

Article

Game Approach to HDR-TS-PV Hybrid Power System Dispatching

Yang Si ^{1,2} , Laijun Chen ^{1,*}, Xuelin Zhang ³, Xiaotao Chen ¹, Tianwen Zheng ^{1,4} and Shengwei Mei ^{1,2,4}

- ¹ Qinghai Key Lab of Efficient Utilization of Clean Energy (TusInstitute for Renewable Energy), Qinghai University, Xining 810016, China; siyang@qhu.edu.cn (Y.S.); chenxiaotao@qhu.edu.cn (X.C.); tianwenscu@163.com (T.Z.); meishengwei@mail.tsinghua.edu.cn (S.M.)
- ² State Key Lab of Control and Simulation of Power Systems and Generation Equipment, Tsinghua University, Beijing 100091, China
- ³ Technical Institute of Physics and Chemistry of China, Beijing 100190, China; zhangxuelin@mail.ipc.ac.cn
- ⁴ Sichuan Energy Internet Research Institute, Tsinghua University, Chengdu 610213, China
- * Correspondence: chenlaijun@qhu.edu.cn; Tel.: +86-13581828764

Featured Application: This research provides a new technical route for grid-connected photovoltaic plants in high-altitude regions and provides an essential theoretical basis for developing power generation systems based on hot dry rock (HDR) geothermal energy.

Abstract: Hot dry rock (HDR) power stations have the potential to serve as an energy storage system for large-scale photovoltaic (PV) plants. For flexible operation, thermal storage (TS) power stations are required to coordinate with HDR power stations. In this study, a hybrid power system is constructed by combining the HDR, TS, and PV plants. Game theory is then introduced into the optimal dispatch of the hybrid power system. Considering HDR, TS, and PV as players, non-cooperative and cooperative game dispatching models are established and verified by a case in the Gonghe basin of Qinghai. Finally, the stability of the coalitions and the rationality of allocation of the hybrid power system is verified, and the sensitivity of critical parameters is analyzed. The results demonstrate that the overall payoff of the hybrid power system is increased by 10.15%. The payoff of the HDR power station is increased by 16.5%. The TS power station has obtained 50% of the total extra profits. The PV plant reduces the impact on the grid to obtain the priority of grid connection. Based on these results, a theoretical basis can be provided for developing generation systems based on the HDR resources in the Gonghe Basin.

Keywords: hot dry rock; hybrid power system; game theory; coordinated dispatching; Shapley value



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1. Introduction

With the increasing clean energy penetration, the power grid's security, stability, and economy have been severely affected by the intermittent and fluctuating nature of power sources. The large-scale transmission and consumption of clean energy face the challenge of a shortage of reliable power sources. This issue is especially prominent for some clean energy bases where clean energy production and transmission are the primary industry [1], such as the Gonghe Basin. This region has tens of millions of kilowatt-level clean energy bases with abundant wind, solar, hydropower, and geothermal power resources. However, because of the lack of flexible and stable power sources, it is difficult to expand the scale of clean energy development further.

Among the various types of clean energy sources, hot dry rock (HDR) power stations have the most stable and reliable operational characteristics [2]. The development of a more flexible operational mode to form a new type of energy storage system, coupled with the vast amount of thermal energy in the geothermal reservoir, would be instrumental to ensure the reliability of grid-connected photovoltaic (PV) plants and to support clean energy

transmission. In [3], geophysical methods were used for geological characterization of the Gonghe Basin on different scales. Finally, the scope and volume of Gonghe HDR resources were evaluated. According to preliminary estimates, the amount of HDR geothermal energy in the Gonghe Basin is equivalent to 55.909 billion tons of standard coal [4]. Considering environmental protection requirements and realization of carbon neutrality constraints [5], comprehensive utilization of HDR geothermal energy will become an essential aspect of the global clean energy supply.

However, the large-scale development of HDR resources still faces several technical and cost constraints [6]. The experimental results and the critical technical challenges of HDR geothermal energy development were summarized in [7]. The hydraulic fracturing method assisted by micro-computed tomography was addressed in [8], which improved the development of HDR geothermal resources. Focusing on the geothermal resources of HDR in Daqing oilfield, China, the research carried out a numerical simulation on reservoir stimulation and economic analysis of HDR power stations [9]. The results show that economy is key for restricting the development of HDR geothermal resources. The geothermal generators in the HDR power stations have low theoretical efficiency limited by the HDR temperature [10]. In order to improve the economics of low-temperature HDR power stations, the energy efficiency and exergy loss of the Kalina cycle were analyzed in detail, and the maximum energy efficiency of 12.7% was obtained [11]. In [12], the adaptability of the organic Rankine cycle (ORC) and Kalina cycle in low-temperature HDR scenarios were further compared and analyzed. The energy efficiency of the geothermal generator was increased to 13.2%. Previous studies have shown that research in improving the efficiency of HDR power station has been lagging owing to the limitations of physical and chemical properties. Therefore, coordinated operation of hybrid power systems with other energy sources, such as PV plants, provides a new technical path for HDR power stations to exploit their potential better and reap better economic benefits.

Extensive research has been conducted by scholars worldwide on the coordinated operation of hybrid power systems [13]. Some studies have been conducted from the perspective of complementation. In [14], a stochastic two-stage unit commitment model and a rolling look-ahead economic dispatch model were established based on the concentrated solar power plant and the wind turbine complementation mechanism. To further improve the reliability of the hybrid power systems, the robust optimization theory was introduced into the optimization dispatch for a hybrid wind-PV-hydropower-thermal system to balance reliability and economy [15]. Considering the scenario of time-of-use (TOU) electricity price and randomness of wind power, a stochastic hourly combinational approach for effective dispatching of the wind plants, cascaded hydropower station, and pumped-storage units was proposed in [16].

With the development of electrochemical energy storage technology, batteries have been widely used to coordinate renewable energy systems [17]. A linear model was used to describe the energy storage dispatching model that minimized the power demand and verified the feasibility of lithium-ion battery storage [18]. In [19], the load following strategy and cycle charging strategy of battery are combined to explore the feasibility of a joint dispatching strategy for PV/diesel/battery hybrid power system. A model for optimizing AC-coupled and DC-coupled PV-battery hybrid power system was proposed in [20], which proved the economics of large-scale lithium battery storage plants under appropriate conditions.

The research on geothermal hybrid power systems is still relatively few. Geothermal generation was used as the power source to optimize the dispatch of wind- PV hybrid power system in the island scenario [21]. An HDR power station scheme combining geothermal generation, absorption refrigeration, and waste heat heating systems was further proposed in [22]. For specific applications, an HDR cogeneration system that combines wind and PV energy as power sources to meet the cold, heat, and electricity demands of an independent micro-energy grid was proposed in [23]. In [24], a new type of combined cooling and power supply system was proposed in order to meet the energy

demand of buildings, which can meet the seasonal cooling and power demand of buildings and maximize the utilization of hot dry rock resources.

The above research can well solve the coordinated dispatching problem and improve the system economy, but the interaction of the hybrid power system participants is not entirely reflected [25]. Therefore, other scholars have discussed the hybrid power system's coordinated operation based on game theory [26]. In [27], game theory was introduced to model a hybrid power system comprising wind turbines, PV plants, and batteries to optimize the dispatching strategy of energy storage systems. The Stackelberg game was used to obtain the charging strategy of electric vehicles and the pricing strategy of charging stations [28]. Cooperative and non-cooperative game methods were used to study automatic distributed optimal economic of automatic generation control in multi-region power systems [29]. A non-cooperative game dispatching model composed of wind power, thermal power, and pumped storage power plants was established to optimize the combined operation effects in different seasons [30]. Through non-cooperative game theory, a power generation dispatch model of a hybrid power system containing wind, wind, and heat was established to maximize the overall profits in the long-distance transmission scenario [31]. A general framework for power system flexibility analysis based on cooperative game theory was proposed for risk design and energy policy design [32]. The potential cooperative behaviors of multiple grid-connected micro-grids were simulated to achieve higher efficiency and better economy [33]. In [34], the payoffs of wind turbines, thermal power stations, and electric vehicles in the power market were studied based on cooperative game theory, and the imputation of the cooperative game was rationally allocated based on the Shapley value. The profit allocation of the hybrid power system in the cooperative game was analyzed in [35]. The results show that the Shapley value is the most stable allocation strategy.

Previous studies have provided extensive theories and methods for the hybrid power system dispatching. However, the characteristics of HDR power stations observed in the energy extraction and conversion process lead to different operational strategies compared to thermal power stations and energy storage power stations. The existing coordinated dispatching models and payoff allocation mechanisms for multi-energy sources are not entirely suitable for HDR power stations. Accordingly, the coordinated operation model and payoff allocation strategy for HDR power stations require further research.

Therefore, the major contributions of this paper are: (1) a new method for designing HDR power stations is presented to reduce the power fluctuations of PV plants and improve the reliability of the power grid; (2) a hybrid power system composed of HDR, TS, and PV plants is constructed, and the coordinated operational characteristics of HDR power stations in the hybrid power system are analyzed; (3) a game pattern with HDR power stations, TS power stations, and PV plants as players is proposed. The non-cooperative game's payoff function and the characteristic function of the cooperative game are then defined; and (4) the game dispatching models are simulated with the case of the Gonghe Basin of Qinghai. Finally, a sensitivity analysis of the two critical parameters of the allowed fluctuation rate, and the penalty coefficient is carried out.

The remainder of this paper is organized as follows. The architecture of the HDR-TS-PV hybrid power system and characteristics of the HDR power station are given in Section 2. The HDR-TS-PV game model is proposed in Section 3. Section 4 simulates a case based on actual data of the Gonghe Basin. An in-depth discussion of the simulation results is carried out in Section 5. Conclusions and further developments are discussed in Section 6.

2. HDR-TS-PV Hybrid Power System Architecture

2.1. Architecture of the Hybrid Power System

Conventional HDR power stations include geothermal mining cycles and ORC generators [36]. Because the extraction of geothermal energy from artificial reservoirs established by hydraulic fracturing requires a bottom hole pressure of 30 MPa to 40 MPa and a pipeline

that is 3 km to 4 km deep [37] and considering the working fluid velocity and the rock elastic modulus, the dynamic response time of the geothermal mining cycle is especially high. Although the annual utilization time can exceed 8000 h, the flexibility of *HDR* power stations is not sufficient to fully exploit the energy storage effect of the reservoirs to provide reliable support for *PV* plants.

Therefore, it is necessary to design a *TS* power station that can be coordinated with *HDR* power stations to improve operational flexibility. The *TS* power station comprised a thermal energy storage exchanger (*TESE*), a thermal energy storage tank, an *ORC* generator, and an electric heating device. The heat-transfer oil (*HTO*) was used as the thermal energy storage medium. The *TS* power station can use the *TESE* to store the waste heat from the *HDR* power station and convert the surplus power from *PV* plants into thermal energy through the electric heating device.

Conversely, conventional battery energy storage stations cannot adapt to the Qinghai plateau's cold climate, have a short cycle life, and cannot directly use geothermal energy. Nevertheless, the *TS* power station is not affected by environmental conditions; it demonstrates the flexible operation of the battery energy storage stations and can store geothermal energy directly, making it suitable for a hybrid power system with an *HDR* power station.

The hybrid power system of the Gonghe Basin was considered as a test case for this research. The region has a plateau continental climate with large temperature variations and experiences rapid changes in weather conditions throughout the day. Although solar energy resources are abundant, the local loads are insufficient and require a large amount of *PV* power to be transmitted for consumption. Therefore, the local government has formulated a policy that renewable energy power stations should be equipped with energy storage systems with a capacity of 5% to 10%. An *HDR-TS-PV* hybrid power system architecture was constructed with a typical 200 MWp *PV* plant equipped with an *HDR* power station and a *TS* power station, as shown in Figure 1.

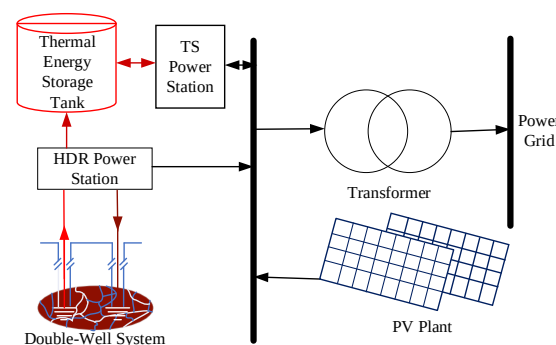


Figure 1. Architecture of the hybrid power system.

As Figure 1 shows, the *HDR* power station was designed according to the temperature of the *HDR* source, which was calculated considering the optimal working fluid flow and the power generation efficiency given in [11], and its capacity was set at 6.6 MW. The *TS* power station was coordinated with the *HDR* power station, whose capacity was also set at 6.6 MW. The *HDR-TS-PV* hybrid power system improves the operational flexibility and economy of the *HDR* power station through the adjustable *TS* power station and simultaneously enhances the reliability of the *PV* plant. In this hybrid power system, the *HDR* power station, *TS* power station, and *PV* plant are connected to the low voltage side of the same transformer. To coordinate the operation of the three elements, this study makes the following assumptions:

1. The *HDR* power station is a standard double-well system [4];
2. The effects of network congestion and line capacity on the system are ignored;
3. The *TOU* price is regulated by the power selling side.

2.2. Operating Characteristics of HDR Power Station in Hybrid Power System

The HDR power station, as shown in Figure 2, is composed of a geothermal mining cycle and ORC generator, coupled with a heater. The geothermal mining cycle consists of underground HDR fracture channels, a production well, a reinjection well, a circulating pump, and the heater. The brine is driven by the circulating pump from the reinjection well into the underground HDR fracture channels to absorb geothermal energy, then from the production well into the heater to release the heat and re-enter the reinjection well.

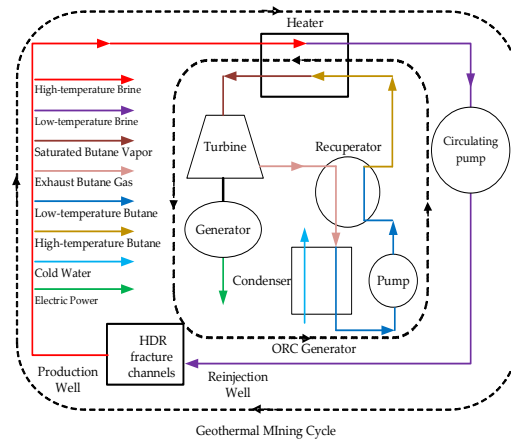


Figure 2. Structure chart of the hot dry rock (HDR) power station.

The ORC generator includes the heater, a recuperator, a turbine, a condenser, a generator, and a pump. The liquid organic working fluid butane is driven by the pump to enter the heater for absorbing the heat released by the brine. The butane with the saturated vapor state then enters the turbine to expand and convert heat into mechanical energy. The residual energy still contained in the exhaust butane gas is transferred to the low-temperature liquid butane through the recuperator. The exhaust butane gas finally condenses into the low-temperature liquid butane in the condenser and then enters the next cycle again. A more detailed discussion of the ORC could be found in [38].

Several days are required for the HDR power station to establish a stable geothermal mining cycle, and a similar period is required to adjust the geothermal working fluid pressure and flow rate, and the fluid used is usually brine. Therefore, compared to thermal power plants, the power ramp rate of conventional HDR power stations is low, and frequent start and stop cannot be achieved. In the actual operation, the HDR power station consistently maintains its geothermal mining cycle by alternately configuring two circulating pumps. This feature further urges the ORC generators to continuously generate electricity in order to fully exploit the geothermal energy for higher economic benefits. The continuous power generation model of a conventional HDR power station [12] is

$$P_{Hc}^t = \eta_P m_r^t c_{pr} (T_{HDR} - T_{Well}) \quad (1)$$

where P_{Hc}^t represents the output power, m_r^t is the mass flow of brine, c_{pr} is the specific heat capacity of brine, and η_P is the ORC generator's efficiency. T_{HDR} and T_{Well} represent the outlet temperature of the production well and the temperature of the reinjection well, respectively.

It should be noted that under the hybrid power system architecture shown in Figure 1, part of the continuous geothermal energy generated by the geothermal mining cycle can be stored in the thermal energy storage tank through the TESE so that the geothermal energy flow is decoupled from the electrical energy flow of the ORC generator. Therefore, the HDR power station can fully utilize the fast adjustment speed and wide range of operating

conditions of the ORC generator to provide reserves without losing geothermal energy. The flexible power generation model of the HDR power station can be expressed as follows:

$$m_{\alpha}^t + m_{\beta}^t = m_r^t, \quad (2)$$

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

$$P_{Hf}^t = \eta_P m_{\alpha}^t c_{pr} (T_{HDR} - T_{Well}), \quad (4)$$

where Equation (2) represents the model of the brine distribution, m_{α}^t represents the mass of the brine used for power generation, and m_{β}^t represents the brine used for thermal energy storage. Q_{β}^t is the thermal power input to the TESE in Equation (3), and T_{β} represents the waste heat temperature of the brine after TESE. The output power of the HDR power station can then be described by Equation (4), where, P_{Hf}^t represents the output power.

3. HDR-TS-PV Game Model

3.1. ElementTS of the Game

Compared with other coordinated dispatching methods, game theory can better clarify the internal mechanisms of multi-agent competition and cooperation to quantify each party's benefits. The elements of the game include Player, Strategy, and Payoff.

1 Player

The HDR power station, TS power station, and PV plant are the three players, denoted by H, T, and P, respectively.

2 Strategy

The operational goal of the HDR power station is to obtain as much profit as possible to rapidly recoup the high costs of construction by changing the mass flow of brine to dispatch the power. Therefore, the strategy set of the HDR power station is

$$\Omega_H = \left\{ P_{Hf}^t \mid P_H^{\min} \leq P_{Hf}^t \leq P_H^{\text{install}} \right\}, \quad (5)$$

where P_H^{install} represents the installed capacity of the HDR power station, and $P_H^{\min}$ is the output power that meets the minimum power generation requirements of the ORC generator, which is generally 10% of the installed capacity.

The TS power station primarily realizes the arbitrage of the electricity price peak-valley difference by dispatching purchased power and generating power. Therefore, the strategy set of the TS power station is

$$\Omega_T = \left\{ \begin{array}{l} P_{\text{purch}}^t \mid 0 \leq P_{\text{purch}}^t \leq P_{\text{heat}}^{\max} \\ P_T^t \mid P_T^{\min} \leq P_T^t \leq P_T^{\text{install}} \end{array} \right\}, \quad (6)$$

where P_{purch}^t is the electric power purchased from the grid during the low TOU price period and limited by the maximum power $P_{\text{heat}}^{\max}$ of the electric heating device. P_T^t represents the power generation capacity of the TS power station, and its upper and lower limits are the installed capacity P_T^{install} and the ORC generator and the minimum power generation condition $P_T^{\min}$, respectively.

The operational goal of a PV plant is to formulate a credible output power plan based on the weather forecast data to increase the credible capacity connected to the grid as much as possible so as to reduce the loss of surplus power and penalty incurred by abandoning loads. its strategy set is

$$\Omega_P = \left\{ P_{PV}^t \mid 0 \leq P_{PV}^t \leq P_{PV}^{\text{install}} \right\}, \quad (7)$$

where P_{PV}^t is the credible output power of the PV plant, and its corresponding installed capacity is the credible capacity of the PV plant, denoted by P_{PV} . $P_{PV}^{install}$ represents the installed capacity of the PV plant.

3 Payoff

All three players profit by selling electricity to the grid so that we can define the payoff vector of the game as

$$I = (I_H, I_T, I_P), \quad (8)$$

where I_H , I_T and I_P represent the payoff of the HDR power station, TS power station, and PV plant, respectively.

Each player has an independent and equal status and can either compete in a non-cooperative game or try to increase profits through cooperation. The coordination dispatching models of the two types of games are given below.

3.2. HDR-TS-PV Non-Cooperative Game and Payoff Functions

If all three players are independent and try to maximize their profits, they naturally constitute a non-cooperative game of competition with each other. This paper first presents the payoff functions of the three players in non-cooperative games in order to compare and analyze the results of the subsequent cooperative game dispatching model.

3.2.1. Payoff Function of HDR Power Station

Owing to the continuity of the geothermal mining cycle, the brine mass flow of the HDR power station cannot be adjusted in the non-cooperative game in order to avoid heat loss. The flexibility of the ORC generator cannot be fully utilized, and only the continuous power generation mode can be adopted. Therefore, according to Equation (1), the payoff function of the HDR power station is

$$I_H = \sum_{t=1}^T c_e^t P_{Hc}^t. \quad (9)$$

3.2.2. Payoff Function of TS Power Station

In the non-cooperative game, the TS power station purchases electricity from the power grid during the low TOU price period and converts it into thermal energy. During the high TOU price period, the TS power station generates electricity for arbitrage. The payoff function is

$$I_T = \max \sum_{t=1}^T c_e^t (P_T^t - P_{purch}^t). \quad (10)$$

The output power of the TS power station to the power grid can be modeled as

$$P_T^t = \eta_P m_{dc}^t c_{po} (T_h - T_l), \quad (11)$$

where m_{dc}^t is the mass flow of the HTO during the power generation period and c_{po} is the specific heat capacity of the HTO. T_h and T_l represent the temperature of the HTO used for power generation and its temperature after power generation, respectively.

The operation of the TS power station must also account for the following thermal storage state constraints and thermal energy store/release constraints:

$$S_h^t = \eta_h S_h^{t-1} + (Q_c^t - Q_{dc}^t / \eta_{dc}) \Delta \tau, \quad (12)$$

$$Q_c^t = \eta_e P_{purch}^t, \quad (13)$$

$$Q_{dc}^t = m_{dc}^t c_{po} (T_h - T_l), \quad (14)$$

where S_h^t is the thermal storage energy in the tank, Q_c^t is the input thermal power when the TS power station is storing thermal energy, Q_{dc}^t is the released thermal power, η_h is the

thermal preservation coefficient of the thermal energy storage tank, η_{dc} is the efficiency of the thermal release process, η_e is the electric heating efficiency, and $\Delta\tau$ is the time interval.

3.2.3. Payoff Function of PV Plant

The output power of the PV plants can be modeled using solar irradiance and the installed capacity [39]. According to the weather forecast, the PV plant obtains the predicted output power as the credible power generation in the first stage. The curtailed electricity and the abandoned loads are obtained from the actual solar irradiance in the second stage. This type of problem can usually be described by a Bayesian game model [34]: the two players of the game are the PV plants and nature, where the PV plants make decisions based on predicted values, and nature determines the joint probability of the actual solar irradiance. The payoff function of the PV plant is

$$I_P = \sum_{t=1}^T [c_e^t \bar{P}_{PV}^t - \sum_{k=1}^K \pi_k (c_e^t P_{PVcur}^{k,t} - c_{ph}^t P_{PVal}^{k,t})], \quad (15)$$

where k is the number of types of solar irradiance, π_k is the probability of each type, $\bar{P}_{PV}^t$ represents the predicted value of the output power based on the solar irradiance in the non-cooperative game. $P_{PVcur}^{k,t}$ and $P_{PVal}^{k,t}$ are the curtailed power and the abandoned loads under each type, and c_{ph}^t is the penalty price for abandoned loads. The models of $\bar{P}_{PV}^t$, $P_{PVcur}^{k,t}$, and $P_{PVal}^{k,t}$ are

$$\bar{P}_{PV}^t = \lambda_{PV}^t \bar{P}_{PV}, \quad (16)$$

$$P_{PVcur}^{k,t} = \max\{\bar{\xi}_{PV}^{k,t} - \bar{P}_{PV}^t, 0\}, \quad (17)$$

$$P_{PVal}^{k,t} = \min\{\bar{\xi}_{PV}^{k,t} - \bar{P}_{PV}^t, 0\}, \quad (18)$$

$$|\bar{\xi}_{PV}^{k,t} - \bar{P}_{PV}^t| \leq \varphi \quad (19)$$

where λ_{PV}^t is the power generation coefficient of the PV plant predicted according to the solar irradiance [39] and $\bar{\xi}_{PV}^{k,t}$ is the actual output power corresponding to the non-cooperative part of the PV plant. φ is the power predicted error of the PV plant.

The penalty price for abandoning loads, c_{ph}^t is expressed as the product of the penalty coefficient for abandoning loads p and the TOU price c_e^t , namely,

$$c_{ph}^t = p c_e^t. \quad (20)$$

3.3. HDR-TS-PV Cooperation Game Pattern

If the three players in the hybrid power system intend to form coalitions, such as coordinated dispatching with a PV plant, the HDR power station can obtain greater benefits by providing auxiliary services and by the coordinated dispatching with a TS power station, and the HDR power station can use the TOU prices for arbitrage. The three players participate in cooperation under these conditions. Due to the limitations caused by the efficiency of the ORC generator, it is difficult for the TS power stations to profit from the TOU prices. Therefore, the TS power stations need to cooperate with the HDR power station or the PV plant to profit from waste geothermal or surplus PV power with zero marginal costs. Concurrently, because of the requirements of power grid assessment for the PV curtailment power and the abandonment load, the PV plant also cooperates in order to reduce the loss of the curtailed power and the penalty for abandoning the load.

It is observed that through cooperation, the three players can obtain a greater payoff and allocate extra profits through energy settlement, which is only related to the cooperating players. Therefore, cooperation between HDR, TS, and PV can be modeled by the characteristic function game (CFG). CFG uses the tuple $G = \langle N, V \rangle$ to describe the

cooperative game relationship, where $N = \{1, 2, \dots, n\}$ is a set representing the number of players in the coalition. V represents the characteristic function that reflects the payoff of the coalition, which is represented by the mapping relationship $V : F(N) \rightarrow R$. For any S_i of $S_i \in N$, $V(S_i)$ or V_{S_i} represents the overall payoff of the S_i coalition.

In the cooperative game, the three players can form four different coalitions denoted by $\{H, T\}$, $\{H, P\}$, $\{T, P\}$, and $\{H, T, P\}$. The payoff of the players is defined by the tuple $\langle S_n, x \rangle$, where $S_N = \{S_1, S_2, \dots, S_n\}$ is the coalition structure and $x = \{x_1, x_2, \dots, x_n\}$ is the payoff vector. $\langle S_n, x \rangle$ must meet the individual rationality

$$x_i \geq I_i, \forall i \in \{H, T, P\}, \quad (21)$$

where x_i is the payoff received by the player i in the coalition, and I_i represents the payoff of the player i in the non-cooperative game.

3.4. Characteristic Functions of HDR-TS-PV Cooperative Game

In the non-cooperative game, each player can only achieve their best profits through their independent dispatching strategies. By forming coalitions, players have more options for coordinated dispatching, thus expanding the strategy set. Based on the original profit model, HDR and TS power stations can also profit by providing reserves for the PV plant, but their primary strategies are to dispatch output power. Therefore, the strategy sets of the HDR and TS power stations are still Ω_H and Ω_T , respectively. The PV plant can reduce the curtailed power and penalty for abandoning the load by purchasing reserves; therefore, its strategy set also includes

$$\Omega'_P = \{R^t \mid |R^t + \zeta_{PV}^t - P_{PV}^t| \leq \sigma P_{PV}^t\}, \quad (22)$$

where R^t represents the reserves purchased by the PV plant, and σ represents the power fluctuation rate allowed by the grid. In the case of purchasing the reserves, the constraint in Equation (22) always limits the PV plant's output power within a range of $\pm\sigma$ around the predicted value. Therefore, P_{PV}^t can be considered as the credible output power of the PV plant, and its corresponding installed capacity is the credible capacity of the PV plant, denoted by P_{PV} . ζ_{PV}^t represents the actual output power corresponding to the credible capacity part of the PV plant.

Because the actual installed capacity of the PV plant may be greater than the reserve capacity provided by the HDR power station, the installed capacity can be divided into non-cooperative and cooperative parts in the cooperative game.

$$P_{PV}^{install} = P_{PV} + \bar{P}_{PV}, \quad (23)$$

In a non-cooperative game, the players cannot use their respective resource characteristics and operating modes to achieve complementary advantages. Through cooperation, players can fully coordinate the dispatching of resources to maximize profits. The operating models and the profit models can be innovated to expand payoff sources, thereby increasing the overall payoff of the hybrid power system. The characteristic function of each coalition is described below.

3.4.1. Characteristic Function of HDR-TS Coalition

In the HDR-TS coalition, the TS power station stores part of the HDR geothermal mining cycle's thermal energy in the low TOU price periods and then reuses the stored thermal energy to generate power in the high TOU price periods for arbitrage. The characteristic function of the HDR-TS coalition is

$$V_{\{H,T\}} = \max \sum_{t=1}^T c_e^t (P_{Hf}^t + P_T^t). \quad (24)$$

According to the flexible generation model of the *HDR* power station described in Equations (2)–(4), the heat exchange constraints for the *TS* power station to obtain geothermal energy from the *HDR* power station are

$$Q_c^t = m_c^t c_{po} (T_c - T_l), \quad (25)$$

$$Q_c^t = \eta_{ex} Q_\beta^t, \quad (26)$$

where T_c represents the thermal energy storage temperature of the HTO, Q_β^t represents the waste heat power of the *HDR* power station, and η_{ex} is the heat exchange efficiency of the TESE. Additionally, the constraints of the optimization problem Equation (24) also include Equations (1), (12) and (14).

3.4.2. Characteristic Function of *HDR-PV* Coalition

In the *HDR-PV* coalition, the *HDR* station flexibly distributes the mass flow of the brine to provide reserves for the *PV* plant, which can then increase the overall payoff of the coalition by reducing the curtailment power and penalty for abandoning loads. The characteristic function of the *HDR-PV* coalition is

$$V_{\{H,P\}} = \max \sum_{t=1}^T \sum_{k=1}^K \pi_k c_e^t (P_{Hf}^{k,t} + P_{PV}^{k,t}) + I_P, \quad (27)$$

where I_P represents the payoff of the non-cooperative game part of the *PV* plant, which is calculated according to Equation (15).

The reserve dispatching constraints for the *HDR-PV* coalition are

$$R_{Hf}^{k,t} = \Delta m_\alpha^{k,t} \eta_{PCpr} (T_r - T_\alpha), \quad (28)$$

$$R_{Hf}^{k,t} + \zeta_{PV}^{k,t} \leq (1 + \sigma) P_{PV}^t, \quad (29)$$

$$R_{Hf}^{k,t} + \zeta_{PV}^{k,t} \geq (1 - \sigma) P_{PV}^t, \quad (30)$$

where $R_{Hf}^{k,t}$ represents the reserves provided by the *HDR* power station, and $\Delta m_\alpha^{k,t}$ is the brine mass flow required when the reserves are dispatched.

3.4.3. Characteristic Function of *TS-PV* Coalition

In the *TS-PV* coalition, the *TS* power station converts the electricity purchased from the grid during the low *TOU* price periods and the surplus *PV* power into thermal energy for storage. During the high *TOU* price periods or shortage periods of the *PV* plant, the stored thermal energy is used to generate revenue and provide reserves for the *PV* plant. The *TS* power station achieves profitability through the zero-cost electricity generated by the surplus *PV* power. Simultaneously, the *PV* plant increases its credible capacity and reduces the penalty for abandoning loads by purchasing reserves, thus forming a cooperative game pattern. The characteristic function of the *TS-PV* coalition is

$$V_{\{T,P\}} = \max \sum_{t=1}^T \sum_{k=1}^K \pi_k c_e^t (P_T^{k,t} + P_{PV}^{k,t} - P_{Purch}^{k,t}) + I_P. \quad (31)$$

The *TS* power station provides an up-reserve through the ORC generator to realize the profits and a down-reserve through electric heating devices to absorb surplus *PV* power. The reserve constraints of the *TS-PV* coalition are

$$R_{TS}^{k,t} = \Delta m_{dc}^{k,t} \eta_{PCpo} (T_c - T_l), \quad (32)$$

$$R_{TS}^{k,t} + \zeta_{PV}^{k,t} + P_{PVcur}^{k,t} \leq (1 + \sigma) P_{PV}^t, \quad (33)$$

$$R_{TS}^{k,t} + \zeta_{PV}^{k,t} + P_{PVcur}^{k,t} \geq (1 - \sigma)P_{PV}^t, \quad (34)$$

where $R_{TS}^{k,t}$ represents the up-reserve provided by the TS power station, $\Delta m_{dc}^{k,t}$ is the mass flow of HTO that needs to be adjusted when the up-reserve is dispatched, and $P_{PVcur}^{k,t}$ represents the surplus PV power consumed when the TS power station provides a down-reserve for the PV plant. The constraints also include Equations (1) and (12).

3.4.4. Characteristic Function of HDR - TS - PV Coalition

When the HDR power station, TS power station, and the PV plant are coordinated for dispatch, the TS power station can store geothermal energy in the thermal energy storage tank for the subsequent generation, which improves the flexibility of the HDR power station and realizes the peak regulation of the geothermal energy. Both the HDR power stations and the TS power stations can simultaneously provide reserves for the plants through flexible output power dispatching strategies, thereby increasing the credible capacity of the PV plant, reducing the curtailment of PV power and the penalty for abandoning loads, and further improving the overall payoffs. The characteristic function of the HDR - TS - PV coalition is

$$V_{\{H,T,P\}} = \max \sum_{t=1}^T \sum_{k=1}^K \pi_k c_e^t (P_{Hf}^{k,t} + P_T^{k,t} + P_{PV}^{k,t}) + I_P. \quad (35)$$

The constraints of the HDR - TS - PV coalition include the operating constraints, thermal storage state constraints, and reserve constraints of their respective systems, including Equations (1)–(4), (12), (25), (28)–(30), (32)–(34). They are not repeated here.

4. Case Study

4.1. System Parameters

Based on the weather conditions in the Gonghe Basin of Qinghai and TOU price, a fictitious hybrid power system was constructed to verify the models and the methods proposed in this paper. In addition to abundant solar energy resources, the Gonghe Basin also has high-quality HDR resources [40,41]. The scenario diagram of the fictitious hybrid power system is shown in Figure 3. The solar irradiance and the TOU price curves are shown in Figure 4.

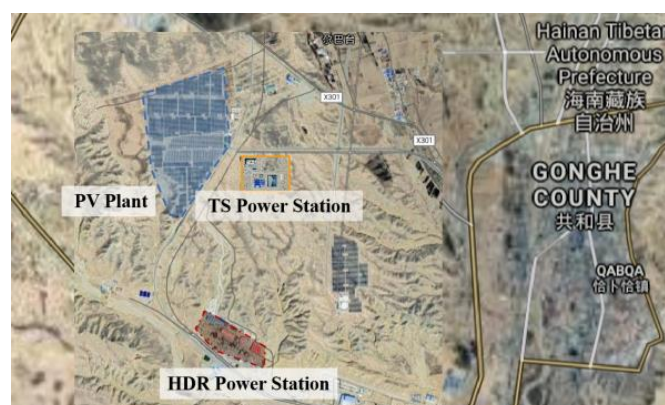


Figure 3. Scenario diagram of the hybrid power system.

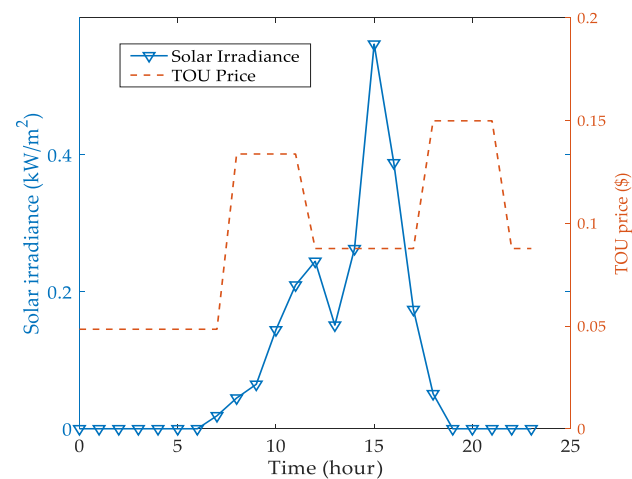


Figure 4. Solar irradiance and TOU price curve.

The Latin hypercube method [42] is adopted to generate 10,000 scenarios using the actual solar irradiance data, which are finally reduced to 100 typical scenarios [43] as the types observed in nature. The system parameters are listed in Table 1.

Table 1. System parameters.

System Parameters	Values
Installed capacity of HDR power station $P_H^{install}$ (MW)	6.6
Installed capacity of PV plant $P_{PV}^{install}$ (MW)	200
Installed capacity of TS power station $P_T^{install}$ (MW)	6.6
Brine temperature at the producing well T_{HDR} (°C)	200
Brine mass flow m_r^t (kg/s)	75
Brine temperature at the reinjection well T_{Well} (°C)	75
Initial temperature of HTO T_l (°C)	25
Specific heat capacity of HTO c_{po} (kJ/(kg·°C))	1.938
Specific heat capacity of brine c_{pr} (kJ/(kg·°C))	4.2
ORC generator efficiency η_p (%)	13.2 [12]
Heat preservation coefficient η_h (%)	99
Efficiency of TESE η_{ex} (%)	90
Power predicted error of the PV plant φ (%)	20
Allowed fluctuation rate σ (%)	0–10
Penalty coefficient p	2–5

4.2. Dispatching Results

Each payoff function and characteristic function is linear programming or mixed-integer linear programming, which was solved by software MATLAB2016b and CPLEX12.8. The results are shown in Table 2.

Table 2. Dispatching results of cooperative and non-cooperative games.

Coalition Forms	Cooperative Payoff (\$/Day)	Non-Cooperative Payoff (\$/Day)
{H}	—	14,674
{P}	—	41,510
{T}	—	0
{H,T}	19,192	14,675
{H,P}	55,900	56,184
{T,P}	42,139	41,511
{H,T,P}	61,888	56,185

It can be observed from Table 2 that the payoff of the *TS* power station is zero because it cannot profit in the non-cooperative game. The payoff of the *HDR-PV* coalition is lower than the sum of the two non-cooperative game payoffs, i.e.,

$$V_{\{H,P\}} < I_H + I_P. \quad (36)$$

These results show that the *HDR* power station and the *PV* plant cannot form a stable coalition. Figure 5 shows the results for the coordinated operation of the *HDR-PV* coalition. The *HDR* power station provides reserves to increase the credible capacity of the *PV* plant by replacing geothermal energy with the curtailed power and the abandoned loads. However, the cost of abandoning geothermal energy is greater than the sum of the curtailed power and penalty for abandoning loads. Therefore, the coordinated operation of the *HDR* power station and *PV* plant cannot increase the overall payoff, making the *HDR-PV* coalition unstable.

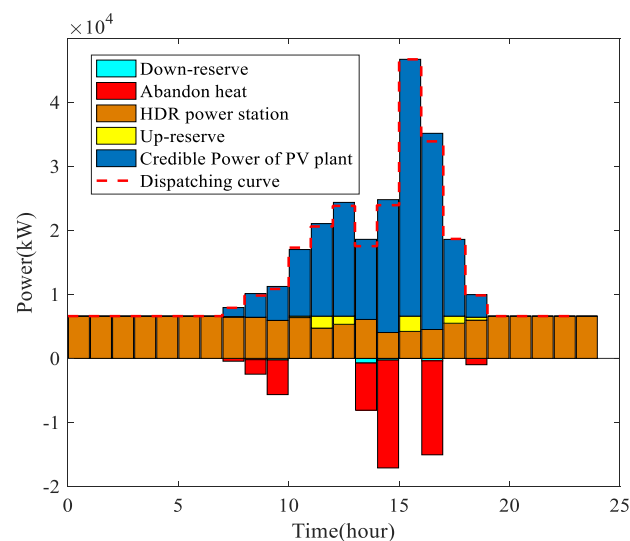


Figure 5. The coordinated operation of hot dry rock-photovoltaic (*HDR-PV*) coalition.

When the *TS* power station joins the *HDR-PV* coalition to form a grand coalition, the abandoned geothermal energy used to stabilize the fluctuation of the *PV* plant is reused by the *TS* power station to generate new profits. The results of the grand coalition cooperative game dispatching are shown in Figure 6. During the low TOU price period (0:00–7:00), both the *HDR* and *TS* power stations maintain minimum output power. The continuous geothermal energy is stored in the thermal energy storage tank of the *TS* power station while ensuring the safety of the geothermal mining cycle. During the *PV* generation period (8:00–18:00), the *HDR* and *TS* power stations provide reserves corresponding to the credible output power of the *PV* plant. The *HDR* power station is then operated at full power to maximize profits. The *TS* power station converts all the stored thermal energy into electricity during the high TOU price period (19:00–22:00).

In the end, the three players tend to form an *HDR-TS-PV* grand coalition. The overall payoff of the hybrid power system in each game form is shown in Table 3.

The coordinated dispatching results of the grand coalition obtained by the cooperative game dispatching model proposed in this paper are shown in Figure 7.

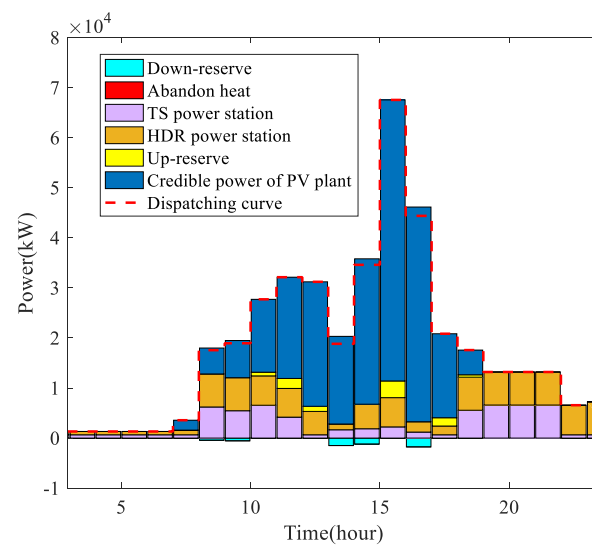


Figure 6. The coordinated operation of hot dry rock-thermal storage-photovoltaic (HDR-TS-PV) coalition.

Table 3. The overall payoff of each coalition.

Coalition Form	Overall Payoff (\$/Day)
[[H],[P],[T]]	56,185
[[H,T],[P]]	60,702
[[H,P],[T]]	55,900
[[T,P],[H]]	56,814
[[H,T,P]]	61,888

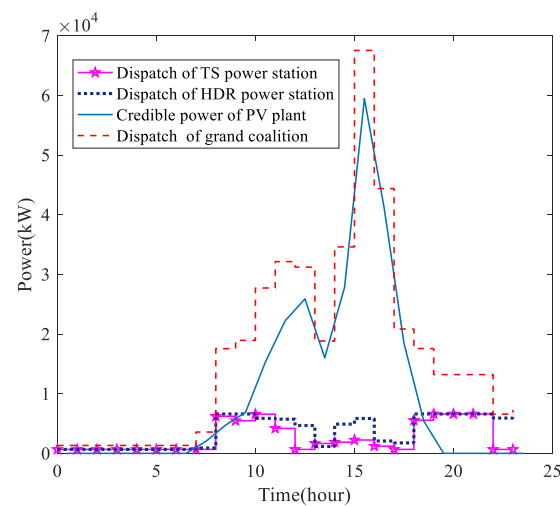


Figure 7. The coordinated dispatching of HDR-TS-PV coalition.

4.3. Stability Analysis of Coalitions

In general, the payoff allocation of the coalition is not unique, and the set of all the stable allocations is defined as a core. In this paper, we adopt the minimum core (ϵ -core) method to analyze the stability of the coalitions, namely

$$\inf\{\epsilon : \epsilon - \text{core}(G) \neq \emptyset\} \quad \text{s.t.} \quad \epsilon - \text{core}(G) = \left\{ \langle S_n, x \rangle \mid \sum_{i \in S} x_i \geq V(S) - \epsilon, \forall S \subseteq N \right\} \quad (37)$$

where $core(G)$ is the core set of the coalition and ε is the relaxation variable [44]. If the lower bound of ε is equal to zero, then the $core(G)$ is non-empty before relaxation. Thus, the coalition is stable.

According to the overall payoff in Table 3, three players can form a stable grand coalition with a non-empty core through Equations (7) and (36). The stable allocation set of the grand coalition is shown in Figure 8.

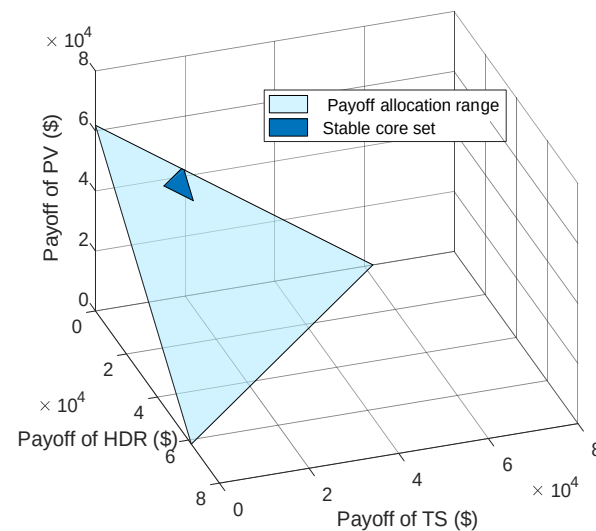


Figure 8. Stable allocation set.

4.4. Allocation Strategy Based on Shapley Value

A stable coalition cannot guarantee the rationality of the payoff allocation. Therefore, it is necessary to study the fairness method of payoff allocation to provide a fair allocation strategy. The Shapley value is the fairest and most reasonable payoff allocation value among equal players [45]. It is based on marginal contributions and is widely used in cooperative games. Considering that there is no difference in status and weight between the HDR power station, the TS power station, and the PV plant, the Shapley value is adopted as the payoff allocation strategy. The simplified calculation [46] of the Shapley value can be expressed as

$$x_i = \frac{1}{n!} \sum_{S \subseteq N, i \in S} (|S|-1)!(n-|S|)!(V(S) - V(S \setminus \{i\})), \quad (38)$$

where $|S|$ is the number of elements in the subset S and $V(S \setminus \{i\})$ represents the remaining players in the sub-coalition after excluding player i .

Table 4 shows the allocation results of the three players based on the Shapley value. Further analysis of the stability of this allocation strategy through Equation (37) shows that the allocation obtained by the Shapley value is stable, as shown in Figure 9.

Table 4. Allocation based on Shapley value.

Player	Payoff (\$/Day)	Extra Profits (\$/Day)
HDR power station	17,072	2397
PV plant	41,963	453
TS power station	2854	2854

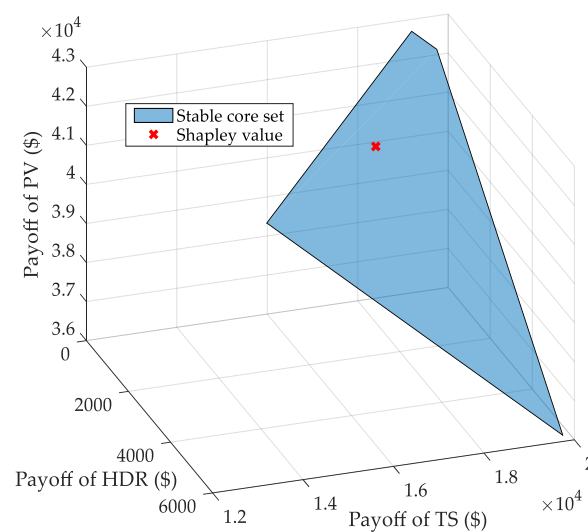


Figure 9. Stability of the Shapley value.

4.5. Sensitivity Analysis

The extra profits of the grand coalition generated by the cooperative game are closely related to the allowed fluctuation rate that the power grid can tolerate and the penalty coefficient for abandoning loads. Therefore, based on the preceding section, the allowed fluctuation rate and penalty coefficient are varied to further analyze the role of the HDR, PV, and TS plants in the grand coalition.

Under the parameters in Table 1, the allowed fluctuation rates are set at 0%, 1%, 2%, and 3%. Simultaneously, when the penalty coefficients are 2, 3, 4, and 5, respectively, the payoff of the grand coalition and the extra profits obtained by each player are calculated. Figure 10 shows the relationship between the overall payoffs, the allowed fluctuation rate, and the penalty coefficient.

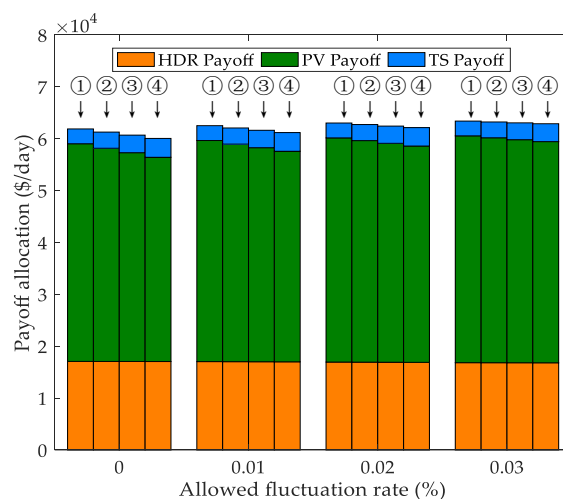


Figure 10. The payoff allocation in the grand coalition.

In Figure 10, ①, ②, ③, and ④ correspond to the scenarios where the penalty coefficients p are equal to 2, 3, 4, and 5, respectively. The overall payoff of the coalition increases with the increasing allowed fluctuation rate, mainly due to an increase in the grid-connected power of the PV plant and the penalty reduction. The overall payoff of the coalition decreases with an increase in the penalty coefficient, and the payoff of the PV plant is affected directly by the penalty coefficient. However, the payoff of the HDR power station is almost constant, reflecting the characteristics of stability and continuity of

HDR resources. The TS power station is mainly responsible for creating profits and saving penalties by supporting the grid connection of the PV plant.

Figure 11 shows the changes in the allocation of the extra profits to the HDR, PV, and TS power stations with the change in the allowed fluctuation rate. The overall extra profits decrease with an increase in the allowed fluctuation rate, which indicates that the extra profits of the coalition decrease with an increase in the ability of the power grid to withstand power fluctuation. These extra profits are mainly caused by the curtailment of energy and penalty cost generated by the PV plant. Simultaneously, the extra profits of the HDR power station do not change with the penalty coefficient changes and are not sensitive to the allowed fluctuation rates, indicating that the extra profit of the HDR power station is obtained by the peak regulation of geothermal energy, which is not affected by the PV plant.

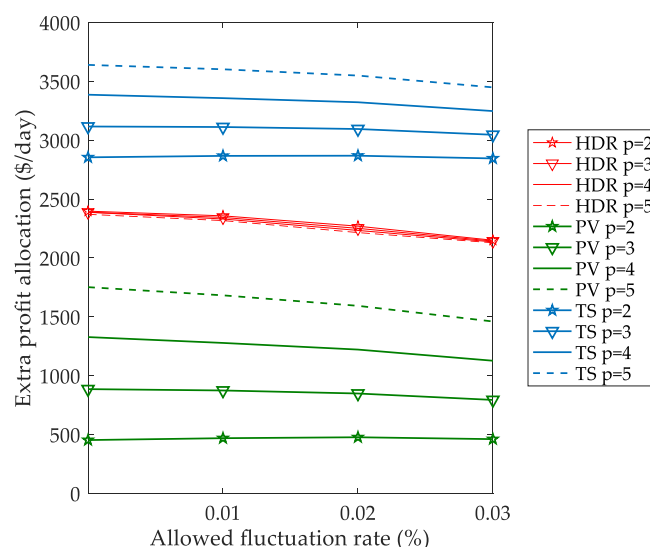


Figure 11. The extra profits allocation of HDR-TS-PV coalition.

The variation trends of the extra profits obtained by the PV and TS power stations are similar. The higher the penalty coefficient, the more the extra profits that are allocated. The relationship between the penalty coefficient and extra profits indicates that the TS power station is the main contributor that supports the grid connection of the PV station, realizes the value of the surplus PV power, and reduces the penalty.

Analysis of Figures 10 and 11 shows that the extra profits in the grand coalition, generated by the cooperative game, result from three factors. First, owing to the peak-regulating effect of the TS power station, the HDR generation period shifts from the low TOU price period to the high TOU price period. Second, through the flexible operation of the HDR and the TS power stations, a greater capacity of the PV station can track the dispatching curve, thus reducing the penalty. Third, the curtailed power and geothermal energy are stored and utilized by the TS power station.

5. Discussion

Further analysis of payoff and extra profits was carried out to reveal the role of the players in the hybrid power system and the source of the extra profits. It can be seen from Table 2 that under the TOU price given in Figure 3, the arbitrage operation of the TS power station cannot be profitable due to the low power generation efficiency of the ORC generator. As a result, the TS power station can only benefit by abandoning heat and electricity with zero marginal cost through cooperating with HDR power station or PV plant. Therefore, its dispatching strategy is to always adopt a minimum generation operation in low TOU price periods and PV generation periods in order to store as much as possible the waste heat and surplus power, as shown in Figure 7. It can be seen from the

actual operation shown in Figure 6 that under this operating strategy, the *TS* power station can play a peak shaving role by storing geothermal energy, which realizes its payoff and makes the geothermal energy mainly generated in high TOU price periods, thereby creating extra profits. Simultaneously, the *TS* power station can recover the waste heat of the *HDR* power station when the down reserve is provided to the *PV* plant, further improving the system profits. As can be seen from the allocation results in Table 4, the extra profits of the *TS* power station accounted for 50.04% of the total extra profits. This result further shows that the *TS* power station has the most considerable marginal contribution to the extra profits, reflecting the decisive role of the *TS* power station in the game relationship.

Due to its operating characteristics, the *HDR* power station cannot cooperate with the *PV* plant without abandoning heat, so it cannot provide auxiliary services for the *PV* plant alone. Since the *TS* power station can directly store geothermal energy, it can help the *HDR* power station realize arbitrage. Table 3 shows that when the *HDR* power station and the *TS* power station cooperate, the payoff of the *HDR-TS* coalition increases by 8.04% relative to the non-cooperation operation, and the overall payoff of the grand coalition only increases by 1.95% relative to the *HDR-TS* coalition when the *PV* plant joins. The extra profits in Table 4 show that the *HDR* power station is allocated 42.02% of the overall extra profits. This result shows that the increased profits of the hybrid power system in the cooperative game mainly come from the peak shaving arbitrage of geothermal energy. Figures 10 and 11 also show that the *HDR* power station is not affected by grid parameters σ and p , which further clarifies that the payoff and extra profits of the *HDR* power station mainly come from its geothermal energy.

Table 3 shows that when the *PV* plant and the *TS* power station cooperate, the overall payoff of the hybrid system only increased by 1.12%. In the grand coalition, the extra profits of the *PV* plant accounted for only 7.94%. It can be seen that the contribution of the *PV* plant to the extra profits of the hybrid system is small. The main interest of *PV* plants participating in the coordinated dispatch of the hybrid power system is to increase the credible capacity and reduce the impact on the grid so as to obtain the priority of grid connection. This result is also reflected in Figures 10 and 11. The increase in the allowed fluctuation rate and the penalty coefficient decrease indicates that the grid's ability to absorb fluctuating power has increased. A strong power grid increases the non-cooperative payoff of the *PV* plant and decreases the cooperative extra profits, thereby reducing the willingness of the *PV* plant to cooperate.

Moreover, since the temperature of the geothermal reservoir is a critical parameter that restricts the operating performance of the *HDR* power station, we conducted a preliminary simulation on the influence of the temperature change on the overall payoff of the hybrid power system. According to previous research [38], when the temperature is 170 °C, the energy efficiency of *ORC* is 12.7%. Simulation with these parameters shows that when the temperature drops to 170 °C, the overall payoff of the hybrid power system is 54,285 \$/day, a drop of 12.28%. The credible capacity of *PV* plants participating in cooperative games is reduced by 28.78%. The preliminary results indicate that after the *HDR* power station has been operating for about 10 years, the three players' willingness to participate in the cooperative game will decrease. More in-depth research on the influence of more *HDR* power station parameters on the hybrid power system is needed in future research.

6. Conclusions

For the grid-connection requirements of large-scale *PV* plants, we first proposed the technical route of using *HDR* power stations to provide reserves for *PV* plants in this study. The operating characteristics of conventional *HDR* power stations were analyzed, and a scheme for using *TS* power stations to improve the operating flexibility of *HDR* power stations was proposed. In this study, a hybrid power system consisting of an *HDR* station, a *TS* station, and a *PV* plant was designed, and a coordinated dispatching method was provided based on game theory. First, taking *HDR* power station, *TS* power station, and *PV* plant as players, the non-cooperative game model and the characteristic function game

model of the hybrid power system dispatching were established. The optimization of the dispatching models describes the decision-making processes of the players.

Consequently, the coordinated dispatching strategy of the players was obtained by calculating the optimal value of the payoff functions and the characteristic functions that can be transformed into linear optimization problems or mixed-integer linear optimization problems. The case analysis was based on actual data in the Gonghe Basin. The results show that only cooperation can maximize the overall payoff and the individual profits of the system. Due to heat loss, the HDR power station cannot form a coalition with the PV plant alone, reflecting the significant role of the TS power station in the system. Finally, the sensitivity analysis of the allowed fluctuation rate and the penalty coefficient shows that they significantly influence the overall payoff of the system and the operating strategies of each player. However, the profits of the HDR power station are not significantly affected by the two parameters, which reflects its stable characteristics. The main goal of PV plants in the cooperative game is to increase credible capacity and reduce the impact on the grid, and TS power station is the key to achieving extra profits for HDR power station and PV plant. This study provides an essential theoretical basis for developing power generation systems based on HDR geothermal energy in the Gonghe basin of Qinghai, China.

One limitation of this study is that the grid topology and capacity constraints are simplified when constructing the game dispatching model and calculating the payoff allocation of the hybrid power system. The influence of the grid structure on the hybrid power system will be further investigated in future studies.

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References

1. Cai, B.; Xue, Y.; Fan, Y.; Wen, Y.; Yang, X.; Yang, S.; Li, Z.; Wang, H. Optimization on Trans-regional Electricity Transmission Scale of China's Western Renewable Energy Base: The case study of Qinghai Province. *EDP Sci.* **2020**, *143*, 02012. [\[CrossRef\]](#)
2. Lu, S.-M. A global review of enhanced geothermal system (EGS). *Renew. Sustain. Energy Rev.* **2018**, *81*, 2902–2921. [\[CrossRef\]](#)
3. Xu, T.; Liang, X.; Feng, B.; Jiang, Z. Geologic setting of the potential EGS site at the Gonghe basin, China: Suitability for re-search and demonstration of hot dry rock geothermal energy development. In Proceedings of the 44th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 11–13 February 2019; Stanford University: Stanford, CA, USA, 2019.
4. Yan, X.; Yanguang, L.; Wang, G.; Lu, Y. Optimal injection rate of water in the Guide Basin hot dry rock mining project. *Energy Explor. Exploit.* **2019**, *37*, 721–735. [\[CrossRef\]](#)
5. Nabernegg, S.; Bednar-Friedl, B.; Muñoz, P.; Titz, M.; Vogel, J. National Policies for Global Emission Reductions: Effectiveness of Carbon Emission Reductions in International Supply Chains. *Ecol. Econ.* **2019**, *158*, 146–157. [\[CrossRef\]](#)
6. Breede, K.; Dzebisashvili, K.; Liu, X.; Falcone, G. A systematic review of enhanced (or engineered) geothermal systems: Past, present and future. *Geotherm. Energy* **2013**, *1*, 4. [\[CrossRef\]](#)
7. Brown, D.; Du Teaux, R.; Kruger, P.; Swenson, D.; Yamaguchi, T. Fluid circulation and heat extraction from engineered geo-thermal reservoirs. *Geothermics* **1999**, *28*, 553–572. [\[CrossRef\]](#)

8. Kumari, W.; Ranjith, P.; Perera, M.; Li, X.; Li, L.; Chen, B.; Isaka, B.A.; De Silva, V. Hydraulic fracturing under high temperature and pressure conditions with micro CT applications: Geothermal energy from hot dry rocks. *Fuel* **2018**, *230*, 138–154. [\[CrossRef\]](#)
9. Zhang, Y.-J.; Li, Z.-W.; Guo, L.-L.; Gao, P.; Jin, X.-P.; Xu, T.-F. Electricity generation from enhanced geothermal systems by oilfield produced water circulating through reservoir stimulated by staged fracturing technology for horizontal wells: A case study in Xujiaweizi area in Daqing Oilfield, China. *Energy* **2014**, *78*, 788–805. [\[CrossRef\]](#)
10. Quick, H.; Michael, J.; Huber, H.; Arslan, U. History of international geothermal power plants and geothermal projects in Germany. In Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 25–29 April 2010; pp. 25–29.
11. Fallah, M.; Mahmoudi, S.M.S.; Yari, M.; Ghiasi, R.A. Advanced exergy analysis of the Kalina cycle applied for low temperature enhanced geothermal system. *Energy Convers. Manag.* **2016**, *108*, 190–201. [\[CrossRef\]](#)
12. Fiaschi, D.; Manfreda, G.; Rogai, E.; Talluri, L. Exergoeconomic analysis and comparison between ORC and Kalina cycles to exploit low and medium-high temperature heat from two different geothermal sites. *Energy Convers. Manag.* **2017**, *154*, 503–516. [\[CrossRef\]](#)
13. Guo, S.; Liu, Q.; Sun, J.; Jin, H. A review on the utilization of hybrid renewable energy. *Renew. Sustain. Energy Rev.* **2018**, *91*, 1121–1147. [\[CrossRef\]](#)
14. Xu, T.; Zhang, N. Coordinated Operation of Concentrated Solar Power and Wind Resources for the Provision of Energy and Reserve Services. *IEEE Trans. Power Syst.* **2016**, *32*, 1260–1271. [\[CrossRef\]](#)
15. Peng, C.; Xie, P.; Pan, L.; Yu, R. Flexible Robust Optimization Dispatch for Hybrid Wind/Photovoltaic/Hydro/Thermal Power System. *IEEE Trans. Smart Grid* **2015**, *7*, 751–762. [\[CrossRef\]](#)
16. Dabbaghjamesh, M.; Mehraeen, S.; Kavousifard, A.; Igder, M.A. Effective dispatching operation of coordinated and uncoordinated wind-hydro and pumped-storage in generation units with modified JAYA algorithm. In Proceedings of the IEEE Industry Applications Society Annual Meeting 2017, Cincinnati, OH, USA, 1–5 October 2017; pp. 1–8.
17. Cebulla, F.; Naegler, T.; Pohl, M. Electrical energy storage in highly renewable European energy systems: Capacity requirements, spatial distribution, and storage dispatch. *J. Energy Storage* **2017**, *14*, 211–223. [\[CrossRef\]](#)
18. Nottrott, A.; Kleissl, J.; Washom, B. Energy dispatch schedule optimization and cost benefit analysis for grid-connected, photovoltaic-battery storage systems. *Renew. Energy* **2013**, *55*, 230–240. [\[CrossRef\]](#)
19. Aziz, A.S.; Tajuddin, M.F.N.; Adzman, M.R.; Ramli, M.A.; Mekhilef, S. Energy Management and Optimization of a PV/Diesel/Battery Hybrid Energy System Using a Combined Dispatch Strategy. *Sustainability* **2019**, *11*, 683. [\[CrossRef\]](#)
20. Diorio, N.; Denholm, P.; Hobbs, W.B. A model for evaluating the configuration and dispatch of PV plus battery power plants. *Appl. Energy* **2020**, *262*, 114465. [\[CrossRef\]](#)
21. Moga, D.; Petreus, D.; Muresan, V.; Stroia, N.; Cosovici, G. Optimal generation scheduling in islanded microgrids. *IFAC PapersOnLine* **2016**, *49*, 135–139. [\[CrossRef\]](#)
22. Zare, V. A comparative thermodynamic analysis of two tri-generation systems utilizing low-grade geothermal energy. *Energy Convers. Manag.* **2016**, *118*, 264–274. [\[CrossRef\]](#)
23. Si, Y.; Chen, L.; Zhang, X.; Mei, S. Capacity optimization of micro energy network with hot dry rock enhanced geothermal system. *Power Syst. Technol.* **2020**, *44*, 1603–1611.
24. Li, T.; Jia, Y.; Wang, J.; Meng, N.; Liu, Q.; Qin, H. Energy, economic and environmental evaluation of a novel combined cooling and power system characterized by temperature and humidity independent control. *Energy Convers. Manag.* **2020**, *215*, 112929. [\[CrossRef\]](#)
25. Abapour, S.; Nazari-Heris, M.; Mohammadi-Ivatloo, B.; Tarafdar-Hagh, M. Game Theory Approaches for the Solution of Power System Problems: A Comprehensive Review. *Arch. Comput. Methods Eng.* **2018**, *27*, 81–103. [\[CrossRef\]](#)
26. He, J.; Li, Y.; Li, H.; Tong, H.; Yuan, Z.; Yang, X.; Huang, W. Application of Game Theory in Integrated Energy System Systems: A Review. *IEEE Access* **2020**, *8*, 93380–93397. [\[CrossRef\]](#)
27. Mei, S.; Wang, Y.; Liu, F.; Zhang, X.; Sun, Z. Game Approaches for Hybrid Power System Planning. *IEEE Trans. Sustain. Energy* **2012**, *3*, 506–517. [\[CrossRef\]](#)
28. Yuan, W.; Huang, J.; Zhang, Y.J.A. Competitive Charging Station Pricing for Plug-In Electric Vehicles. *IEEE Trans. Smart Grid* **2015**, *8*, 1–13. [\[CrossRef\]](#)
29. Wang, Z.; Liu, F.; Chen, L.; Mei, S. Distributed economic automatic generation control: A game theoretic perspective. In Proceedings of the 2015 IEEE Power & Energy Society General Meeting, Denver, CO, USA, 26–30 July 2015; pp. 1–5.
30. Yang, G.; Fu, J.; Wang, D.; Liu, Y.; Luo, H. Study on Non-Cooperative Game Dispatching of Regional Power System with Wind-Thermal-Pumped Storage Power. In Proceedings of the 2017 IEEE International Conference on Energy Internet (ICEI), Beijing, China, 17–21 April 2017; pp. 24–29.
31. Yuan, T.; Ma, T.; Sun, Y.; Chen, N.; Gao, B. Game-Based Generation Scheduling Optimization for Power plants Considering Long-Distance Consumption of Wind-Solar-Thermal Hybrid Systems. *Energies* **2017**, *10*, 1260. [\[CrossRef\]](#)
32. Kristiansen, M.; Korpås, M.; Svendsen, H.G. A generic framework for power system flexibility analysis using cooperative game theory. *Appl. Energy* **2018**, *212*, 223–232. [\[CrossRef\]](#)
33. Du, Y.; Wang, Z.; Liu, G.; Chen, X.; Yuan, H.; Wei, Y.; Li, F. A cooperative game approach for coordinating multi-microgrid operation within distribution systems. *Appl. Energy* **2018**, *222*, 383–395. [\[CrossRef\]](#)

34. Zhigang, W.; Minru, X.; HaiXiao, Z.; Yao, W.; Zehua, Y.; Ai, W.; Jiwu, L.; Zheng, S.; Shuting, L. Research on Profit Distribution Strategy of Electric Vehicles Absorbing Wind Power Based on Cooperative Game. In Proceedings of the 2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China, 20–22 October 2018; pp. 1–6.
35. Liu, J.; He, D. Profit Allocation of Hybrid Power System Planning in Energy Internet: A Cooperative Game Study. *Sustainability* **2018**, *10*, 388. [\[CrossRef\]](#)
36. Zhang, Y.; Zhao, G.F. A global review of deep geothermal energy exploration: From a view of rock mechanics and engineering. *Geomech. Geophys. Geo-Energy Geo-Resour.* **2020**, *6*, 4. [\[CrossRef\]](#)
37. Aliyu, M.D.; Archer, R.A. Thermo-hydro-mechanical model of multifracture HDR geothermal reservoirs. *Geotherm. Resour. Counc. Trans.* **2020**, *44*, 1–28.
38. Zhang, X.; Zhang, T.; Xue, X.; Si, Y.; Zhang, X.; Mei, S. A comparative thermodynamic analysis of Kalina and organic Rankine cycles for hot dry rock: A prospect study in the Gonghe Basin. *Front. Energy* **2020**, *14*, 889–900.
39. Zhang, S.; Cheng, H.; Zhang, L.; Bazargan, M.; Yao, L. Probabilistic evaluation of available load supply capability for the distribution system. *IEEE Trans. Power Syst.* **2013**, *28*, 215–3225. [\[CrossRef\]](#)
40. Si, Y.; Zhang, X.; Mei, S.; Fan, Y.; Zhang, T.; Xue, X. Preliminary study on HDR power generation technology and application of HDR in Gonghe, Qinghai Province. *Glob. Energy Interconnect.* **2018**, *1*, 322–329.
41. Zhao, X.; Zeng, Z.; Wu, Y.; He, R.; Wu, Q.; Zhang, S. Interpretation of gravity and magnetic data on the hot dry rocks (HDR) delineation for the enhanced geothermal system (EGS) in Gonghe town, China. *Environ. Earth Sci.* **2020**, *79*, 1–13. [\[CrossRef\]](#)
42. Shu, Z.; Jirutitijaroen, P.; Leite da Silva, A.M.; Singh, C. Accelerated state evaluation and Latin hypercube sequential sampling for composite system reliability assessment. *IEEE Trans. Power Syst.* **2014**, *29*, 1692–1700. [\[CrossRef\]](#)
43. Liu, D.C.; Ma, H.R.; Wang, B.; Gao, W.; Wang, J.; Yan, B. Operation optimization of regional integrated energy system with CCHP and energy storage system. *Autom. Electr. Power Syst.* **2018**, *42*, 113–120.
44. Mei, S.; Wei, W.; Liu, F. On engineering game theory with its application in power systems. *Control. Theory Technol.* **2017**, *15*, 1–12. [\[CrossRef\]](#)
45. Fudenberg, D.; Tirole, J. *Game Theory*; MIT Press: Cambridge, MA, USA, 1992; pp. 436–444.
46. Hart, S.; Mas-Colell, A. *Cooperation: Game-Theoretic Approaches*; Springer: New York, NY, USA, 1997; pp. 43–51.