Global Energy Interconnection 9 (2026) 544–554

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journal homepage: www.elsevier.com/locate/gloei

Research on benefit coordination mechanism in renewable energy multi-energy complementary systems

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Received 8 August 2024; revised 9 February 2026; accepted 27 February 2026

Abstract

Cooperation among multiple stakeholders in the complementary integration of renewable energy sources (hydro, wind, and solar power) can enhance the incremental benefits of each participant as well as the overall efficiency of the cooperative alliance. The interest coordination mechanism stands as a pivotal element in the development of such multi-energy complementary systems. This study adopts a three-tier hierarchical model comprising a primary layer, secondary layer, and tertiary layer. The primary layer is an efficiency-oriented cooperative game model based on collective rationality, which determines the installed capacities of hydro, wind, and solar power within the alliance by requiring that the incremental financial internal rate of return (FIRR) exceed the benchmark FIRR for joining the hydro-wind-solar integrated alliance. The secondary layer is a participation-oriented non-cooperative game model rooted in individual rationality. Building on the installed capacities defined by the primary layer, it calculates the FIRR for each energy type when developed independently and compares it with the incremental FIRR of alliance participation to assess the willingness of stakeholders to join the alliance. The tertiary layer is an equity-oriented bargaining game model. Leveraging the incremental FIRR from the primary layer and the individually rational FIRR from the secondary layer, it ascertains the equitable FIRR for each stakeholder through bargaining based on the principle of fairness. A case study of a specific renewable energy multi-energy complementary system validates the feasibility and effectiveness of the proposed mechanism.

Keywords: Hydro-wind-solar; Multi-energy complementarity; Benefit coordination mechanism; Cooperative game; Non-cooperative game; Bargaining game; Primary-secondary-tertiary; Hierarchical decision-making

0 Introduction

Wind and solar power generation are inherently intermittent and unpredictable [1]. Their output fluctuations not only threaten the safe and stable operation of power systems but also increase power transmission costs, limiting the scale of new energy development and utilization capacity [2]. To ensure the large-scale grid integration of variable wind and solar power plants, there is an urgent need to enhance power system flexibility for reliable power supply [3]. The stochastic nature of wind and solar generation dictates that their grid-connected operation relies on the auxiliary support of hydropower stations with regulatory capabilities. The complementary operation of wind-solar and hydropower systems helps improve the absorption capacity of renewable energy in existing power grids. However, while hydropower regulation brings significant economic benefits to wind and solar power generation, it also exacerbates interest conflicts among different power generation entities. Existing studies have mostly focused solely on the overall economic analysis of hydro-wind-solar configuration systems [4–6]. In reality, hydropower,

Peer review under the responsibility of Global Energy Interconnection Group Co. Ltd.

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https://doi.org/10.1016/j.gloei.2026.02.003

wind power, and solar power are usually dominated by different stakeholders, leading to a coexistence of multiple interest subjects [7]. For the economic benefit evaluation of hydro-wind-solar complementary systems, it is not only necessary to scientifically define and accurately quantify the overall benefits but also, more critically, to fairly distribute the overall benefits in proportion to the contribution of each stakeholder. This ensures reasonable compensation and coordinated development among different interest subjects. The core of this process lies in converting the economic benefits brought by hydropower stations to stakeholders such as wind and solar power producers into their legitimate financial income, ultimately achieving multi-party win–win cooperation between hydropower stations and wind-solar stakeholders [8,9]. To incentivize renewable energy generation entities (including hydropower, wind power, and solar power) to realize the coupled utilization and coordinated operation of heterogeneous energy sources, the incremental benefits generated by synergy must be allocated fairly, efficiently, and reasonably to all interest subjects. In view of this, it is essential to explore solutions to interest conflicts among renewable energy generation entities and develop scientific methods for distributing the synergistic benefits of hydro-wind-solar hybrid power generation systems with hydropower participation.

Extensive research has been conducted on the operational mechanisms and benefit evaluation of multi-energy complementary systems integrating hydropower, wind power, and solar power [10], with a primary focus on system operational characteristics and complementary values [11]. Ref. [12] highlights that hydropower can function as a natural energy storage resource for renewable energies. Leveraging its reservoir regulation capacity and cascaded joint dispatch capabilities, hydropower enables the effective utilization of the spatiotemporal complementarity among hydropower, wind power, and solar power. Ref. [13] developed a two-player investment game model and evaluated equilibrium outcomes under different scenarios of wind-hydro resource correlation. The study found that a high degree of negative correlation between resources helps enhance diversification and improve the returns of individual investors. For multi-park integrated energy systems (MPIES), Ref. [14] constructed an asymmetric Nash bargaining game model where participants negotiate over energy transactions. A joint optimization method for capacity configuration and operation of multi-interconnected energy hub (EH) integrated energy systems based on Nash bargaining game was proposed. Case studies validated the effectiveness of the proposed method in reducing system operating costs and improving the profitability of energy storage equipment. Addressing the scale optimization challenge in the complementary operation of cascaded hydropower stations with wind and solar plants, Ref. [15] presented an approach that balances operational risks and benefits. A multi-scale nested joint operation model was established, which optimizes the configuration scale of wind and solar plants cooperating with hydropower stations through refined evaluation of the hybrid system's operational risks and benefits. Ref. [16] developed a three-dimensional comprehensive evaluation framework for hydro-wind-solar hybrid systems, enabling a holistic assessment of complementary operational benefits and potential risks. The results demonstrated that the complementary mode significantly increases total system power generation, power generation profits, and transmission line utilization efficiency, with hydropower providing compensatory benefits to wind and solar power generation. Ref. [17] proposed an optimization planning model for multi-energy complementary integrated energy systems based on game theory. Targeting the maximization of system economic efficiency, the model takes the capacity of each participant as a decision variable and designs five game modes to verify the existence of Nash equilibrium. Simulation experiments were conducted to solve the Nash equilibrium strategies for each mode.

With the formation of multi-stakeholder cooperation in hydro-wind-solar complementary systems, existing literature has focused on the synergistic benefit allocation mechanism of hydro-wind-solar integrated systems, exploring methods for the fair distribution of incremental benefits/-costs and the maintenance of alliance stability under multi-agent cooperation models. Ref. [18] took large-scale clean energy bases as the research object, constructing two scenarios: independent operation and complementary operation of hydropower stations with wind and solar plants. It quantified the interest relationships among different power generation entities and proposed an interest compensation mechanism between hydropower stations and wind-solar plants based on a contribution quantification model and compensated electricity contribution values. For hydro-wind-solar hybrid power generation systems incorporating cascaded hydropower, Ref. [19] established a cooperative game framework and adopted the Minimum Cost Remaining Surplus (MCRS) method as a synergistic benefit allocation scheme that balances fairness, rationality, and computational feasibility. Ref. [20] developed a cooperative game operation mechanism for hydro-wind-solar systems and proposed an improved Shapley value method integrated with comprehensive correction factors such as risk level and effort degree for benefit distribution, which can incentivize all entities to participate more actively in alliance cooperation. Addressing the incremental benefits generated by the joint operation of hydropower-participated hydro-wind-solar complementary power generation systems owned by multiple stakeholders, Ref. [21] conducted a quantitative analysis and employed various allocation methods—including the proportional allocation method, marginal benefit method, Shapley value method, and Aumann-Shapley value method, to calculate and measure the incremental benefit distribution among all stakeholders.

Expanding to broader multi-energy complementary alliances, encompassing wind power, solar power, and other flexible regulatory resources, their synergistic benefit allocation mechanisms have emerged as a research focus [22,23]. Existing studies predominantly adopt game-theoretic approaches to explore multi-stakeholder interest coordination and fair distribution. Ref. [24] focuses on the cooperative model of multi-virtual power plants (VPPs) integrated with wind-solar-storage systems. It establishes a multi-objective optimization model incorporating economic benefit maximization and carbon emission reduction. By quantifying the marginal contributions of each participant using the Shapley value method, the study achieves effective allocation of incremental alliance benefits, successfully addressing the design of collaborative operation mechanisms and reasonable interest distribution among VPPs. For cross-regional integrated energy systems involving electricity-heat-hydrogen multi-energy sharing, Ref. [25] constructs a cooperative game framework based on generalized Nash bargaining theory. The cooperative game process is decoupled into two sub-problems: alliance benefit maximization and benefit distribution equilibrium. The adaptive alternating direction method of multipliers (ADMM) is employed for model solution, providing an effective pathway for interest coordination in cross-regional multi-energy synergy. Ref. [26] proposes a cooperative game-based model for large-scale multi-source joint outward transmission and benefit distribution, integrating wind power, solar power, and thermal power. It compares the system profit levels under joint transmission and independent transmission modes, and allocates the benefits generated by the tripartite joint operation using an improved Shapley value method. Ref. [27] focuses on integrated energy systems (IES) incorporating demand response, establishing a coordinated optimal operation model for multi-energy hubs. Leveraging time-of-use (TOU) electricity price incentives, the model minimizes the total operating costs of multiple stakeholders. Simultaneously, cooperative game theory is applied to distribute the cost savings and benefits derived from the collaborative operation of all participants.

Synthesizing the literature across the three aforementioned aspects, several research limitations remain evident: First, existing studies rarely conduct a coupled analysis of the complementary mechanisms and economic compensation mechanisms within hydro-wind-solar integrated renewable energy multi-energy complementary alliances. Second, regarding the research on interest coordination mechanisms, the bargaining transition relationship between non-cooperative and cooperative games is insufficiently explored. Third, there is a lack of synergistic consideration of multiple value objectives involving the coupling of efficiency, participation and fairness, and the hierarchical relationships in the decision-making process of interest coordination mechanisms have not been thoroughly investigated. Against this backdrop, this study constructs a core framework for the interest coordination mechanism of hydro-wind-solar integrated systems: realizing the transition from individual rationality-based non-cooperative games to collective rationality-based cooperative games through bargaining games. To address the multi-objective requirements of alliance collective rationality (efficiency), individual rationality (participation), and fair bargaining, a three-tier hierarchical system (primary-secondary-tertiary) is established. This system resolves three core issues: (1) determining the optimal installed capacity and scope of the alliance under the joint optimization of hydro-wind-solar multi-stakeholders; (2) optimizing individual optimal return rates and analyzing the motivation for alliance participation; and (3) fairly distributing the incremental benefits of wind and solar power participation in the alliance through bargaining. Specifically, the primary layer adopts a cooperative game approach to analyze the formation mechanism of the hydro-wind-solar integrated alliance and design an incentive-compatible mechanism. Based on the marginal contributions of each stakeholder to the alliance, it aims to maximize the overall alliance benefits and determines the installed capacity of each stakeholder. The secondary layer employs a non-cooperative game approach, with the installed capacity and scope defined by the primary layer as constraints, to solve for the investment strategy that maximizes individual benefits, namely the objective of participation based on individual rationality. If the benefits obtained by an individual under non-cooperative game conditions are lower than their contribution to the alliance when participating in it, enforceable agreements are established to convert individual strategic choices under non-cooperative games into joint actions under cooperative games. The tertiary layer adopts a fair bargaining game approach, taking the incremental FIRR of each individual in the alliance (determined by the primary layer) as the bargaining upper bound and the independent FIRR of each individual without alliance participation (determined by the secondary layer) as the negotiation breakdown point. Through communication and negotiation, the game structure is optimized, and a fair bargaining solution is derived to achieve the equitable distribution of alliance benefits.

1 Methodology

1.1 Logical relationships of the three-tier game model system

To establish an interest coordination mechanism for the hydro-wind-solar integrated alliance involving multiple power generation stakeholders, it is essential to realize three objectives: efficiency, participation, and fairness through the reasonable distribution of incremental benefits. Accordingly, this study develops a three-tier objective function system with a master–slave hierarchical structure. The logical positioning and core tasks of each tier are as follows: Guided by the collective rationality of cooperative game theory [28], the primary tier determines the optimal installed capacity and scope of the hydro-wind-solar integrated alliance, adhering to the priority criterion that the incremental FIRR for each stakeholder joining the alliance exceeds the benchmark incremental FIRR for alliance participation. Rooted in the individual rationality of non-cooperative game theory [29], the secondary tier optimizes the power generation strategy of each stakeholder and solves for their individual optimal FIRR under the constraint of the installed capacities of hydropower, wind power, and solar power determined by the primary tier, thereby assessing the willingness of each stakeholder to join the alliance. Guided by the fairness principle of bargaining game theory [30], the tertiary tier takes the collectively rational FIRR determined by the primary tier as the upper bound of negotiations and the individually rational FIRR determined by the secondary tier as the negotiation breakdown point. It achieves the fair distribution of incremental benefits gained by the alliance among different stakeholders through a bargaining negotiation mechanism.

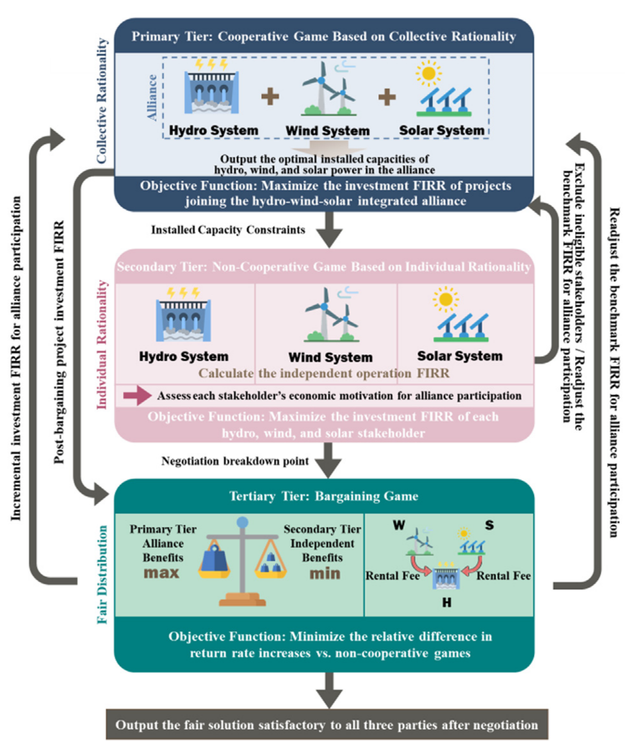

Fig. 1. Logical relationship diagram of the three-tier game theoretic model.

The logical relationships of the three-tier game model are illustrated in Fig. 1:

The primary tier adopts a cooperative game framework. It determines the installed capacity configuration of hydropower, wind power, and solar power within the alliance based on the optimization principle that the incremental FIRR of wind and solar power projects is not lower than the benchmark FIRR for alliance participation. The configuration results are transmitted to the secondary and tertiary tiers as constraint conditions. Meanwhile, the primary tier receives feedback on the individually rational FIRR from non-cooperative games provided by the secondary tier and the post-bargaining FIRR provided by the tertiary tier. Through this dual feedback, the primary tier judges the feasibility of alliance formation. The hydro-wind-solar integrated alliance can only be formed if two conditions are met: first, the collectively rational FIRR of the primary tier is greater than the individually rational FIRR of the secondary tier; second, the post-bargaining FIRR of the tertiary tier is greater than the individually rational FIRR from the non-cooperative games of the secondary tier.

The secondary tier employs a non-cooperative game framework. It first accepts the installed capacities and stakeholder scope output by the primary tier as boundaries, then optimizes the investment strategy of each stakeholder based on the individual rationality of non-cooperative game theory, and further solves for the individually rational FIRR. If the individually rational FIRR is greater than the incrementally collectively rational FIRR of the alliance, the corresponding stakeholder lacks the incentive to participate in the alliance and should be excluded from the alliance. This information is fed back to the primary tier, which then readjusts the target benchmark FIRR for alliance participation and re-optimizes the installed capacities of hydropower, wind power, and solar power within the alliance. Conversely, if the individually rational FIRR is less than the incremental FIRR of alliance participation, the secondary tier transmits this individually rational FIRR to the tertiary tier as the negotiation breakdown point for bargaining games.

The tertiary tier adopts a bargaining game framework. It constructs negotiation boundaries by comprehensively receiving the incremental FIRR of alliance participation from the cooperative game of the primary tier and the individually rational FIRR from the non-cooperative game of the secondary tier. If all stakeholders are satisfied with the post-bargaining FIRR, fair distribution is implemented, and the results are fed back to the primary and secondary tiers, completing the entire model solution and decision-making process. If any stakeholder is dissatisfied with the post-bargaining results, the information is fed back to the primary tier, which then readjusts the benchmark FIRR for alliance participation and re-optimizes the installed capacities and scope of each stakeholder in the alliance.

1.2 Primary tier: efficiency-oriented cooperative game model guided by collective rationality

Hydropower stations, wind power plants, and solar power plants all participate directly in the hydro-wind-solar integrated alliance as independent investment entities. Despite differences in their interest demands, the complementary regulation and joint operation of resources can generate synergistic incremental benefits characterized by a "$1 + 1 + 1 > 3$" effect. The realization of this benefit relies on the cooperative behaviors and rule compliance of all entities, which justifies the adoption of cooperative game theory to construct the primary tier model. Cooperative game theory excels at accurately depicting the collaborative logic among multiple entities. Its core feature of emphasizing overall rationality ensures that all entities adhere to the agreements formulated by the alliance, ultimately maximizing the overall benefits of the alliance through the complementary regulation and joint operation of hydropower, wind power, and solar power resources. Building on this, the primary tier optimizes and determines the optimal installed capacity configuration of hydropower, wind power, and solar power within the hydro-wind-solar integrated alliance based on the principle of collective rationality, laying a foundation for subsequent benefit distribution and inter-entity collaboration.

In accordance with the aforementioned economic optimization logic of collective rationality, wind power and solar power projects are sorted in ascending order of their investment cost per kWh. The incremental FIRR associated with alliance expansion by incorporating additional wind and solar projects is calculated as follows (Eq. (1)):

$$f_m^{\mathrm{l}} = \arg_x\left\{\sum_{j}^{j\in\{\mathrm{w,s}\}}\sum_{t=1}^{T}\left[\sum_{k=1}^{m}\left(E_{k,j,t}^{\mathrm{l}}\cdot P_{j,t}-C_{k,j}^{\mathrm{l}}\right)\right.\right.$$
$$\left.\left.-\sum_{k=1}^{m-1}\left(E_{k,j,t}^{\mathrm{l}}\cdot P_{j,t}-C_{k,j}^{\mathrm{l}}\right)\right]\cdot(1+x)^{-t}=0\right\} \tag{1}$$

The incremental $\mathrm{FIRR}(f_m^{\mathrm{l}})$ for alliance expansion with additional wind and solar projects must not be lower than the benchmark $\mathrm{FIRR}(i^{\mathrm{l}})$ of the hydro-wind-solar integrated alliance, which serves as the economic optimization criterion for alliance inclusion (Eq. (2)). Accordingly, candidate projects are sequentially admitted to the alliance subject to the incremental FIRR criterion.

$$f_m^{\mathrm{l}} \geqslant i^{\mathrm{l}} \tag{2}$$

where f_m^{l}—the incremental FIRR, defined as the discount rate at which the present value of the differences in annual net cash flow between the new hydro-wind-solar integrated alliance formed after incorporating additional wind or solar power projects and the original alliance equals zero; superscript l—the primary-tier alliance; $\arg_x\{\}$—the operator that returns the value of x satisfying the equation; t—the time index within the project calculation period; T—the total calculation period; j—the project type, with $j \in \{\mathrm{w, s}\}$ corresponds to wind power plants and solar power plants, respectively; $P_{j,t}$—the on-grid electricity price of type-j power stations at time t; m—the project sequence number in alliance inclusion; $E_{k,j,t}^{\mathrm{l}}$—the on-grid electricity volume of the $k-$th type -j project in the alliance at time t; $C_{k,j}^{\mathrm{l}}$—the investment cost of the $k-$th type-j project in the alliance; i^{l}—the target benchmark FIRR of the alliance.

1.3 Secondary tier: participation-oriented non-cooperative game model guided by individual rationality

Hydropower stations, wind power plants, and solar power plants operate within a power system constrained by limited power resources, leading to inherent interest competition regarding installed capacity, on-grid electricity volume, and other key factors. Each investor aims to maximize individual benefits by optimizing their own power station capacity and electricity generation levels. This scenario constitutes a typical non-cooperative game where investors compete fairly through optimal power generation strategies to achieve individual profit maximization. The hydro-wind-solar integrated alliance can generate certain excess benefits through collaborative operation, ensuring that each member gains more than they would under independent operation. To further highlight the synergistic advantages of the alliance, analyze the motivation mechanism for each entity to participate, and provide a basis for the negotiation breakdown point in subsequent alliance bargaining games, it is necessary to construct a non-cooperative game model for hydropower, wind power, and solar power operating independently in the power system. This model characterizes the optimal investment decision-making behavior of each entity without the constraints of the alliance.

Participants in the secondary-tier non-cooperative game include three types of entities: hydropower stations, wind power plants, and solar power plants. The game strategy of each entity consists of power generation output schemes across different time periods. Wind and solar power plants often need to be paired with supporting energy storage systems in light of the inherent volatility of their power output to ensure output stability. The profit function of each game participant is a strategy combination function, as it is influenced not only by their own strategy choices but also by those of other participants. Based on the installed capacities of hydropower, wind power, and solar power in the hydro-wind-solar integrated alliance determined by the primary tier, the secondary tier optimizes the investment strategy of each entity to maximize their target rate of return in accordance with the principle of individual rationality. The calculation of the investment

FIRR for hydropower, wind power, and solar power investors under non-cooperative game conditions is expressed as follows (Eq. (3)):

$$f^{\mathrm{g}}_{m,j} = \arg_x\left\{\sum_{t=1}^{T}\left[\sum_{k=1}^{m}\left(E^{\mathrm{g}}_{k,j,t}\cdot P_{j,t} - C^{\mathrm{g}}_{k,j}\right)\right]\cdot(1+x)^{-t} = 0\right\},\quad j\in\{\mathrm{h,w,s}\} \tag{3}$$

A corresponding entity has the economic incentive to participate in the integrated alliance if its individually rational investment FIRR does not exceed the incremental target investment FIRR of the alliance, i.e.:

$$f^{\mathrm{l}}_{m} \geqslant f^{\mathrm{g}}_{m,j},\quad j\in\{\mathrm{h,w,s}\} \tag{4}$$

where $f^{\mathrm{g}}_{m,j}$—the investment FIRR of the $m-$ th project of type-j under individual rationality in non-cooperative game; superscript g—the secondary-tier individual-rationality scenario; $E^{\mathrm{g}}_{k,j,t}$—the on-grid electricity volume of the $k-$ th type-j project at time t; $C^{\mathrm{g}}_{k,j}$—the investment cost of the $k-$ th type-j project.

1.4 Tertiary tier: equity-oriented bargaining game model guided by alliance formation

Hydropower, wind power, and solar power belong to distinct stakeholders. When deciding whether to participate in the hydro-wind-solar integrated alliance, each stakeholder acts independently and rationally. They can improve their own investment FIRR through bargaining, ensuring that the actual benefits obtained from alliance participation exceed those from independent operation. This problem can be modeled as a fair bargaining game aimed at the coordinated optimization of collective and individual rationality. While helping the alliance secure additional benefits, the bargaining game enables the fair distribution of these extra benefits among all stakeholders, ultimately reaching a distribution consensus that balances collective and individual interests.

Benefit distribution is implemented based on the marginal contribution of each member to the hydro-wind-solar integrated alliance. The FIRR of hydropower, wind power, and solar power under non-cooperative games is selected as the negotiation breakdown point for bargaining, and the FIRR of each stakeholder is designated as the subjective utility evaluation indicator in the game process. This process continues until no party can further improve its benefits by adjusting its negotiation strategy independently. By solving this equilibrium solution, the final bargaining strategy is determined, and an optimal benefit distribution scheme that balances the satisfaction of all parties is formulated. The regulatory capability of hydropower can effectively enhance the quality of on-grid electricity and the actual grid-connected electricity volume of wind and solar power. To reflect this contribution, the benefits that hydropower brings to wind and solar power within the alliance can be compensated to hydropower stations through a rental fee mechanism. In this study, the on-grid electricity volume of wind and solar power in the alliance is used as the calculation base, and an electricity rental rate per kWh is set to calculate the compensation fee for hydropower. The payment of rental fees can adjust the investment FIRR of each stakeholder in the alliance, realizing the fair redistribution of alliance benefits among stakeholders. The calculation of the hydropower investment FIRR after bargaining is shown below (Eq. (5)):

$$f^{\mathrm{b}}_{m,\mathrm{h}} = \arg_x\left\{\sum_{t=1}^{T}\left[E^{\mathrm{l}}_{m,\mathrm{h},t}\cdot P_{\mathrm{h},t} + \sum_{p=1}^{P}\left(E^{\mathrm{l}}_{p,\mathrm{w},t}\cdot z_{p,\mathrm{w}}\right) + \sum_{q=1}^{Q}\left(E^{\mathrm{l}}_{q,\mathrm{s},t}\cdot z_{q,\mathrm{s}}\right) - C^{\mathrm{l}}_{m,\mathrm{h}}\right]\cdot(1+x)^{-t} = 0\right\} \tag{5}$$

where $f^{\mathrm{b}}_{m,\mathrm{h}}$—the investment FIRR of the $m-th$ hydropower project after bargaining; superscript b—the tertiary-tier bargaining scenario; $E^{\mathrm{l}}_{p,\mathrm{w},t}$, $E^{\mathrm{l}}_{q,\mathrm{s},t}$—the on-grid electricity volumes of the $p-$ th wind power plant and $q-$ th solar power plant in the alliance, respectively; $z_{p,\mathrm{w}}$, $z_{q,\mathrm{s}}$—the rental fees paid by wind power plants and solar power plants to compensate hydropower stations, respectively; P, Q—the numbers of wind power and solar power projects in the alliance, respectively. $C^{\mathrm{l}}_{m,\mathrm{h}}$—the investment cost of the $m-$ th hydropower project in the alliance.

The calculation of the investment FIRR for wind and solar power plants following bargaining is expressed as follows (Eq. (6)):

$$f^{\mathrm{b}}_{m,j} = \arg_x\left\{\sum_{t=1}^{T}\left(E^{\mathrm{l}}_{m,j,t}\cdot P_{j,t} - E^{\mathrm{l}}_{m,j,t}\cdot z_{m,j} - C^{\mathrm{l}}_{m,j}\right)\cdot(1+x)^{-t} = 0\right\},\ j\in\{\mathrm{w,s}\} \tag{6}$$

where $f^{\mathrm{b}}_{m,j}$—the investment FIRR of the $m-$ th project of type-j after bargaining, with $j\in\{\mathrm{w,s}\}$ representing wind power and solar power, respectively; $z_{m,j}$—the rental fee paid by the corresponding wind power or solar power project.

The difference between the investment FIRR of each stakeholder under cooperative games and that under non-cooperative games is defined as the economic contribution of the individual to the alliance. The individually rational investment FIRR under non-cooperative games represents the theoretical minimum benefit that an individual can obtain, and it also serves as the negotiation breakdown point. To ensure fairness in benefit distribution, the fairness objective is set to minimize the difference between the maximum and minimum percentage increases in the actual post-bargaining investment FIRR of each stakeholder relative to their individually rational FIRR under non-cooperative games. The corresponding expression for the fairness objective function is shown below (Eqs. (7) and (8)):

$$d^{\mathrm{b}} = \max_{\substack{m=1,\cdots,M \\ j\in\{\mathrm{h,w,s}\}}} \left(\frac{f^{\mathrm{b}}_{m,j} - f^{\mathrm{g}}_{m,j}}{f^{\mathrm{g}}_{m,j}} \right) - \min_{\substack{m=1,\cdots,M \\ j\in\{\mathrm{h,w,s}\}}} \left(\frac{f^{\mathrm{b}}_{m,j} - f^{\mathrm{g}}_{m,j}}{f^{\mathrm{g}}_{m,j}} \right) \tag{7}$$

$$\min d^{\mathrm{b}} \tag{8}$$

where d^{b}—the bargaining fairness value; $f^{\mathrm{b}}_{m,j}$—the post-bargaining investment FIRR of the $m-$th project of type-j participating in the hydro-wind-solar integrated alliance; $f^{\mathrm{g}}_{m,j}$—the individually rational investment FIRR of the $m-$th project of type-j under non-cooperative games;M—the total number of stakeholders in the alliance.

1.5 Constraints

The constraint conditions of the three-tier model are mainly categorized into four types: power system constraints, economic indicator constraints, power station planning constraints, and power station operation constraints. Power system constraints cover the capacity limit of transmission channels, power balance constraints (including demand response and load shedding), output fluctuation constraints of hydropower, wind power, and solar power, and curtailment limit of hydropower, wind, and solar power. Economic indicator constraints include constraints on economic metrics such as return on investment and payback periods for hydropower, wind power, and solar power projects, requiring that projects incorporated into the integrated system possess independent economic viability. Planning constraints encompass non-negative integer decision variables, installed capacity limits, restrictions on the number of power stations, geographical location constraints of power stations, policy restrictions, constraints on the earliest construction time, reservoir capacity constraints, and 0–1 variables indicating whether hydropower, wind power, or solar power stations are to be constructed. Operation constraints include reservoir water level constraints, constraints on reservoir release, discharge, and generating flow, hydraulic connections between cascaded reservoirs, output constraints of hydropower, wind power, and solar power, water balance constraints, ramping rate limits, and reserve capacity limits.

2 Case study

2.1 Basic conditions and parameter setting

A hydropower station with multi-year regulation capacity was selected as the research object, with an installed capacity of 1000 MW and an annual power generation of approximately 2.7 billion kWh. The surrounding area of this hydropower station is rich in wind and solar resources: the technically developable wind power capacity is about 1500 MW with an annual utilization hour count of 1900 h, while the technically developable solar power capacity is about 500 MW with an annual utilization hour count of 900 h. Relying on the regulation capacity of this hydropower station to drive the development of surrounding wind and solar power, an integrated multi-energy complementary model for renewable energy can be implemented. If the integrated renewable energy development model is not adopted (i.e., wind and solar power plants adopt an independent grid-connection mode), wind and solar power plants must comply with relevant requirements: they need to be equipped with energy storage power not less than 10% of their installed capacity, and the continuous charging-discharging duration of energy storage must be no less than 2 h, with the unit investment cost of energy storage being 1000 CNY/kWh. Other key parameters are set as follows: the on-grid electricity price is 0.35 CNY/kWh; the unit investment cost of the hydropower station is 2.66 CNY/kWh; the installed capacity of each individual wind and solar power station is planned to be 100 MW, with their unit investment costs being 5500 CNY/kW and 3000 CNY/kW, respectively.

Using the research method proposed in this study, a quantitative analysis was conducted on the interest coordination mechanism during the formation of the renewable energy integrated alliance.

2.2 Analysis of cooperative game results based on collective rationality

An 8760-hour hourly output time-series simulation method was adopted to optimize the economically reasonable scale of the hydro-wind-solar integrated alliance. Each wind and solar power station had an installed capacity of 100 MW, and wind and solar power projects were sequentially incorporated into the alliance in ascending order of their investment cost per kWh. Throughout the capacity expansion process, the incremental FIRR for joining the alliance must always be no less than 6.5%.

The optimized configuration results of the hydro-wind-solar integration are shown in Fig. 2. It can be observed that a total of 11 wind power plants (W1, W2, …, W11)

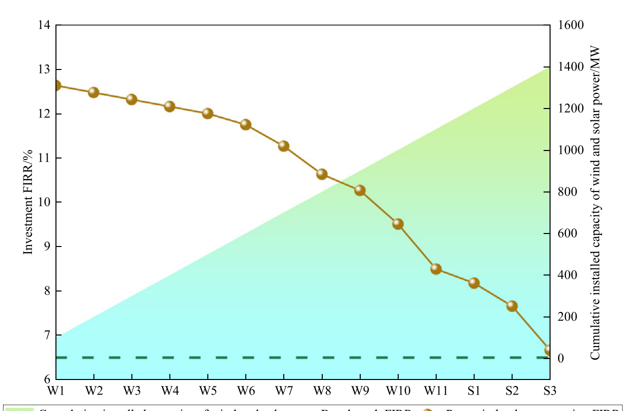

Fig. 2. Relationship between variation of investment FIRR and cumulative installed capacity after wind and solar project connection.

and 3 solar power plants (S1, S2, S3) were included in the alliance. If the capacity of wind or solar power plants is further increased, the incremental FIRR will be lower than the benchmark rate of return. After aggregating the wind and solar resources in the alliance, the total installed capacity of wind power reaches 1100 MW and that of solar power reaches 300 MW. Based on the collective rationality cooperative game framework, the investment FIRR values corresponding to wind power and solar power under this configuration are 11.198% and 7.510%, respectively.

As shown in Fig. 2, with the sequential connection of wind and solar power plants, the cumulative installed capacity of wind and solar power continues to increase, the investment per unit capacity gradually rises, and the system's accommodation capacity becomes increasingly saturated, these factors collectively lead to a decline in the corresponding rate of return. Therefore, the investment FIRR of wind and solar power shows an overall downward trend after incorporation, which is consistent with the principle of diminishing marginal benefits. Meanwhile, the dashed line in the figure represents the benchmark FIRR of 6.5%, which serves as the critical threshold for the economic rationality of alliance expansion. The FIRR values of all 14 finally included wind and solar stations are higher than this threshold.

The variation characteristics of wind and solar curtailment in the hydro-wind-solar integrated system are shown in Fig. 3. The data in the figure exhibits distinct phased patterns: in the initial connection phase with low wind and solar installed capacity, the superimposed output of wind-solar power and hydropower base load does not exceed the upper limit of the transmission channel capacity. The system has sufficient accommodation capacity for wind and solar resources, so the curtailment of wind and solar power remains at 0; as the installed capacity of wind and solar power continues to increase, it exceeds the transmission upper limit of the channel. The regulation capacity of hydropower can no longer fully resolve the conflict between wind-solar output fluctuations and transmission capacity, leading to a significant upward trend in wind and solar curtailment. The reduction in solar curtailment after the integration of solar power is attributed to the certain complementary effect between wind and solar power.

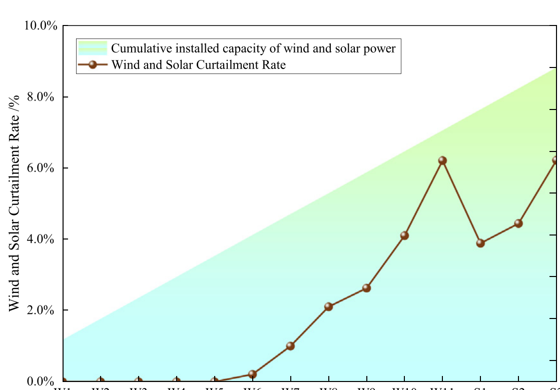

Fig. 3. Variation of wind and solar curtailment rates with the gradual integration of wind and solar projects into hydropower station.

2.3 Analysis of non-cooperative game results based on individual rationality

Following the principle of individual rationality, the secondary tier calculates the investment FIRR for hydropower, wind, and solar power plants under independent development, with the constraint of the economically viable scale of the hydro-wind-solar integrated alliance determined by the primary tier. The specific results are as follows: The investment FIRR of the hydropower station under independent development is 8.000%. For the 1100 MW wind farm formed by aggregating 11 wind power stations: Its theoretical annual power generation is 2.09 billion kWh. In accordance with the renewable energy grid-connection requirements of the region, an energy storage system of 110 MW/2h is configured. Meanwhile, constrained by the capacity of the transmission channel, the wind curtailment volume under the energy storage configuration is 171.4 million kWh, and the effective on-grid electricity volume is 1.9186 billion kWh. After integrating the main wind power investment (6.05 billion CNY) and the energy storage investment (220 million CNY), the unit investment cost per kWh of on-grid electricity is 3.268 CNY/kWh, resulting in an investment FIRR of 7.815% for wind power. For the 300 MW solar power plant formed by aggregating 3 solar power stations: Its theoretical annual power generation is 270 million kWh. In line with the regional renewable energy grid-connection requirements, an energy storage system of 30 MW/2h is configured. Also constrained by the transmission channel capacity, the solar curtailment volume under the energy storage configuration is 6.73 million kWh, and the effective on-grid electricity volume is 263.27 million kWh. After combining the main solar power investment (900 million CNY) and the energy storage investment (60 million CNY), the unit investment cost per kWh of on-grid electricity is 3.646 CNY/kWh, leading to an investment FIRR of 6.416% for solar power.

Under the collective rationality framework of the primary tier, the investment FIRR values of wind and solar power plants in the hydro-wind-solar integrated alliance are 11.198% and 7.510%, respectively. It follows that the individually rational FIRR values of wind and solar power plants in the secondary tier (7.815% and 6.416%) are both lower than their corresponding FIRR values in the alliance scenario. This indicates that the 1100 MW wind power and 300 MW solar power have economic incentives to participate in the hydro-wind-solar integrated alliance and can enter the bargaining game stage of the tertiary tier to further explore the internal interest coordination mechanism of the alliance.

2.4 Analysis of fair bargaining game results for alliance formation

In this study, the fairness criterion is defined as the range of percentage increases in the investment FIRR of different stakeholders after bargaining (relative to their individually rational investment FIRR) being zero. In other words, the relative increases in the rates of return of hydropower, wind power, and solar power after bargaining when compared with their rates of return under the individual rationality scenario are equal. After coordination through the bargaining game in the tertiary tier, the investment FIRR values of hydropower, wind power, and solar power plants are 8.780%, 8.577%, and 7.042%, respectively. Compared with their individually rational FIRR values under non-cooperative games in the secondary tier (8.000%, 7.815%, and 6.416%), the percentage increase in the rate of return for all three types of stakeholders is 9.75%, which meets the fairness constraint. In the corresponding benefit distribution mechanism, the hydropower station receives compensation rental fees of 32.7 million CNY and 0.73 million CNY from wind power and solar power, respectively. The rental rates for wind power and solar power are 0.0159 CNY/MWh and 0.0028 CNY/MWh, shown in Fig. 4.

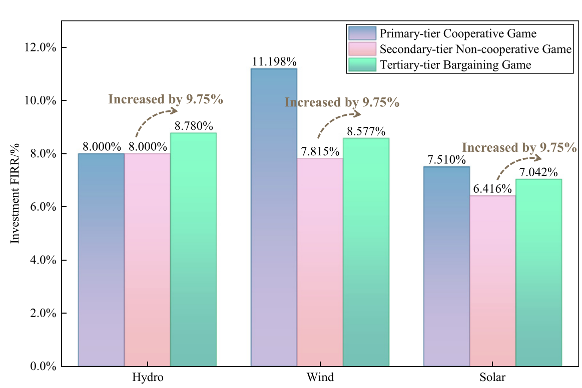

Fig. 4. Investment FIRR under different game scenarios.

3 Research conclusions

Against the backdrop of incentivizing multiple stakeholders to participate in the cooperation and operation of renewable energy complementary systems, this study takes three types of energy entities: hydropower, wind power, and solar power, as the research objects. From three dimensions, specifically collective efficiency of renewable energy integration, individual rational participation, and fairness of bargaining, a three-tier hierarchical game model of primary-secondary-tertiary is established: the primary tier makes decisions first, followed by the secondary and tertiary tiers. Information feedback among the tiers forms a closed-loop iteration, which cycles until a scheme meeting the demands of all parties is achieved. The key conclusions of this study are as follows:

1) The primary tier introduces cooperative game theory to establish a capacity optimization configuration model for the hydro-wind-solar integrated alliance based on collective rationality. This model ensures the overall optimality of the alliance. Significant incremental power generation benefits can be achieved through multi-energy complementary cooperation within the alliance, and hydropower, wind power, and solar power can all obtain reasonable incremental returns from the cooperation.
2) The secondary tier incorporates non-cooperative game theory to develop an investment FIRR calculation model based on individual rationality. By comparing the differences in investment FIRR between collective rationality and individual rationality scenarios, the willingness of each stakeholder to participate in the alliance is clarified, and the negotiation breakdown point for bargaining games is transmitted to the tertiary tier. Analysis results show that through integrated complementary cooperation, both the individual benefits of hydropower, wind power, and solar power entities and the overall benefits of the alliance are improved compared with the independent operation scenario.
3) The tertiary tier adopts fair bargaining game theory to realize the fair and reasonable distribution of incremental benefits in the multi-stakeholder energy system. It takes the collectively rational incremental investment FIRR transmitted from the primary tier as the upper bound of bargaining and the individually rational investment FIRR from the secondary tier as the negotiation breakdown point. Results indicate that after distribution through this mechanism, all participating stakeholders obtain certain incremental benefits compared with the non-cooperative mode, which not only guarantees the fairness of distribution but also strengthens the stability of the alliance.

CRediT authorship contribution statement

Yanyue Wang: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chongru Liu:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

We declare that we have no conflict of interest.

Acknowledgment

This work was supported by Power Construction Corporation of China Science and Technology Project (DJ-HXGG-2024-03).

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