax the limit on the total capacity of the proposed HPS. Subsequently, we perform the sensitivity analysis on the impact of allowed fluctuation rate σ on capacity allocation, and the results are shown in Table V.

TABLE V
SENSITIVITY ANALYSIS RESLUTS OF ALLOWED FLUCTUATION RATE ON CAPACITY ALLOCATION

σ (%)	Capacity of HDR plant (MW)	Capacity of TS plant (MW)	Capacity of PV plant (MW)	Total quality of HTO (ton)	Payoff of HPS ($/year)	Annual cost of HPS ($/year)
3	6.6	10	138.67	2786	25190000	7200000
5	6.6	10	177.28	2803	32930000	8510000
7	6.6	10	241.62	2801	43390000	10570000
10	6.6	10	414.49	2799	71410000	16120000

As shown in Table V, the capacity of HDR plant always maintains the maximum installable capacity, which is limited by the physical parameters of the GMC. The TS plant is limited by the total geothermal energy exploitation yield. The quality of HTO that is required largely by the TS plant remains stable. With the increase of the ability of the power grid to withstand power fluctuation, the period and scale of the HDR plant and TS plant required to provide reserves for the PV plant in the proposed HPS are reduced accordingly, whereas the capacity allocation result of the PV plant is increased. The payoff of the proposed HPS increases mainly from the incremental part of the PV plant. A comparison with Table III shows that when the maximum capacity of the proposed HPS is relaxed, the system is able to allocate 48.66% more capacity of the PV plant on the premise of satisfying 3% of the allowed fluctuation rate. It is achieved by increasing the capacity of the TS plant. However, owing to the limitation on the geothermal energy, the upper limit of the capacity of the TS plant is 10 MW.

Furthermore, the influence of the allowed fluctuation rate on the stability and payoff allocation of the HDR-TS-PV coalition is analyzed, and the results are shown in Fig. 7. It can be observed that the increased allowed fluctuation rate shrinks the scope of the stable core set of the HDR-TS-PV coalition, and the payoff based on the Shapley value is gradually close to the edge of the stable core set. Due to the increase of capacity, the payoff of the PV plant increases obviously. The payoff of the HDR plant remains stable, while the payoff of the TS plant decreases gradually. When the allowed fluctuation rate is more than 10%, the HDR-TS-PV coalition is unstable. This shows that when the ability of the power grid to withstand fluctuations is gradually close to the prediction ability of the PV plant, the PV plant no longer needs the HDR or TS plants to provide reserves, so the willingness of cooperation is reduced. The HDR plant relies on the stable geothermal energy, and its payoff remains stable. The payoff of the TS plant will mainly come from the peak shaving service in cooperation with the HDR plant.

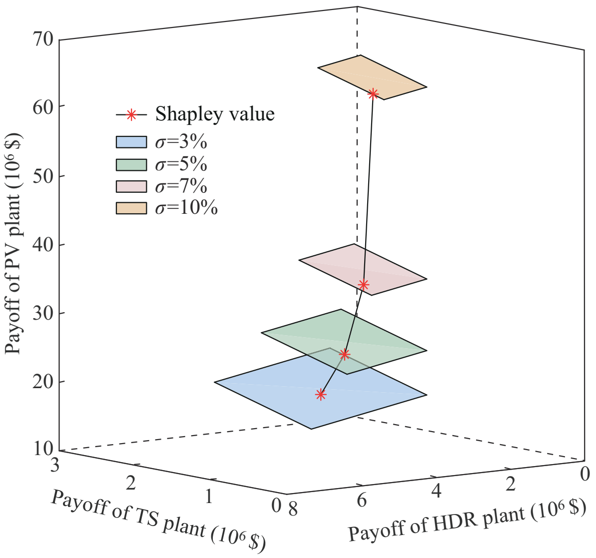

Fig. 7. Influence of allowed fluctuation rate on stability and payoff allocation of HDR-TS-PV coalition.

Moreover, the total quality of HTO in Table V varies negligibly with the allowed fluctuation rate. This result reflects that the geothermal energy has been adequately stored and utilized. The ratio of the capacity of stable power supply

(HDR plant and TS plant) to the capacity of the PV plant in the proposed HPS is 1:8 under both the limited and relaxed conditions of the total capacity. At the same time, the external parameter boundaries are addressed to give full play to the complementary role of the proposed HPS under the source parameters and environmental conditions mentioned in this paper, i.e., the electricity price discount is less than 8%, the allowable fluctuation rate is less than 10%, and the penalty coefficient is more than 5.

VI. CONCLUSION

The HDR geothermal energy has the advantages of being stable, continuous, and unaffected by meteorological factors, which is highly preferable for providing energy storage services for grid-connected PV plants in alpine and high-altitude areas. However, conventional HDR plants are not adequately flexible to operate under such conditions and cooperate with TS plants to form a hybrid PV-storage power system. In this paper, we design the framework of an HPS consisting of HDR, TS, and PV plants, adopt the concept of game theory to construct the game pattern model of the proposed HPS with the HDR plant, TS plant, and PV plant as the players, and propose the payoff function of each player. Furthermore, the NCG and CG approaches for capacity allocation to maximize the payoff of the proposed HPS are established based on the capacity allocation strategy of each game player.

Finally, the model and approaches proposed in this paper are validated using the data of practical PV plants and HDR geothermal energy resources in the Gonghe Basin, Qinghai, China as a case study. The results show that the capacity allocation model proposed in this paper can effectively increase the total payoff of the HPS and the individual payoff of each player. Simultaneously, it reduces the system power fluctuation and enhances the grid-connection reliability through EFC constraints. A parameter sensitivity analysis also shows that the penalty coefficient plays a decisive role in the stability of the HDR-TS-PV coalition.

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