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Optimized Operation of Energy Sharing in Microgrids with Shared Energy Storage Based on Nash-Harsanyi Game Theory

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Abstract

Promoting the integration of renewable energy sources is greatly aided by energy storage. However, challenges like high investment costs and low equipment utilization have hindered its further development. The emergence of shared energy storage effectively alleviates these issues. This study investigates the cooperative operation between shared energy storage and multiple microgrids, incorporating coordination of power dispatch by a third-party operator. Firstly, a profit model for multi-agent cooperative operation involving shared energy storage system, clusters of microgrids, and a third-party operator is established. Then, considering the risk preferences of each entity and integrating indicators such as alliance contribution, renewable energy output rate, renewable energy integration rate, the alliance's profit distribution model is developed by introducing the Nash-Harsanyi game theory. Simulation results confirm that the cooperative operation of many microgrids and a shared energy storage system promotes the local microgrid to employ renewable energy while reducing the cost of electricity costs, resulting in increased benefits for all involved entities.

Keywords: Shared energy storage, multiple microgrids, NASH-Harsanyi game, energy sharing, profit distribution.

1. Introduction

In recent years, environmental pollution and climate change have garnered global attention, propelling the advancement of low-carbon policies and carbon-neutral as significant patterns in national development [1]. With the dual objectives of "creating a new power system dominated by new energy sources" and "dual carbon target" introduced, substantial development of renewable energy stands as a pivotal measure in alleviating the energy crisis. However, issues with renewable energy's the fluctuation, unpredictability, and instability significant setbacks to the power grid's supply adequacy and operational stability. On the one hand, ensuring sufficient power supply adequacy in the the electrical system is imperative, but the fluctuation and uncertainty in the static output of new energy units present challenges. On the other hand, the weak stability and vulnerability of new energy units threaten the operating stability of the electricity system.

An essential tool for reducing the oscillations in renewable energy sources is energy storage [2]. Energy storage is able to be thought of an electrical supply with flexible response characteristics across various time scales in the power system [3]. Power control and energy balancing are two benefits of energy storage equipment. It enables the efficient conversion and storage of renewable energy generation, aiding in grid peak shaving, frequency regulation, facilitating multiple energy sources' mutual complementarity, and joint optimized control [4].

The fast response, high flexibility, efficiency, stability, and reliability endow energy storage with a critically strategic position. However, challenges such as high investment costs, low equipment utilization, and constraints related to site installation restrict the advancement of energy storage [5].

With the emerging of the sharing economy concept across various domains within the electricity system, shared energy storage has emerged. It involves the transformation of storage system, initially designed for individual entities, to cater to multiple entities. Through scientific coordination and control, it provides effective services to users [6]. Shared energy storage methods entail users collectively sharing the cost of energy storage and fully utilizing load complementarity. This approach allows all users to share the benefits brought about by energy storage, potentially overcoming the bottlenecks faced by this technology [7].

Currently, research on shared energy storage has become quite extensive. Cui S et al. compared the economic and operational aspects of personal and shared energy storage, indicating that the latter has lower costs and higher utilization rates [8]. Some scholars proposed community-oriented energy storage sharing frameworks [9-11]. Research has confirmed significant advantages in deploying shared energy storage at the generation side [12]. It can address challenges related to the intense fluctuations and instability in renewable energy generation that impact energy scheduling under management control [13]. Moreover, shared energy storage at the generation side can participate in real-time markets, reducing the bias penalty for renewable energy participation in the market, thus enhancing profits [14]. Additionally, study has been implemented on the distribution of benefits when shared energy storage is used in energy trading. In Chen Y's introduction of an asymmetric Nash bargaining model for point-to-point energy transactions based on shared energy storage, cooperative surplus allocation methods inspired by asymmetric Nash bargaining (ANB) theory are examined. [15].

As renewable energy sources become more prevalent in microgrids, microgrid system' security and operational stability are significantly impacted. The construction and development of these system require the support of energy storage. Energy storage compensates for the inherent randomness in new energy sources, fundamentally addressing the challenge of accommodating a substantial amount of renewable energy. Within microgrids, the intrinsic volatility of new energy sources can be lessened by energy storage, enhancing the capacity for renewable energy absorption. It also reduces the frequency of power fluctuations, lessening the impact on the microgrid's interconnected system ultimately facilitating the friendly interconnection of microgrids [16]. To enhance the rate at which renewable energy is consumed and to optimize the use of energy storage, it is essential for calculating the optimal configuration scale of energy storage [17]. Studies on the effects of various forms of energy storage affecting microgrid operating costs have been conducted. Kandari R suggested that compared to a simple battery storage system, hybrid storage systems enhance the dependability and stability of microgrid operations [18]. Further research concluded that hybrid hydrogen and lithium-ion storage system can significantly reduce microgrid costs [19].

However, on the one hand, individual microgrid system have limited scheduling capabilities, resulting in a significant curtailment of renewable energy. Another aspect, the independent investment costs for energy storage in microgrids are high, and the energy storage scheduling behavior within each microgrid tends to be disordered, leading to inefficient operations and wasted energy resources. Hence, it becomes feasible to facilitate energy sharing among diverse microgrids by implementing shared energy storage to interconnect multiple microgrids. This increases the system's stability and economic feasibility by reducing the localized absorption of renewable energy inside the several microgrids. Presently, extensive research exists on the collaborative operation of microgrids. Investigations have been done upon the problems of coordinated operation scheduling of several microgrids, with some studies aimed at reducing the operational costs of microgrids [20], while others focus on enhancing the safety, economy, and reliability of coordinated operation among multiple microgrids [21]. The issue of optimizing the operation of multiple microgrids, considering the coupled trading of carbon emissions and green certificates, has also been studied [22]. Research on the cooperative energy storage of several microgrids has also matured. Cao W presented a paradigm for hybrid storage and electricity -sharing across several microgrids with which the hybrid energy storage system allowed the microgrids to jointly share energy [23]. Shi M et al. presented an approach for scheduling and optimizing several microgrids using a common hydrogen storage device [24], and scholars have also evaluated the viability of utilizing hydrogen in microgrids as an energy storage technology [25].

Benefit allocation stands as a pivotal issue in the shared energy storage-microgrid collective operation. Currently, there is limited literature focusing on benefit distribution. The commonly employed Shapley value profit distribution method considers the marginal contributions of each entity from an output perspective. Both Yu Q et al. and Hu J et al. adopted a cooperative game theory approach based on the Shapley value approach. Yu Q introduced an iterative computation method for the local marginal electricity price of distributed generator units [26], while Hu J et al. focused on how auxiliary service expenses are distributed among wind farms in wind power integration [27]. The coordination between wind power and other generator units during deep peak shaving was investigated by Peng F, with the Shapley value method being employed to calculate each entity's contribution [28]. Wu W argued that solely distributing benefits from current collaborative outcomes was shortsighted, offering a revised Shapley value approach based on the deep peak regulation ability to demand ratio in order to distribute extra profits within the alliance [29]. Different alliances possess distinct characteristics, necessitating the evaluation of each entity's contribution from various perspectives. Thus, in this study, a profit-sharing strategy based on the Nash-Harsanyi bargaining game is presented. This approach considers every entity's preferred level of risk and introduces bargaining power derived from several indicators reflecting different aspects of each entity's contribution. While ensuring fairness, this more comprehensive quantification of each entity's contribution to the alliance maximizes individual benefits, resulting in a more reasonable benefit allocation and higher acceptance among entities. Furthermore, existing literature commonly involves direct energy scheduling between shared energy storage system and microgrids. For enhancing the rationality of power scheduling and coordinate control, a third-party operator is incorporated, given that a shared energy storage system services numerous microgrids. Figure 1 depicts the paper's research path.

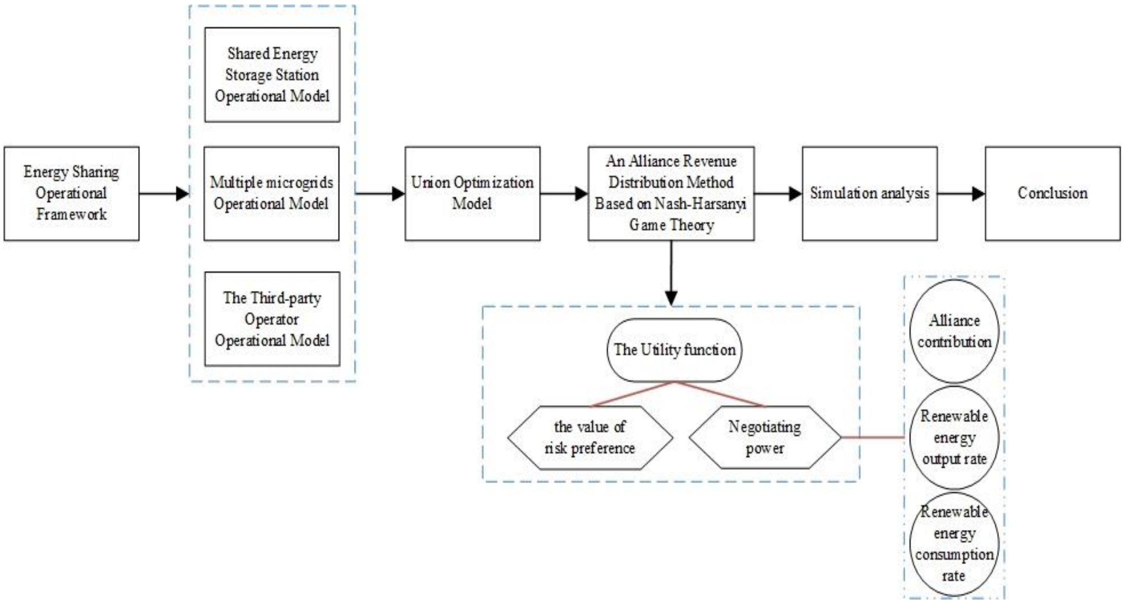

Figure 1 Research route

2. Operating Mode

Due to the shared energy storage system servicing several microgrids, each microgrid having varying demands for storage, the shared energy storage system offer different services tailored to the unique needs of each microgrid. Therefore, considering the involvement of a third-party operator to coordinate and control the flow of electrical energy, service pricing, and transactional payments between the multiple microgrids and the shared energy storage would make the entire power network more rational and efficient.

An energy system shown in Figure 2 is made up of the distribution grid, a shared energy storage system, several microgrids, and a third-party operator.

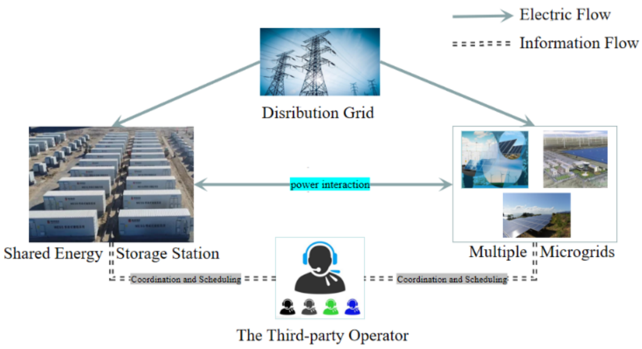

Figure 2 The framework for energy sharing operation among multiple microgrids

2.1 Shared energy storage system

This will be referred to as SESS from now on. Configuring SESS on the customer side can enhance the quality of electrical energy through energy shifting, providing emergency backup, and compensating for reactive power, thus offering added value. In this paper, the charging sources for SESS are the multiple microgrids and the distribution grid, while the sale of electricity is exclusively directed towards the multiple microgrids. SESS purchases and stores electrical energy from the distribution grid and multiple microgrids during low-demand periods with lower electricity prices. Conversely, during high-demand periods with elevated electricity prices, it sells stored electrical energy to the multiple microgrids. This allows the system to profit from price differences and simultaneously reduces instances of renewable energy waste in the multiple microgrids. The revenue for SESS comes from selling electricity to multiple microgrids and residual daily income. Its expenses encompass electricity purchasing from the distribution grid and multiple microgrids, daily investment costs, daily operational costs, and service fees paid to the third-party operator.

2.2 Multiple microgrids

When there's an excess of renewable energy within the multiple microgrids, it can be sold to SESS to reduce wasted renewable energy due to oversupply. Subsequently, SESS can resell this surplus energy to other microgrids facing power shortages. This facilitates energy transfer between different microgrids, advocating for the integration of renewable energy sources locally. Without considering SESS, only the distribution grid can be used by multiple microgrids to purchase, which incurs higher purchasing costs. Upon joining the alliance, multiple microgrids gain the option to buy electricity from both SESS and the distribution grid. A microgrid can purchase electricity from the source at a reduced cost in the event that its self-generated power is insufficient to meet its demands. If the demand still isn't met, it can then turn to the other source for additional electricity. In the energy-sharing system, the benefits for multiple microgrids stem from revenue gained by selling electricity to SESS. Expenses encompass the price of acquiring electricity from SESS and the distribution grid, daily operational costs, and payments to the third-party operator.

2.3 The third-party operator

The third-party operator coordinates the control of electricity flow between SESS and various multiple microgrids, along with managing transaction payments, among other tasks. The operator's revenue sources encompass service fees paid by SESS and multiple microgrids, while costs primarily include daily operational expenses, covering management, platform development, and operational maintenance costs.

3. Multi-Subject Alliance Operational Profit Model

3.1 SESS operational model

3.1.1 Objective function

In order to maximize profit during SESS operation, the objective function is as follows:

$$\max B_{SESS} = B_{SESS\_sell} + B_{SESS\_rv} - C_{SESS\_buy} - C_{inv} - C_{ope} - C_{SESS\_ser} \tag{1}$$

In the formula, B_{SESS} represents the daily total revenue of SESS. B_{SESS_sell} represents the income generated by selling electricity to the microgrid. B_{SESS_rv} stands for the residual value income of SESS. C_{SESS_buy} represents the expenditure for buying electricity from both the multiple microgrids and the distribution grid. C_{inv} represents the SESS investment cost per day. C_{ope} indicates the SESS's daily operating cost. C_{SESS_ser} represents the cost paid by SESS to the operator for services rendered.

a) Revenue from electricity sales by SESS

$$B_{SESS\_sell} = \sum_{i=1}^{n}\sum_{t=1}^{T}\alpha_{i,t}P_{SESS\_sell,i,t} \tag{2}$$

Where n is the quantity of microgrids in the multiple microgrids. T indicates a total quantity of time intervals within the scheduling period. $\alpha_{i,t}$ is the the cost of electricity at moment t that SESS sells to microgrid i . $P_{SESS\_sell,i,t}$ indicates the electricity that SESS sells to the multiple microgrids.

b) The residual value income of SESS

$$B_{SESS\_rv} = C_{inv} * V_r \tag{3}$$

The residual value income in this paper is calculated as a percentage of the daily investment cost. V_r is the percentage of residual value to C_{inv} .

c) The expenditure of SESS for purchasing electricity

$$C_{SESS\_buy} = \sum_{i=1}^{n}\sum_{t=1}^{T}\gamma_{i,t}P_{SESS\_buy,i,t} + \sum_{t=1}^{T}\beta_t P_{SESS\_buy(grid),t} \tag{4}$$

In the formula, $\gamma_{i,t}$ represents the electricity price that SESS purchases from microgrid i at moment t. $P_{SESS\_buy,i,t}$ indicates the electricity that, at moment t, SESS purchases from microgrid i . β_t shows the price of electricity that SESS pays the distribution system at moment t. $P_{SESS\_buy(grid),t}$ indicates the amount of electricity that, at moment t, SESS acquires from the distribution grid.

d) The daily operational cost of SESS

$$C_{ope} = C_{SESS\_ope}\left[\sum_{i=1}^{n}\sum_{t=1}^{T}(P_{SESS\_buy,i,t} + P_{SESS\_sell,i,t}) + \sum_{t=1}^{T}P_{SESS\_buy(grid),t}\right] \tag{5}$$

Where C_{SESS_ope} is the unit transmission cost of SESS.

e) The daily investment cost of SESS

$$C_{inv} = \frac{\eta_{SESS}E_{SESS,\max} + \eta_P P_{SESS,\max}}{T_s} + M_{SESS} \tag{6}$$

Where η_{SESS} is the capacity cost for SESS. $E_{SESS,\max}$ represents SESS's maximum capacity. η_P indicates SESS's power cost. $P_{SESS,\max}$ is SESS's maximum power for charging and discharging. T_s is the service life duration in days for SESS. M_{SESS} is the daily maintenance cost for SESS.

f) SESS pays service fees to the third-party operator

$$C_{SESS\_ser} = C_{SESS}\left[\sum_{i=1}^{n}\sum_{t=1}^{T}\left(P_{SESS\_buy,i,t} + P_{SESS\_sell,i,t}\right)\right] \tag{7}$$

C_{ESS} is the charge for power service per unit paid by SESS to the operator.

3.1.2 Constraints

a) State-of-Charge Constraints for SESS

SESS power capacity cannot be used to charge or discharge more than 90% of its total power.

$$0.1E_{SESS,\max} \le E_{SESS,t} \le 0.9E_{SESS,\max} \tag{8}$$

Within the formula, $E_{SESS,t}$ represents the capacity value of SESS at moment t. $E_{SESS,\max}$ indicates SESS's maximum capacity value.

b) Charging and discharging power constraints of SESS

$$P_{SESS,abs,t} = \sum_{i=1}^{n} P_{SESS\_buy,i,t} \tag{9}$$

$$P_{SESS,relea,t} = \sum_{i=1}^{n} P_{SESS\_sell,i,t} \tag{10}$$

In the formula, $P_{SESS,abs,t}$ indicates SESS's charging power at moment t. $P_{SESS,relea,t}$ indicates SESS's discharging power at moment t. The charging and discharging power of SESS at moment t equals the total of power from mutiple microgrids to SESS.

c) Rating Constraint

$$P_{SESS,\max} = \beta SESS_{\max} \tag{11}$$

Where β is the maximum energy rating of SESS.

d) SESS energy price constraint

To ensure the benefit of SESS, the price at which the system sells energy to the microgrid needs to be higher than the price at which it purchases power from the microgrid.

$$p_{SESS\_buy,MG} \le p_{SESS\_sell,MG} \tag{12}$$

Where $p_{SESS\_buy,MG}$ is the cost that SESS pays to get energy from the microgrid. $p_{SESS\_sell,MG}$ indicates the cost of electricity sold to the microgrid by SESS.

3.2 Multiple microgrids operational model

3.2.1 Objective function

The following objective function represents the operational goal of microgrid entities, which is to reduce operating expenses:

$$\min C_{MG,i} = C_{MG\_buy,i} - B_{MG\_sell,i} + C_{MG\_gas,i} + C_{MG\_ser,i} \tag{13}$$

In the formula, $C_{MG,i}$ represents the operational cost for the ith microgrid. $C_{MG\_buy,i}$ represents the cost of purchasing electricity for the ith microgrid from SESS and the distribution grid. $B_{MG\_sell,i}$ represents the revenue generated by the ith microgrid from selling electricity to SESS. $C_{MG\_gas,i}$ represents the gas cost for the ith microgrid. $C_{MG\_ser,i}$ represents the service fee cost paid by the ithmicrogrid to the third-party operator.

a) The microgrid's cost of purchasing power

$$C_{MG\_buy,i} = \sum_{t=1}^{T} \alpha_{i,t} P_{MG\_buy,i,t} + \sum_{t=1}^{T} \beta_t P_{MG\_buy(grid),i,t} \tag{14}$$

$P_{MG\_buy,i,t}$ indicates the electricity that microgrid i bought from SESS at moment t. $P_{MG\_buy(grid),i,t}$ indicates the electricity that microgrid i bought at moment t from the distribution system.

b) The gas cost of the microgrid

$$C_{MG\_gas,i} = \sum_{t=1}^{T} c_{gas,t} \frac{P_{MT,i}}{\eta_{MT} L_{NG}} \tag{15}$$

Where $c_{gas,t}$ is the gas price in units at moment t. $P_{MT,i}$ represents the Micro-gas Turbines (MT) in microgrid i 's output power at moment t. η_{MT} is the generator's efficiency for the period MT. L_{NG} represents natural gas's calorific value.

c) The revenue from selling electricity generated by the microgrid

$$B_{MG\_sell,i} = \sum_{t=1}^{T} \gamma_{i,t} P_{MG\_sell,i,t} \tag{16}$$

$P_{MG\_sell,i,t}$ indicates the electricity supplied by microgrid i to SESS at moment t.

d) The microgrid pays the third-party operating company service fees

$$C_{MG\_ser,i} = c_{MG} \left[\sum_{t=1}^{T} \left(P_{MG\_buy,i,t} + P_{MG\_sell,i,t} \right) \right] \tag{17}$$

c_{MG} is the charge for power service per unit paid by the microgrid to the operator.

3.2.2 Constraints

a) The electrical power balance constraint

$$\begin{aligned} &P_{PV,i,t} + P_{WT,i,t} + P_{MT,i,t} + P_{MG\_buy,SESS,i,t} + P_{MG\_buy,grid,i,t} \\ &= P_{load,i,t} + P_{MG\_sell,SESS,i,t} + P_{cut,i,t} + P_{train,i,t} \end{aligned} \tag{18}$$

$P_{PV,i,t}$ represents the photovoltaic power generated by microgrid i at moment t. $P_{WT,i,t}$ indicates the amount of electricity produced by the wind turbine in microgrid i at moment t. $P_{MT,i,t}$ represents the electricity produced at moment t by the micro-gas turbines in microgrid i . $P_{MG\_buy,SESS,i,t}$ indicates the electricity that microgrid i purchased from SESS at moment t. $P_{MG\_buy,grid,i,t}$ represents the electricity that microgrid i purchased from the distribution grid at moment t. $P_{load,i,t}$ represents the fixed electrical load in microgrid i at moment t.

$P_{MG\_sell,SESS,i,t}$ indicates the electricity sold from microgrid i to SESS at moment t. $P_{cut,i,t}$ represents the reduction in the electrical load of microgrid i at moment t. $P_{train,i,t}$ indicates the electrical load transfer amount for microgrid i at moment t.

b) Constraints on device outputs within the microgrid

$$\begin{aligned} &0 \le P_{PV,i,t} \le P_{PV,i,t,\max} \\ &0 \le P_{WT,i,t} \le P_{WT,i,t,\max} \\ &P_{MT,i,t,\min} \le P_{MT,i,t} \le P_{MT,i,t,\max} \end{aligned} \tag{19}$$

In the formula, $P_{PV,i,t,\max}$ represents the upper limit of photovoltaic output power in microgrid i at moment t. $P_{WT,i,t,\max}$ represents the upper limit of wind turbines output power in microgrid i at moment t. $P_{MT,i,t,\min}$ and $P_{MT,i,t,\max}$ represents the highest and lowest limits of gas turbine output power in microgrid i at moment t.

c) Constraints on purchasing electricity from the distribution grid

$$0 \le P_{MG\_buy,grid,i,t} \le \varepsilon_{MG\_buy,grid,i,t} P_{MG\_buy,grid,i,\max} \tag{20}$$

where $P_{MG\_buy,grid,i,\max}$ is the upper limit constraint on purchasing electricity from the l distribution grid by microgrid i at moment t. $\varepsilon_{MG\_buy,grid,i,t}$ is the state variable of microgrid i buying electrical power from the external distribution grid at moment t, with a value of 0 or 1.

d) Energy price constraint

$$p_{MG\_sell,SESS} \le p_{MG\_buy,SESS} \tag{21}$$

This equation is equivalent to the energy pricing constraint for SESS. where $p_{MG\_sell,SESS}$ is the price at which microgrids sell electricity to SESS. $p_{MG\_buy,SESS}$ is the price at which microgrids purchase electricity from SESS.

3.3 The third-party operator operational model

The third-party operator's operating purpose is to maximize revenue. Its objective function could be formulated as follows:

$$\max B_{OPE} = B_{OPE\_ser} - C_{OPE} \tag{22}$$

In the formula, B_{OPE} is the revenue of the third-party operator. B_{OPE_ser} is the revenue from service fees collected from SESS and multiple microgrids. C_{OPE} is the daily operating costs.

3.3.1 The revenue of the third-party operator

$$B_{OPE\_ser} = C_{SESS\_ser} + \sum_{i=1}^{n} C_{MG\_ser,i} \tag{23}$$

3.3.2 The daily operating costs

$$C_{OPE} = C_{man} + C_{con} + C_{mai} \tag{24}$$

Where C_{man} is the daily management cost. C_{con} is the platform development cost. C_{mai} is the operating and maintenance expense.

3.4 Union optimization model

The optimal coalition operation model aims to maximize the total earnings of all participating entities.

$$\begin{aligned} &\max B_{union} = B_{SESS} + B_{OPE} - C_{MG,i} \\ &s.t. \quad (8)-(12),(18)-(21) \end{aligned} \tag{25}$$

4. An Alliance Revenue Distribution Method Based on Nash-Harsanyi Game

The Nash-Harsanyi bargaining game is a game theory model used to describe how players allocate payoffs during negotiation. This model is built on Nash bargaining but incorporates Harsanyi's perspective, considering players' beliefs about future uncertainties. The Nash-Harsanyi bargaining model can be applied to analyze various negotiation scenarios such as wage bargaining, company acquisitions, and international trade.

Unlike the standard symmetric Nash game, the Nash-Harsanyi bargaining game considers the effects of numerous circumstances on stakeholders' bargaining power [30]. The problem of competing interests in the distribution of water resources within a river basin was tackled by Fu J using an asymmetric Nash-Harsanyi follower game model [31]. The use of the Nash-Harsanyi game within an alliance was found to be optimal in ensuring fairness and stability by Bai M, providing a new decision-making solution for pollution control in the Taihu Lake Basin [32]. The Nash-Harsanyi bargaining theory is also being applied to address the distribution of benefits between energy producers and consumers in multiple communities within the same distribution network [33].

The solution in the Nash-Harsanyi bargaining game is the Nash bargaining solution, where between two players, there is no other allocation scheme that would give both of them a better outcome than the Nash bargaining solution. This solution is calculated based on the players' power and beliefs about the outcome. Each entity's importance within the alliance varies, resulting in differences in bargaining abilities. By utilizing Bargaining Power (BP), the bargaining abilities of each entity are described [34]. The following represents the Nash-Harsanyi bargaining equilibrium solution:

$$\begin{cases} x_n^* = \arg\max \prod_{n \in N} \left(U_n(x_n) - U_n(d_n)\right)^{bp_n} \\ s.t. U_n(x_n) \geq U_n(d_n) \end{cases} \tag{26}$$

n is the total amount of entities participating in the alliance. x_n represents the percentage of profits distributed to entity n as a proportion of the total profits of the union. d_n represents the negotiation breakdown point, i.e., the percentage of profits distributed to entity n as a proportion of the total profits of the union before joining the alliance. bp_n represents the negotiation power of each entity. $U_n(x_n)$ represents the utility function.

The Nash-Harsanyi equilibrium solution maximizes the alliance's benefits and ensures each entity achieves Pareto-optimal benefits. Consequently, the issue of profit allocation transforms into seeking the Nash-Harsanyi equilibrium solution. From equation (26), it can be observed that the equilibrium solution is related to utility functions and negotiation powers.

4.1 The utility function

The utility function and risk are closely related. In decision analysis, risk refers to situations where choices might lead to uncertain outcomes. When individuals make decisions under uncertainty, they often consider risk factors and incorporate them into the utility function.

According to individuals' attitudes toward risk, they can be categorized into three types: risk-averse, risk-neutral, and risk-seeking. When faced with uncertainty, people who are risk-averse would rather have consistent earnings than take significant risks in the hopes of earning bigger returns. Risk-averse individuals might choose relatively conservative investment strategies to avoid potential loss. In the face of uncertainty, risk neutrality means individuals do not lean toward high or low risks but make investment choices based on a balance between returns and risks. Risk-neutral individuals might choose investment portfolios with moderate risk. Risk seeking denotes individuals who, when faced with uncertainty, prefer high-risk, high-return investment approaches and are willing to take substantial risks to gain higher returns. Risk-seeking individuals might choose investment strategies with high risks and high returns.

The expression for the utility function based on risk preferences is as follows:

$$U_n(x_n)=\begin{cases} c_1+c_2\ln\left(x_n+\dfrac{\beta_n^2}{4(1-\beta_n)}\right) & 0<\beta_n<0.5 \\ x_n \quad \beta_n=0.5 & \\ 1-\left|c_1+c_2\ln\left(1-x_n+\dfrac{1-\beta_n^2}{1-2(1-\beta_n)}\right)\right| & 0.5<\beta_n<1 \end{cases} \tag{27}$$

In the formula, c_1 and c_2 are coefficients. β_n represents the value of risk preference. When $0<\beta_n<0.5$, it is a risk-averse entity. When $\beta_n=0.5$, it is a risk-neutral entity. When $0.5<\beta_n<1$, it is a risk-seeking entity. Once the risk preference value of the entity is determined, substituting points (0, 0) and (1, 1) into the utility function expression allows for calculation.

4.2 Negotiating power

Negotiating power quantifies the actual contributions of each entity to the alliance, where entities with higher negotiating power will obtain a larger share in the distribution of benefits. This paper considers three characteristics of the three entities and introduces three indicators of negotiating power: alliance contribution B_n^1, renewable energy output rate B_n^2, and renewable energy integration rate B_n^3.

4.2.1 Alliance contribution B_n^1

The alliance contribution reflects the level of contribution a subject makes to the alliance after joining.

$$B_n^1=\frac{b(N)-b(N-n)}{b(N)} \tag{28}$$

Where $b(N)$ represents the total alliance profit after the entity joins the alliance. $b(N-n)$ represents the alliance's profit if entity n is removed, considering the remaining entities within the alliance. The closer the value of alliance contribution is to 1, the greater the entity's contribution to the alliance.

4.2.2 Renewable energy output rate B_n^2

The purpose of the microgrid alliance, besides facilitating renewable energy integration, also includes reducing electricity costs. The larger the renewable energy output transmitted from the microgrid to SESS, the more advantageous it is in reducing the microgrid's purchasing cost for electricity. Renewable energy output rate refers to the proportion of renewable energy output transmitted from a specific microgrid entity to SESS about the total renewable energy output of the entire microgrid alliance.

$$B_n^2=\frac{\sum_{t\in T}P_n^{tr}}{\sum_{t\in T}P_N^{tr}} \tag{29}$$

Where P_n^{tr} represents the renewable energy output a certain microgrid supplies to SESS. P_N^{tr} represents the renewable energy output all microgrids supply to SESS. The closer the value of the renewable energy output rate is to 1, the more significant the entity's contribution to cost reduction.

4.2.3 Renewable energy consumption rate B_n^3

$$B_n^3 = \frac{1}{T}\sum_{t\in T}\frac{P_n^{lo}+P_n^{tr}}{P_n^{ge}} \tag{30}$$

Where P_n^{ge} indicates the primary entity's total output of renewable energy. P_n^{lo} indicates the electricity consumption of the main entity's load. P_n^{tr} represents the power supplied by the main entity to SESS. The closer the value of renewable energy consumption rate is to 1, the higher the degree of renewable energy integration by the main entity.

4.2.4 Negotiating power calculation

The impact of the above indicators on negotiating power varies. Hence, it's necessary to determine the weight coefficients for each indicator based on the specific circumstances. The weight vector for the indicators is $W=(w_1,w_2,w_3), w_1+w_2+w_3=1$ .The comprehensive evaluation formula for the negotiating power of participating entities is as follows:

$$S_n = W\cdot\left[B_n^1, B_n^2, B_n^3\right] \tag{31}$$

The negotiation power calculation formula is as follows:

$$bp_n = \frac{S_n}{\sum_{n=1}^{n} S_n} \tag{32}$$

bp_n represents the negotiating power, i.e., the proportion of the comprehensive score of the nth entity's negotiating power in the total score. To ensure the uniqueness of the solution for the Nash-Harsanyi equilibrium, it’s necessary to fulfill $bp_1+bp_2+\cdots+bp_n=1$.

5. Simulation Analysis

5.1 Simulation background

This paper sets up a simulation analysis involving three microgrids, one shared energy storage system, and a third-party operator. Among these, Microgrid A and Microgrid C both possess photovoltaic (PV) and wind turbine (WT) capabilities, while Microgrid B has PV and gas turbines (MT). The electrical load curves, photovoltaic output and wind turbine output of each microgrid are depicted in Figures 3 through 5. The equipment parameters for each microgrid are outlined in Table 1, external energy prices in Table 2, and SESS parameters referenced from Liu D [35], are detailed in Table 3.

Due to the uncertainty associated with the renewable energy output of microgrid entities, their operational costs are significantly affected by output fluctuations. These entities are defined as risk-averse, with a risk preference value set at 0.3. In contrast, the income of SESS and the third-party operator is not sensitive to output fluctuations, classifying them as risk-neutral with a risk preference value set at 0.5.

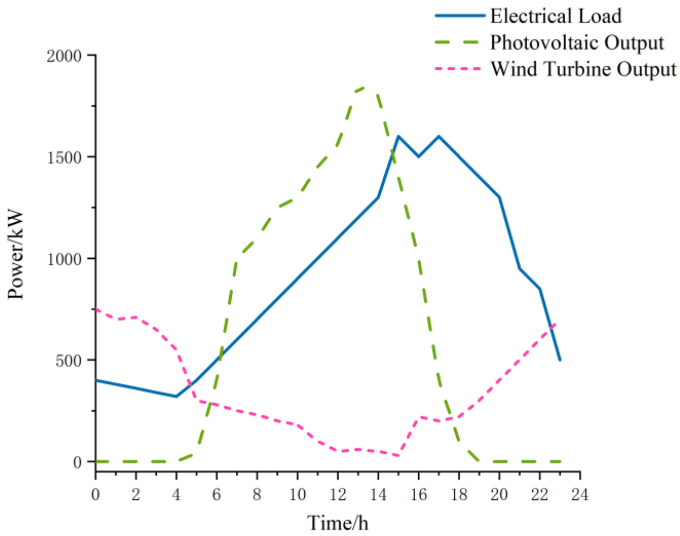

Figure 3 Electrical load, photovoltaic output and wind turbine output of Microgrid A

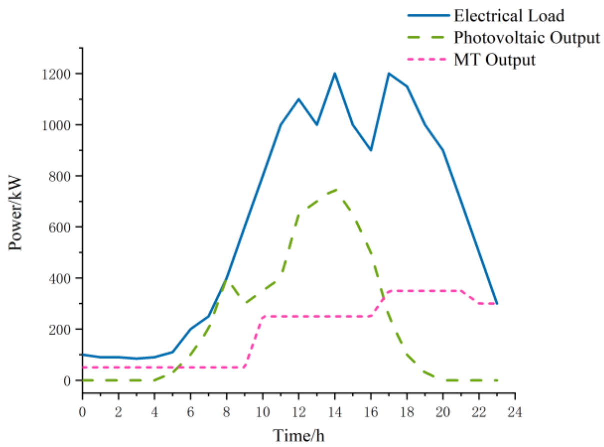

Figure 4 Electrical load, photovoltaic output and MT output of Microgrid B

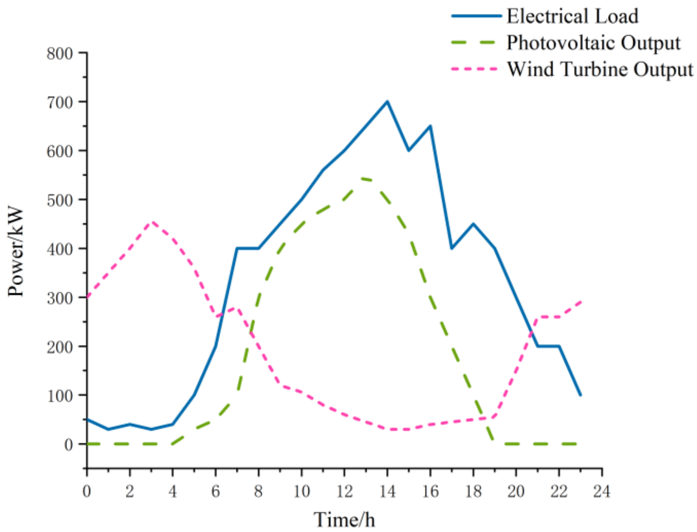

Figure 5 Electrical load, photovoltaic output and wind turbine output of Microgrid C

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Table 1 Parameters of different microgrid devices.

Microgrid	Devices	Parameters
Microgrid A	PV	2000kW·h
	WT	800kW·h
Microgrid B	PV	800kW·h
	MT	380kW·h
Microgrid C	PV	600kW·h
	WT	500kW·h

Table 2 External energy prices.

Work shift	Distribution grid electricity sales prices （yuan/kW）	Natural gas grid sale price （yuan/km³）
0:00-5:00 22:00-24:00	0.50	2.20
5:00-8:00 13:00-17:00	0.80	3.30
8:00-13:00 17:00-22:00	1.20	4.20

Table 3 SESS Parameters.

Parameters	Value
Columetric Cost	1100yuan/kWh
Power Cost	1000yuan/kW
Operation and Maintenance Costs	72yuan/(year·kW)
Charge and Discharge Efficiency	0.95
Transmission Cost per unit power	0.01yuan/kW

5.2 Simulation results analysis

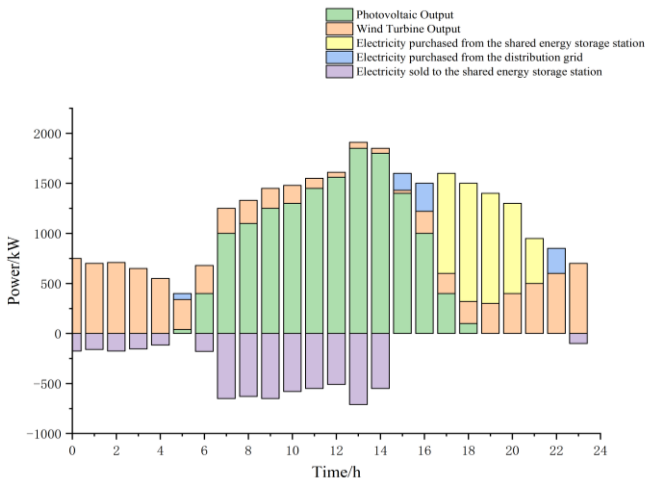

Figure 6 The power balance optimization findings of Microgrid A

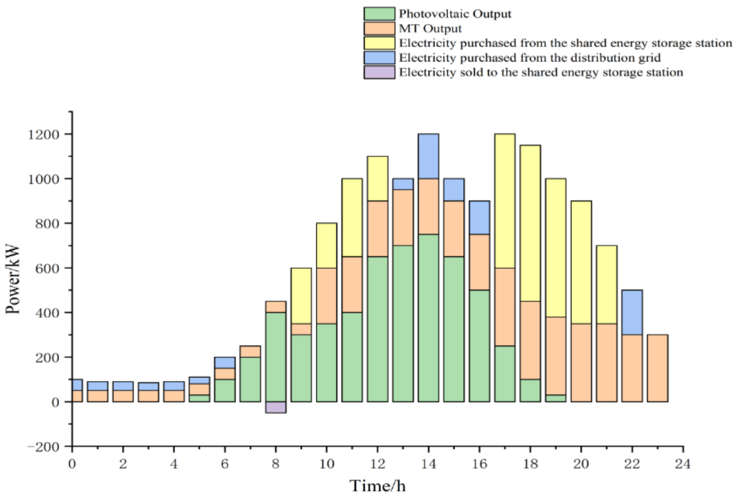

Figure 7 The power balance optimization findings of Microgrid B

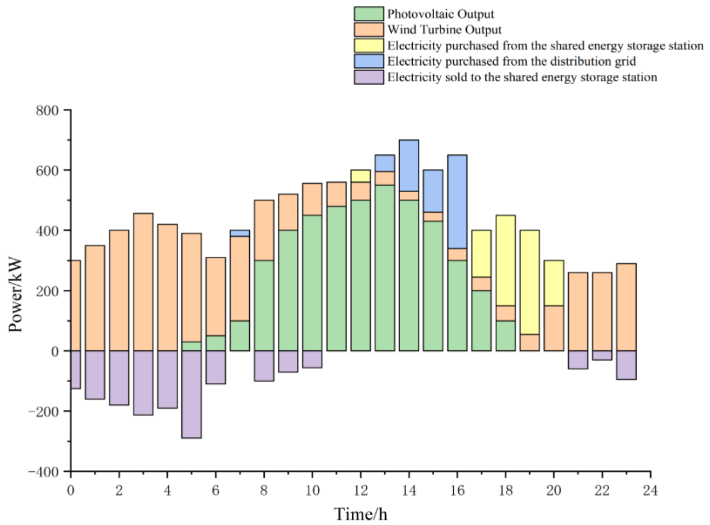

Figure 8 The power balance optimization findings of Microgrid C

Figure 6- Figure 8 display the electricity balance optimization findings of the three microgrids.

Microgrid A exhibits higher wind turbine output from 0:00 to 4:00 and 23:00 to 24:00, with lower load demands during these periods. From 6:00 to 14:00, a significant photovoltaic production can meet the electricity demand. During these time frames, the renewable energy output surpasses the electrical load needs and transfers surplus energy to SESS for energy sharing and subsequent revenue generation. From 15:00 to 23:00, the demand for electricity cannot be met by the generation of renewable energy, requiring external electricity purchases. From 15:00 to 17:00 and 22:00 to 23:00, the distribution grid is less expensive than SESS's selling price. Therefore, purchasing electricity from the distribution system is prioritized. Additional electricity is procured from SESS if the required amount is not met. Conversely, from 17:00 to 22:00, SESS is less expensive than the distribution grid's selling price. Thus, priority is given to purchasing electricity from SESS, with any shortfall being obtained from the distribution grid.

According to the graph, Microgrid B operates as a power-deficient microgrid, scarcely selling electricity to SESS. From 0:00 to 7:00 and 18:00 to 23:00, the photovoltaic output is essentially zero, and the gas turbines' output is insufficient to fulfill the load demand, requiring external electricity purchases. From 0:00 to 7:00 and 22:00 to 23:00, the distribution grid's selling price is equivalent to or less than SESS's price. Consequently, purchasing power from the distribution system is prioritized, with any insufficiency supplemented by purchasing from SESS. However, from 18:00 to 22:00, SESS is being sold for less than the distribution grid is being sold for. Hence, priority is given to purchasing electricity from SESS, with any shortfall being supplemented by purchasing from the distribution grid.

From 9:00 to 18:00, there is a high electricity demand, yet the combined output from the photovoltaic and gas turbines still cannot meet this demand, necessitating external electricity purchases. From 9:00 to 13:00 and 17:00 to 18:00, SESS is being sold for less money than the distribution grid. Therefore, priority is given to purchasing electricity from SESS. Any shortfall is then acquired from the distribution grid. However, from 13:00 to 17:00, The cost of the distribution grid is less than or equivalent to SESS's selling price. Consequently, the distribution grid is the first source of electricity to be purchased, with any insufficient amount being obtained from SESS.

Microgrid C and A exhibit considerable similarities, thus no further detailed analysis is provided.

5.3 Profit distribution

5.3.1 Initial profit calculation

The revenue source of SESS comes from the price difference in selling and purchasing renewable energy output to and from microgrids and the distribution grid, respectively. The third-party operator derive their revenues from service charges paid by the microgrid and SESS. It is noteworthy that the revenue streams of the microgrid companies comprise the proceeds from the sale of renewable energy output to SESS and the differential in the cost of power acquired from SESS compared to the distribution grid. This is because, during certain periods, SESS is being sold for less money than the distribution grid, resulting in reduced electricity procurement costs for the microgrid entities participating in the alliance.

5.3.2 Profit calculation after distribution

Although SESS and the third-party operator do not have renewable energy output, they are indispensable entities within the alliance. Therefore, their renewable energy output and consumption rates are set to 1. Based on the importance of alliance contribution, renewable energy output rate, and renewable energy consumption rate—weighted at 0.3, 0.2, and 0.5, respectively—the negotiation power values for each entity are calculated using formulas (31) to (32). The values for each indicator and the negotiation power results are presented in Table 4.

Table 4 Negotiating power indicators.

		Alliance contribution	Renewable energy output rate	Renewable energy consumption rate	Negotiating power
Shared energy storage system		0.36	1	1	0.24
Microgrid	A	0.26	0.77	0.95	0.21
	B	0.11	0.01	0.99	0.16
	C	0.16	0.22	0.95	0.17
The Third-party Operator		0.11	1	1	0.22

Table 5 presents the results before and after the distribution of profits on the basis of the Nash-Harsanyi game.

Table 5 Results of the distribution of proceeds.

		Profit before distribution (ten thousand yuan)	percentage of revenue	Profit after distribution (ten thousand yuan)
Shared energy storage system		0.11	0.29	0.30
Microgrid	A	0.48	0.19	0.95
	B	0.16	0.15	0.99
	C	0.12	0.14	0.95
The Third-party Operator		0.15	0.24	0.24

Table 6 compares the results of applying the Shapley value and Nash-Harsanyi methods for allocating alliance benefits.

Table 6 Comparison of results of different methodological allocations.

		Shapley (%)	Nash-Harsanyi (%)
Shared energy storage system		0.23	0.29
Microgrid	A	0.22	0.18
	B	0.18	0.15
	C	0.17	0.14
The Third-party Operator		0.20	0.24

After comparing Table 5, it is evident that after profit allocation using the Nash-Harsanyi method, the profits for SESS and the third-party operator increased compared to before allocation. Furthermore, a comparison of Table 6 reveals that the results of the Nash-Harsanyi approach and the Shapley value approach for allocation are largely similar. However, the Nash-Harsanyi method places greater emphasis on the contribution to renewable energy consumption. Hence, it increases the proportion of benefits for SESS and the third-party operator.

In summary, the Nash-Harsanyi method proposed in this paper comprehensively considers each entity's risk preferences, alliance contributions, renewable energy output rates, and consumption rates for profit distribution. This ensures a fair and rational allocation of benefits, guaranteeing the alliance's stable operation.

6. Conclusion

The paper, set against the backdrop of SESS third-party operator-microgrid consortium, proposes the Nash-Harsanyi game theory. Considering the risk preferences of each entity and integrating alliance contributions, renewable energy output rates, and renewable energy consumption rates, among other indicators, it establishes a model for alliance benefit allocation. This model aims to reasonably distribute the benefits brought by the alliance while ensuring maximization of the alliance's overall gains. Through simulation verification, the conclusions are as follows:

The operational profits of each entity increase: SESS 's participation in a consortium among microgrid entities reduces the purchasing costs of individual microgrids. SESS and the third-party operator experience profits following their participation in the consortium.

The profit distribution is more reasonable: The utilization of the Nash-Harsanyi game theory in this paper considers the characteristics of different entities and their significance within the alliance. This approach results in a more rational distribution of benefits more widely accepted by the entities involved.

The renewable energy consumption rate significantly increases: Compared to the individual operation of each microgrid, forming a consortium among microgrid entities facilitates energy exchange between them, leading to a substantial improvement in the renewable energy consumption rate.

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