

# Decision-making Method of Sharing Mode for Multi-microgrid System Considering Risk and Coordination Cost

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**Abstract**—Power sharing can improve the benefit of the multi-microgrid (MMG) system. However, the information disclosure may appear during the sharing process, which would bring privacy risk to a local microgrid. Actually, the risk and coordination cost are different in different sharing modes. Therefore, this paper develops a decision-making method to decide the most suitable one of three mostly used sharing modes (i.e., cooperative game with complete information, cooperative game with incomplete information, and noncooperative game). Firstly, power sharing paradigms and coordination mechanisms in the three modes are formulated in detail. Particularly, different economic operation models of MMG system are included to analyze the economic benefit from different sharing modes. Based on the different disclosed information, the risk cost is evaluated by using the simplified fuzzy analytic hierarchy process (FAHP). And the coordination cost for different sharing modes is expressed in different functions. In addition, a hierarchical evaluation system including three decision-making factors (e.g., economics, risk, and coordination) is set up. Meanwhile, a combination weighting method (e.g., the simplified FAHP combined with the anti-entropy weight method) is applied to obtain the weight of each factor for comprehensive evaluation. Finally, the optimal sharing solution of MMG system is decided by comparing and analyzing the difference among the three sharing modes. Numerical results validate that the proposed method can provide a reference to deciding a suitable sharing mode.

**Index Terms**—Multi-microgrid system, power sharing, risk cost, coordination cost, fuzzy analytic hierarchy process (FAHP), combined weighting method.

## NOMENCLATURE

### A. Indices

$i, j$	Indices of microgrids (MGs)
$k$	Index of power sharing modes
$m, n$	Indices of decision-making factors
$p, q$	Indices of risk evaluation criterions
$t$	Index of time periods

### B. Sets

$N$	Set of MGs
$T$	Set of time periods

### C. Parameters

$k_{BT}, k_{WT}, k_{PV}$	Operating cost coefficients of battery (BT), wind turbine (WT), and photovoltaic (PV) system
$\beta$	Equivalent pollutant emission factor related to the purchasing power from main grid
$\gamma$	Pollution emission price
$c_t^{\text{buy}}, c_t^{\text{sell}}$	Electricity purchasing and selling prices from/to main grid
$P_{\text{grid}}^{\text{max}}$	The maximum exchanged power with main grid
$P_{m2m}^{\text{max}}$	The maximum exchanged power between MGs
$\lambda_{\text{bid},i}^{\text{min}}, \lambda_{\text{bid},i}^{\text{max}}$	Lower and upper bounds of bidding price of MG $i$
$P_{\text{bid},i}^{\text{min}}, P_{\text{bid},i}^{\text{max}}$	Lower and upper bounds of bidding power of MG $i$
$\delta_1, \delta_2, \delta_3$	Coordination coefficients of three sharing modes

### D. Variables

$\lambda_t^{\text{buy}}, \lambda_t^{\text{sell}}$	Purchasing and selling prices of power from/to other MGs in the $t^{\text{th}}$ time period
$\lambda_{i,t}^{\text{bid}}$	Bidding price of MG $i$ in the $t^{\text{th}}$ time period
$\lambda_t$	Clearing price of MG $i$ in the $t^{\text{th}}$ time period
$\omega_i$	Exchanged power contribution of MG $i$
$P_{i,t}^{\text{WT}}, P_{i,t}^{\text{PV}}$	Power of WT and PV of MG $i$ in the $t^{\text{th}}$ time period

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$P_{i,t}^{\text{buy,grid}}, P_{i,t}^{\text{sell,grid}}$	Purchasing and selling power of MG $i$ from/to main grid in the $t^{\text{th}}$ time period
$P_{i,t}^{\text{buy,m2m}}, P_{i,t}^{\text{sell,m2m}}$	Purchasing and selling power of MG $i$ from/to other MGs in the $t^{\text{th}}$ time period
$P_{i,t}^{\text{load}}$	Load demand of MG $i$ in the $t^{\text{th}}$ time period
$P_{i,t}^{\text{ch}}, P_{i,t}^{\text{dis}}$	Charging and discharging power of BT of MG $i$ in the $t^{\text{th}}$ time period
$P_{i,t}^{\text{buy,m2m}'}, P_{i,t}^{\text{sell,m2m}'}$	Actual purchasing and selling power of MG $i$ from/to other MGs in the $t^{\text{th}}$ time period
$P_{i,t}^{\text{sell,grid}'}, P_{i,t}^{\text{buy,grid}'}$	Actual purchasing and selling power of MG $i$ from/to main grid in the $t^{\text{th}}$ time period
$P_{i,t}^{\text{m2m}}$	Clearing power of MG $i$ in the $t^{\text{th}}$ time period
$P_{i,t}^{\text{ex}}$	Exchanged power of MG $i$ in the $t^{\text{th}}$ time period
$R_t$	Supply-demand ratio in the $t^{\text{th}}$ time period
$S_t^{\text{supply}}, S_t^{\text{demand}}$	Total power supply and demand of multi-microgrid (MMG) system in the $t^{\text{th}}$ time period
$Z_{i,t}^{\text{buy,grid}}, Z_{i,t}^{\text{sell,grid}}$	States of purchasing and selling power from/to main grid of MG $i$ in the $t^{\text{th}}$ time period
$Z_{i,t}^{\text{buy,m2m}}, Z_{i,t}^{\text{sell,m2m}}$	States of purchasing and selling power from/to other MGs of MG $i$ in the $t^{\text{th}}$ time period

## I. INTRODUCTION

**M**ICROGRID (MG) is a small and controllable power grid that integrates distributed generations (e.g., wind and solar generation), loads, and energy storage devices [1]. MG not only provides power for its internal loads, but also acts as an independent stakeholder participating in electricity trading [2]. However, the stochastic output of the renewables brings a challenge to balance the energy supply and demand [3]. With the development of sharing economy, power sharing as an emerging business model is proven to be an effective way to address the above problem [4].

Multiple interconnected MGs can exchange power with each other to balance local demands and make full use of excessive renewables by forming a multi-MG (MMG) system [5]-[7]. Several typical sharing modes are widely adopted to model the power sharing process of MMG system, which are cooperative game with complete information (namely centralized management), cooperative game with incomplete information (namely hierarchical management), and noncooperative game (namely distributed management), respectively. Cooperative game with complete information is a traditional way to conduct power sharing. In this way, interconnected MGs are regarded as a large virtual MG which aims at maximizing economic benefits [8]-[10]. Reference [8] formulated an optimization dispatching problem for the cooperative alliance of MGs considering energy interaction. It demonstrated that the cooperative game of MGs effectively reduced the operation cost of the alliance. An improved coalition game theory based on consensus algorithm was proposed in [9] for demand-side management of smart MGs. In [10], motivated by the cooperative game theory, a group of individual MGs was treated as one coalition with the aim of minimizing the total operation cost. However, this cooperative behavior may increase the privacy risk of each participant [11], [12].

To decrease the privacy risk, hierarchical energy manage-

ment mode based on the cooperative game with incomplete information has been explored in many studies [13]-[15]. This mode provides partial decision-making authorities for participants since only power supply/demand quantities are determined by themselves. A hierarchical approach was developed in [13] to solve transactive energy sharing problems in residential MGs. Individuals in [13] were allowed to make their own decisions for optimal resource utilization without sharing any information, and then share energy supply and demand information with the central manager and neighbors for load balance. Reference [14] pointed out that the minimum information exchange was required between MGs and the distribution system in a bi-level hierarchical energy trading scheme. In [15], the dynamical internal transaction price was defined based on the supply and demand ratio (SDR) for facilitating power sharing. This hierarchical energy management mode led to the decrease in information exchange between collaborators, which made the trading scheme relatively privacy-preserving.

Different from the previous two modes, participants are considered as price-makers in the sharing mode with the non-cooperative game [16]-[18]. Reference [16] designed a uniform pricing mechanism for energy trading between MGs, wherein subjects were considered as self-interested identities to iteratively adjust their bids until a state of Nash equilibrium was reached. In [17], an optimal bidding strategy based on the  $Q$ -Learning algorithm was proposed for MGs under the uniform-price auction, which can help bidders learn from experience and make full use of the public information of the market. Reference [18] developed a secure distributed energy management scheme for energy exchange in MMG system, where each MG only submitted information of trading quantities and prices to preserve the information privacy.

Among the above mentioned three modes, most studies are willing to employ the first mode (e.g., cooperative game with complete information) since it is relatively easy to design and implement. But the second mode (e.g., cooperative game with incomplete information) is relatively secure in privacy-preserving and relatively independent for each participant in decision-making process. Besides, independent entities in the third mode (e.g., noncooperative game) were provided by full decision-making authorities to influence the market price by making bidding strategies including trading quantities and price. Actually, it is hard to identify which power sharing mode is the most suitable when applied into real-world scenarios due to the existence of many influence factors (e.g., economic benefits, risk, etc.). Most of the existing studies only focus on the expected benefits under given sharing modes. Few studies explore decision-making methods to obtain the most suitable sharing mode. Based on the foregoing discussion, this paper pays attention to three decision-making factors that affect performance of sharing modes, which are economics (related to expected benefits), risk (related to privacy-preserving), and coordination (related to management mode). The key to deciding a sharing mode lies in the construction of comprehensive evaluation system, where the weight choice is the core problem [19]. In this pa-

per, a combination weighting method (subjective weight combined with objective weight) is used to obtain relatively rational factor weights. This weighting method takes into account the preference of the decision-maker for factors while guaranteeing the objectivity of decision-making process [20]. Subjective weights are acquired by the simplified fuzzy analytic hierarchy process (FAHP), whereas objective weights are determined by the anti-entropy weight method (A-EWM). The FAHP is an extension of the analytic hierarchy process (AHP) by adding fuzzy set theory to deal with imprecise and uncertain problems [21] (e.g., privacy risk assessment). As the basis of A-EWM, the entropy method determines weights based on the amount of information transmitted by indicators to a decision-maker [20]. Compared with the entropy method, the A-EWM shows relatively good robustness and low sensitivity to index difference [22].

Thus, this paper develops a general method to decide the optimal power sharing mode of MMG system. Firstly, three different power sharing modes of MMG system are formulated with related coordination mechanisms and operation models, which shows difference in terms of the management process, information exchange, and economic benefit. Secondly, a hierarchical evaluation system based on the decision-making method is presented, where three decision-making factors including economics, risk, and coordination are selected for comprehensive evaluation. The evaluation system is constructed by a simplified fuzzy analytic hierarchy process for the determination of subjective weight and evaluation of risk cost. In order to quantify the coordination cost, we introduce a coordination coefficient that varies in different sharing modes due to different management forms. Afterwards, a combination weighting method (e.g., the simplified FAHP combined with the A-EWM) is used for combining the weight distribution of those factors. Then, comprehensive evaluation values of the three sharing modes are calculated by the exact numerical values of decision-making factors and their combined weights. Finally, case studies demonstrate that the proposed method can help MGs identify the most appropriate sharing modes.

The rest of this paper is organized as follows. Section II presents the model formulation for three different power sharing modes, with their corresponding coordination mechanisms. Section III presents the decision-making on power sharing mode of MMG system, and gives the quantification method of risk and coordination cost. Case studies on three power sharing modes are conducted in Section IV. Finally, conclusions are drawn in Section V.

## II. MODEL FORMULATION FOR THREE DIFFERENT POWER SHARING MODES

In this section, three mostly used power sharing modes are briefly described. Because of the difference in information exchange and management forms, different sharing modes may result in different risk and coordination costs. It is noteworthy that a market operator (named “energy sharing coordinator”, short as “coordinator” in this paper) is necessary to coordinate the power exchange among multiple MGs

in those modes. Besides, the objective function for each mode is to minimize the economic cost for better analyzing the difference of shared power results.

### A. Cooperative Game with Complete Information (Mode 1)

#### 1) Power Sharing Paradigm and Coordination Mechanisms

Mode 1 represents the centralized management. As shown in Fig. 1, the coordinator can monitor all information including renewable energy, storage system, and load in each MG. That is to say, MGs entrust the coordinator to manage their energy in the form of a large virtual MG. The coordinator essentially makes a centralized optimization strategy for the MMG system after receiving the electricity price of the main grid, load demand, and forecasting data of wind and photovoltaic (PV) power in each MG. Finally, the coordinator publishes the scheduling result including the output of controllable devices, the exchange power with the main grid, and the shared power among different MGs.

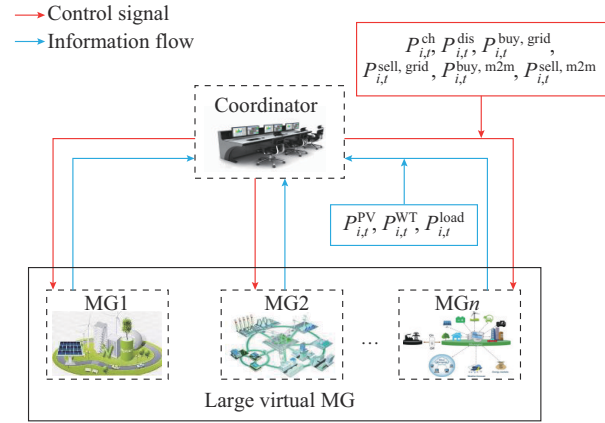


Fig. 1. Power sharing paradigm based on mode 1.

#### 2) Power Sharing Model

In this sharing mode, the coordinator aims at minimizing the economic cost of the MMG system. The objective function (1) includes three different cost terms, which are illustrated in (2). Equation (2) represents the operation and maintenance cost of battery, wind turbine, and PV devices. Equation (3) denotes the pollutant emission cost, which is related to the purchased electricity from the main grid. Besides, the electricity purchasing/selling cost is also considered, as shown in (4).

$$\min \sum_{i \in N} \sum_{t \in T} (C_{i,t}^{\text{ope},1} + C_{i,t}^{\text{emi},1} + C_{i,t}^{\text{grid},1}) \quad (1)$$

$$C_{i,t}^{\text{ope},1} = k_{\text{BT}} (P_{i,t}^{\text{ch}} + P_{i,t}^{\text{dis}}) + k_{\text{WT}} P_{i,t}^{\text{WT}} + k_{\text{PV}} P_{i,t}^{\text{PV}} \quad (2)$$

$$C_{i,t}^{\text{emi},1} = \gamma \beta P_{i,t}^{\text{buy,grid}} \quad (3)$$

$$C_{i,t}^{\text{grid},1} = c_t^{\text{buy}} P_{i,t}^{\text{buy,grid}} - c_t^{\text{sell}} P_{i,t}^{\text{sell,grid}} \quad (4)$$

#### 3) Constraints

Power balance of each MG is realized by:

$$\begin{aligned} P_{i,t}^{\text{PV}} + P_{i,t}^{\text{WT}} + P_{i,t}^{\text{dis}} + P_{i,t}^{\text{buy,grid}} + P_{i,t}^{\text{buy,m2m}} = \\ P_{i,t}^{\text{load}} + P_{i,t}^{\text{ch}} + P_{i,t}^{\text{sell,grid}} + P_{i,t}^{\text{sell,m2m}} \end{aligned} \quad (5)$$

The storage system constraints can be found in [5]. Power transmission between MG and the main grid is limited by:

$$\begin{cases} 0 \leq P_{i,t}^{\text{buy, grid}} \leq P_{\text{grid}}^{\text{max}} Z_{i,t}^{\text{buy, grid}} \\ 0 \leq P_{i,t}^{\text{sell, grid}} \leq P_{\text{grid}}^{\text{max}} Z_{i,t}^{\text{sell, grid}} \\ Z_{i,t}^{\text{buy, grid}} \in \{0, 1\} \\ Z_{i,t}^{\text{sell, grid}} \in \{0, 1\} \\ Z_{i,t}^{\text{buy, grid}} + Z_{i,t}^{\text{sell, grid}} \leq 1 \end{cases} \quad (6)$$

The internal trading power between MGs is also constrained by:

$$\begin{cases} 0 \leq P_{i,t}^{\text{buy, m2m}} \leq P_{\text{m2m}}^{\text{max}} Z_{i,t}^{\text{buy, m2m}} \\ 0 \leq P_{i,t}^{\text{sell, m2m}} \leq P_{\text{m2m}}^{\text{max}} Z_{i,t}^{\text{sell, m2m}} \\ Z_{i,t}^{\text{buy, m2m}} \in \{0, 1\} \\ Z_{i,t}^{\text{sell, m2m}} \in \{0, 1\} \\ Z_{i,t}^{\text{sell, m2m}} + Z_{i,t}^{\text{buy, m2m}} \leq 1 \end{cases} \quad (7)$$

## B. Cooperative Game with Incomplete Information (Mode 2)

### 1) Power Sharing Paradigm and Coordination Mechanisms

Mode 2 represents the hierarchical management. As shown in Fig. 2, the power trading process between MGs is regarded as a bi-level framework, where the upper coordinator conducts power balance among different MGs while each individual MG in the lower level performs the self-management activity according to its own resources and targets. Thus, in the interaction between upper and lower levels, MGs in the lower level firstly make their own economic operation strategies and then exchange information (just power supply and demand information) with each other. Meanwhile, the information is uploaded to the upper platform. Afterwards, the upper coordinator decides the sharing price by a pricing model according to the power supply and demand information, which can guide the operation decision of MGs after the price is returned to the lower level. An equilibrium can be finally reached after several iterations.

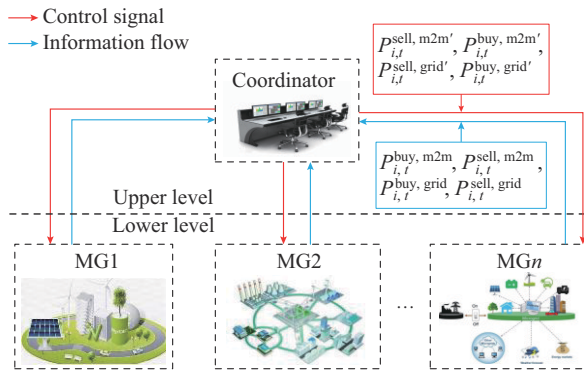


Fig. 2. Power sharing paradigm based on mode 2.

### 2) Power Sharing Model

#### 1) Upper-level model

In mode 2, the coordinator just needs to conduct the power matching activity since only power supply/demand information without prices is submitted by each MG. The matching process is realized by the supply-demand ratio model, which also contributes to the generation of sharing price. Ex-

pressions of the total power supply and demand after the self-management of MGs are given as:

$$\begin{cases} S_t^{\text{supply}} = \sum_{i=1}^N P_{i,t}^{\text{sell, m2m}} \\ S_t^{\text{demand}} = \sum_{i=1}^N P_{i,t}^{\text{buy, m2m}} \end{cases} \quad (8)$$

Then, the supply-demand ratio can be obtained by:

$$R_t = S_t^{\text{supply}} / S_t^{\text{demand}} \quad (9)$$

Several piecewise functions related to the supply-demand ratio are used for modeling the internal pricing and power matching. Especially, the electricity prices of purchasing and selling are described by (10) and (11), respectively, while (12) and (13) describe the actual trading power supply and demand after the balance of supply and demand, respectively.

$$\lambda_t^{\text{sell}} = \begin{cases} c_t^{\text{sell}} & S_t^{\text{supply}} = 0 \text{ or } S_t^{\text{demand}} = 0 \\ \frac{c_t^{\text{buy}}(c_t^{\text{buy}} + c_t^{\text{sell}})}{c_t^{\text{buy}}(1 + R_t) + c_t^{\text{sell}}(1 - R_t)} & R_t < 1 \\ \frac{c_t^{\text{sell}} + c_t^{\text{buy}}}{2} & R_t = 1 \\ \lambda_t^{\text{buy}} / R_t + c_t^{\text{sell}}(1 - 1/R_t) & R_t > 1 \end{cases} \quad (10)$$

$$\lambda_t^{\text{buy}} = \begin{cases} c_t^{\text{buy}} & S_t^{\text{supply}} = 0 \text{ or } S_t^{\text{demand}} = 0 \\ \lambda_t^{\text{sell}} R_t + c_t^{\text{buy}}(1 - R_t) & R_t < 1 \\ \frac{c_t^{\text{sell}} + c_t^{\text{buy}}}{2} & R_t = 1 \\ \frac{c_t^{\text{sell}}(c_t^{\text{buy}} + c_t^{\text{sell}})}{c_t^{\text{sell}}(1 + 1/R_t) + c_t^{\text{buy}}(1 - 1/R_t)} & R_t > 1 \end{cases} \quad (11)$$

When  $S_t^{\text{supply}} > S_t^{\text{demand}}$ , the expressions of actual exchange power are shown as:

$$\begin{cases} P_{i,t}^{\text{sell, m2m}'} = P_{i,t}^{\text{sell, m2m}} / R_t \\ P_{i,t}^{\text{buy, m2m}'} = P_{i,t}^{\text{buy, m2m}} \\ P_{i,t}^{\text{sell, grid}'} = P_{i,t}^{\text{sell, grid}} + P_{i,t}^{\text{sell, m2m}} - P_{i,t}^{\text{sell, m2m}'} \\ P_{i,t}^{\text{buy, grid}'} = P_{i,t}^{\text{buy, grid}} \end{cases} \quad (12)$$

When  $S_t^{\text{supply}} < S_t^{\text{demand}}$ , the expressions of actual exchange power are given as:

$$\begin{cases} P_{i,t}^{\text{sell, m2m}'} = P_{i,t}^{\text{sell, m2m}} \\ P_{i,t}^{\text{buy, m2m}'} = P_{i,t}^{\text{buy, m2m}} R_t \\ P_{i,t}^{\text{sell, grid}'} = P_{i,t}^{\text{sell, grid}} \\ P_{i,t}^{\text{buy, grid}'} = P_{i,t}^{\text{buy, grid}} + P_{i,t}^{\text{buy, m2m}} - P_{i,t}^{\text{buy, m2m}'} \end{cases} \quad (13)$$

#### 2) Lower-level model

Each MG aims at minimizing their economic cost. Specifically, the internal transaction cost is added to the objective function (14) in mode 2, as shown in (16).

$$\min \sum_{t \in T} (C_{i,t}^{\text{ope}, 2} + C_{i,t}^{\text{emi}, 2} + C_{i,t}^{\text{m2m}, 2} + C_{i,t}^{\text{grid}, 2}) \quad (14)$$

$$C_{i,t}^{\text{emi}, 2} = \gamma \beta P_{i,t}^{\text{buy, grid}'} \quad (15)$$



$$C_{i,t}^{m2m,2} = \lambda_t^{\text{buy}} P_{i,t}^{\text{buy},m2m'} - \lambda_t^{\text{sell}} P_{i,t}^{\text{sell},m2m'} \quad (16)$$

$$C_{i,t}^{\text{grid},2} = c_t^{\text{buy}} P_{i,t}^{\text{buy},\text{grid}'} - c_t^{\text{sell}} P_{i,t}^{\text{sell},\text{grid}'} \quad (17)$$

where the expression of  $C_{i,t}^{\text{ope},2}$  is the same as (2), which is not given for simplification.

### 3) Constraints

The following is the expression of power balance for a single MG.

$$P_{i,t}^{\text{PV}} + P_{i,t}^{\text{WT}} + P_{i,t}^{\text{dis}} + P_{i,t}^{\text{buy},\text{grid}'} + P_{i,t}^{\text{buy},m2m'} = P_{i,t}^{\text{load}} + P_{i,t}^{\text{ch}} + P_{i,t}^{\text{sell},\text{grid}'} + P_{i,t}^{\text{sell},m2m'} \quad (18)$$

Other constraints are the same as that in mode 1.

## C. Noncooperative Game (Mode 3)

### 1) Power Sharing Paradigm and Coordination Mechanisms

Mode 3 is described as the distributed management. As shown in Fig. 3, the sharing process can also be described by a bi-level framework and the coordinator plays a role in market clearing. In the lower-level model, MGs firstly make their own optimal operation strategies according to the behaviors (offers/bids) of other MGs. Then bidders (MGs) report their private information (both reservation price and quantity) to the clearing platform (coordinator) without information exchange between MGs. In the upper-level model, the coordinator clears the market according to the submitted information and issues the market clearing outcomes, including the uniform trading price and amount of energy allocated to each MG.

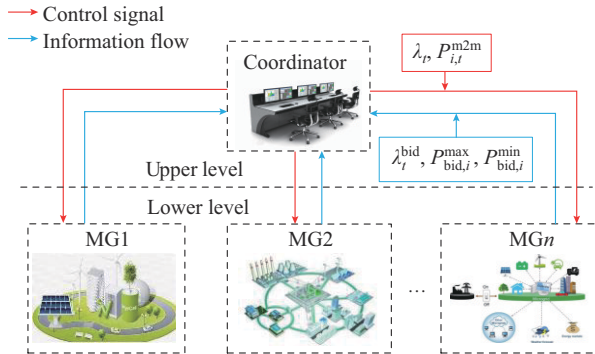


Fig. 3. Power sharing paradigm based on mode 3.

### 2) Power Sharing Model

The clearing platform aims at maximizing the social welfare, whose objective function is presented as:

$$\max \sum_{i \in N} \sum_{t \in T} P_{i,t}^{m2m} \lambda_{i,t}^{\text{bid}} \quad (19)$$

The MG involved in this round of bidding aims at minimizing its economic cost, which is expressed by:

$$\min \sum_{t \in T} (C_{i,t}^{\text{ope},3} + C_{i,t}^{\text{emi},3} + C_{i,t}^{m2m,3} + C_{i,t}^{\text{grid},3}) \quad (20)$$

$$C_{i,t}^{m2m,3} = \lambda_t P_{i,t}^{m2m} \quad (21)$$

where the expressions of  $C_{i,t}^{\text{ope},3}$ ,  $C_{i,t}^{\text{emi},3}$ , and  $C_{i,t}^{\text{grid},3}$  are the same as those in (2), (3), and (4), respectively. If  $P_{i,t}^{m2m} > 0$ , MG  $i$  is a seller; otherwise, MG  $i$  is a buyer in this round of bidding.

### 3) Constraints

MGs realize their power balance by:

$$P_{i,t}^{\text{PV}} + P_{i,t}^{\text{WT}} + P_{i,t}^{\text{dis}} + P_{i,t}^{\text{buy},\text{grid}} + P_{i,t}^{m2m} = P_{i,t}^{\text{load}} + P_{i,t}^{\text{ch}} + P_{i,t}^{\text{sell},\text{grid}} \quad (22)$$

Other constraints are the same as that in mode 1 except for (7). Besides, some additional constraints should be added into mode 3, as shown below.

$$\begin{cases} \lambda_{\text{bid},i}^{\min} \leq \lambda_{i,t}^{\text{bid}} \leq \lambda_{\text{bid},i}^{\max} \\ P_{\text{bid},i}^{\min} \leq P_{i,t}^{m2m} \leq P_{\text{bid},i}^{\max} \\ \sum_{i \in I} P_{i,t}^{m2m} = 0 \end{cases} \quad (23)$$

## III. DECISION-MAKING ON POWER SHARING MODE OF MMG SYSTEM

In Section II, we established economic operation models with the corresponding coordination mechanisms of three power sharing modes. In this section, a simplified FAHP method is firstly introduced to evaluate the risk cost considering different shared information. Subsequently, the coordination cost is expressed in different functions based on different management forms. Then, a combination weighting method (e.g., the simplified FAHP combined with the A-EWM) is used to determine the weights of three decision-making factors (economics, risk, and coordination). And the result of comprehensive evaluation can be calculated by the linear weighted sum method. According to the calculated results, the sharing mode with the best comprehensive performance can be selected.

### A. Hierarchical Evaluation System

In addition to the economic benefits, the risk and coordination cost cannot be ignored when decisions are made on sharing modes. Thus, three decision-making factors including economics ( $B_1$ ), risk ( $B_2$ ), and coordination ( $B_3$ ) are devised. And their relative importance in comprehensive evaluation can be determined. The evaluation system, as shown in Fig. 4, is structured hierarchically at different levels ( $H_1, H_2, H_3, H_4$ ) by using the simplified FAHP. Specifically,  $H_1$  and  $H_2$  consist of the main evaluation system while  $H_3$  and  $H_4$  are the complements for the evaluation of privacy risk.

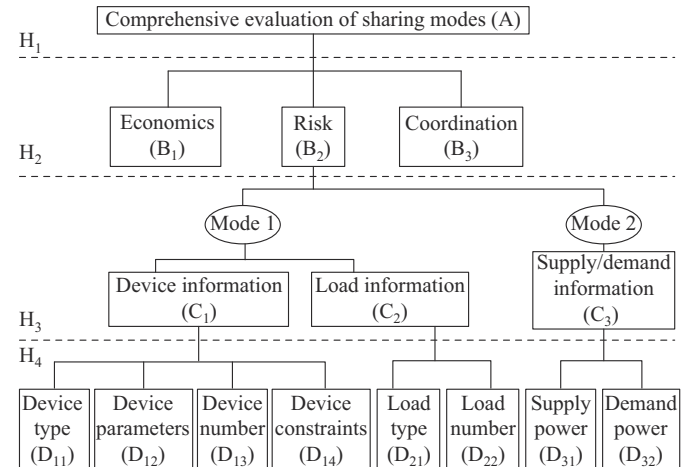


Fig. 4. Hierarchical evaluation system of sharing modes using simplified FAHP.

## B. Quantification of Risk and Coordination Cost in Power Sharing

### 1) Risk Cost Evaluation by Simplified FAHP

As shown in Fig. 4, the evaluation system of privacy risk is composed of  $H_3$  (criterion level) and  $H_4$  (index level), whose criteria are different shared information in sharing modes mentioned above. For mode 1, all personal information including information of device and load is submitted by MGs, while only power supply/demand information is provided by MGs in mode 2. However, there is no information published in mode 3 since MGs are competitors rather than cooperators.

The simplified FAHP is a subjective weighting method based on mathematics and psychology [23], whose improvement lies in the use of the triangular fuzzy numbers in the pairwise comparison compared with AHP. Those risk evaluation criteria are subjective and qualitative. Thus, it is more desirable to use the fuzzy evaluation method (e.g., FAHP) considering the uncertainty and imprecision of evaluation process. The risk evaluation process using the simplified FAHP can be described in detail as follows.

*Step 1:* pairwise comparison matrix establishment. By assuming that there are  $u$  factors in an evaluation level, the evaluation factor is denoted as  $a_p$  ( $p=1, 2, \dots, u$ ).  $a_{pq}$  is the relative importance of  $a_p$  to  $a_q$ . The pairwise comparison matrix for the relative importance is expressed in Fig. 5, where  $a_{pq}$  ( $p, q=1, 2, \dots, u$ ) is expressed with triangular fuzzy number. The fuzzy value is related to three key parameters  $l_{pq}$ ,  $m_{pq}$ ,  $u_{pq}$ , where  $l_{pq}$  and  $u_{pq}$  are the lower and upper boundary values, respectively, and  $m_{pq}$  is the most likely value.

	$a_1$	$a_2$	...	$a_u$
$a_1$	$a_{11}$	$a_{12}$	...	$a_{1u}$
$a_2$	$a_{21}$	$a_{22}$	...	$a_{2u}$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$a_u$	$a_{u1}$	$a_{u2}$	...	$a_{uu}$

Fig. 5. Expression of pairwise comparison matrix for relative importance.

*Step 2:* consistent matrix generation and consistency check. Select each most likely value  $m_{pq}$  in the above pairwise comparison matrix to form the matrix  $\mathbf{M}$ , which is shown below:

$$\mathbf{M} = \begin{bmatrix} m_{11} & m_{12} & \dots & m_{1u} \\ m_{21} & m_{22} & \dots & m_{2u} \\ \vdots & \vdots & \ddots & \vdots \\ m_{u1} & m_{u2} & \dots & m_{uu} \end{bmatrix} \quad (24)$$

Then, the consistent matrix  $\mathbf{M}_1$  can be generated by using (25) and (26).

$$\mathbf{M}_1 = \begin{bmatrix} m_{11,1} & m_{12,1} & \dots & m_{1u,1} \\ m_{21,1} & m_{22,1} & \dots & m_{2u,1} \\ \vdots & \vdots & \ddots & \vdots \\ m_{u1,1} & m_{u2,1} & \dots & m_{uu,1} \end{bmatrix} \quad (25)$$

$$\begin{cases} m_p = \sum_{h=1}^u m_{ph} \\ m_q = \sum_{h=1}^u m_{qh} \\ m_{pq,1} = \frac{m_p - m_q}{2(u-1)} + 0.5 \end{cases} \quad (26)$$

The consistency of the consistent matrix  $\mathbf{M}_1$  is examined using (27) and (28). If matrix  $\mathbf{M}_1$  satisfies the consistency conditions, the pairwise comparison matrix in Fig. 5 is approximate to be consistent; otherwise, return to *Step 1* and regenerate another pairwise comparison matrix.

$$\varepsilon = \max(|m_{pq,1} - m_{pq}|) < 0.2 \quad (27)$$

$$\sigma = \frac{1}{u} \sqrt{\sum_{p=1}^u \sum_{q=1}^u (m_{pq,1} - m_{pq})^2} < 0.1 \quad (28)$$

where  $\varepsilon$  and  $\sigma$  are the parameters of consistency check.

*Step 3:* non-fuzzy matrix generation and subjective weight determination. Convert the pairwise comparison matrix into the following non-fuzzy matrix  $\mathbf{M}_2$  using (29) and (30), and calculate the weight of each evaluation factor using (31).

$$\mathbf{M}_2 = \begin{bmatrix} m_{11,2} & m_{12,2} & \dots & m_{1u,2} \\ m_{21,2} & m_{22,2} & \dots & m_{2u,2} \\ \vdots & \vdots & \ddots & \vdots \\ m_{u1,2} & m_{u2,2} & \dots & m_{uu,2} \end{bmatrix} \quad (29)$$

$$m_{pq,2} = \frac{l_{pq}}{2(l_{pq} + 2)} + \frac{2m_{pq}}{3} + \frac{u_{pq}}{6} \quad (30)$$

$$w_p = \frac{\sum_{q=1}^u m_{pq,2} - 0.5}{\sum_{p=1}^u \left( \sum_{q=1}^u m_{pq,2} - 0.5 \right)} \quad (31)$$

where  $w_p$  is the weight of the  $p^{\text{th}}$  risk evaluation factor.

*Step 4:* risk cost calculation. Convert the weight of each evaluation factor into score using (32).

$$W_p = \frac{w_p - \bar{w}}{w^+ - \bar{w}} d + c \quad (32)$$

where  $W_p$  is the evaluation score of the  $p^{\text{th}}$  risk evaluation factor;  $w^+$  and  $\bar{w}$  are the maximum and average values, respectively; and constants  $c$  and  $d$  are assigned to be 80 and 20, respectively.

Finally, the risk cost can be evaluated for different sharing modes through final evaluation score.

### 2) Quantification of Coordination Cost

In this paper, the coordination cost is an abstract concept affected by two main factors such as the management form and number of participants. In order to integrate the impact of those elements, three nonlinear equations suitable for the three sharing modes are devised. In particular, the coordination coefficients ( $\delta_1$ ,  $\delta_2$ , and  $\delta_3$ ) are determined with consideration of management forms. For example,  $\delta_1$  of mode 1 is set to be 0.1, which means that the coordination between MGs is relatively easy in centralized management. But  $\delta_2$  of

mode 2 is set to be 0.5, because the hierarchical management increases the coordination difficulty. Considering that MGs are no longer cooperators in the distributed management, it is more difficult to coordinate all participants. We set  $\delta_3$  of mode 3 to be 0.9. The expressions of coordination cost of the three modes are listed as:

$$C_{c,1} = \delta_1 \sqrt[4]{N} \times 10^3 \quad (33)$$

$$C_{c,2} = \delta_2 \sqrt[3]{N} \times 10^3 \quad (34)$$

$$C_{c,3} = \delta_3 \sqrt[2]{N} \times 10^3 \quad (35)$$

where  $C_{c,1}$ ,  $C_{c,2}$ , and  $C_{c,3}$  are the coordination costs of mode 1, mode 2, and mode 3, respectively. As seen from the above discussion, the exponent of variable  $N$  varies in different modes. That is because the coordination cost of mode 3 is greatly affected by the sharing scale (e.g., number of participants), while the impact of sharing scale on coordination cost is minimal for mode 1.

### C. Comprehensive Evaluation of Power Sharing Modes

#### 1) Evaluation Method and Process

As shown in Fig. 4, three decision-making factors ( $B_1$ ,  $B_2$ , and  $B_3$ ) are listed to evaluate the comprehensive performance of sharing modes. In previous part of the paper, the three factors have been already evaluated as exact numerical values, which enables them to be objective and quantitative. Thus, an objective weighting method can be introduced to determine the objective weights of those decision-making factors.

The A-EWM is executed based on objective data, which can avoid personal interference to a large extent. Thus, this method is regarded as the objective weighting method in this paper. But the subjective tendencies of decision-makers are not taken into account. Therefore, this paper adopts a combination weighting method based on the simplified FAHP and the A-EWM for carrying out the comprehensive evaluation of sharing modes. This combination method helps balance the subjective experience of experts and the objective information in the data during the evaluation process [24]. The comprehensive evaluation flow chart of sharing modes is shown in Fig. 6.

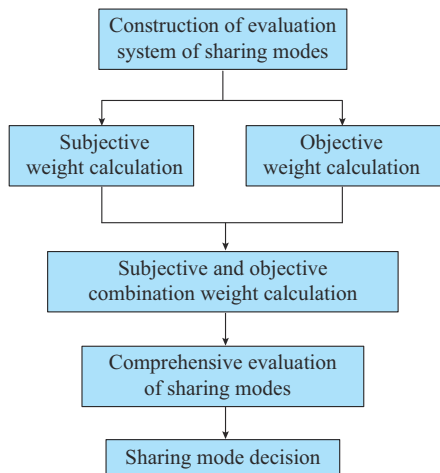


Fig. 6. Comprehensive evaluation flow chart of sharing modes.

#### 2) Weight Determination of Decision-making Factors

The simplified FAHP used for subjective weight determination has been described in Section III-B. The subjective weight of each decision-making factor varies in different sharing modes. Besides,  $w_{mk}$  indicates subjective weight of the  $m^{\text{th}}$  decision-making factor in the  $k^{\text{th}}$  sharing mode.

The subjective weight is arbitrary while the objective weight is unique. Therefore, three modes share the same objective weights of decision-making factors. In addition,  $g_m$  indicates the objective weight of the  $m^{\text{th}}$  decision-making factor. The determination process of objective weights based on the A-EWM is described as follows.

*Step 1: evaluation matrix establishment and normalization.* The evaluation matrix  $X$  is shown below, where rows represent decision-making factors while columns represent sharing modes.  $v$  and  $w$  are the number of rows and columns, respectively. Then, matrix  $X$  is converted into the normalized matrix  $Y$  using (37) and (38). Significantly, three decision-making factors proposed in this paper belong to the negative index. Equation (38) is applicable to the normalization for such indexes.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1w} \\ x_{21} & x_{22} & \cdots & x_{2w} \\ \vdots & \vdots & \ddots & \vdots \\ x_{v1} & x_{v2} & \cdots & x_{vw} \end{bmatrix} \quad (36)$$

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1w} \\ y_{21} & y_{22} & \cdots & y_{2w} \\ \vdots & \vdots & \ddots & \vdots \\ y_{v1} & y_{v2} & \cdots & y_{vw} \end{bmatrix} \quad (37)$$

$$y_{mk} = \frac{x_m^{\max} - x_{mk}}{x_m^{\max} - x_m^{\min}} \quad (38)$$

where  $x_m^{\max}$  and  $x_m^{\min}$  are the maximum and minimum values in the  $m^{\text{th}}$  row of matrix  $X$ , respectively.

*Step 2: anti-entropy and weight calculation.* The anti-entropy and weight of each sharing mode are calculated as:

$$\begin{cases} E_k = - \sum_{m=1}^v p_{mk} \ln(1 - p_{mk}) \\ p_{mk} = \frac{y_{mk}}{\sum_{m=1}^v y_{mk}} \end{cases} \quad (39)$$

$$\theta_k = \frac{1 - E_k}{v - \sum_{k=1}^w E_k} \quad (40)$$

where  $E_k$  and  $\theta_k$  are the anti-entropy and weight of the  $k^{\text{th}}$  sharing mode, respectively; and  $p_{mk}$  is the proportion of the  $m^{\text{th}}$  element in the  $k^{\text{th}}$  column in normalized matrix  $Y$ . In (39),  $\lim_{p_{mk} \rightarrow 1} p_{mk} \ln(1 - p_{mk}) = 0$ .

*Step 3: score calculation and objective weight distribution.* The weight mean scores of decision-making factors can be obtained by (41). Then, (42) can be used to calculate the objective weight of each decision-making factor.

$$Z_m = \sum_{k=1}^w \theta_k y_{mk} \quad (41)$$

$$g_m = Z_m / \sum_{m=1}^v Z_m \quad (42)$$

where  $Z_m$  and  $g_m$  are the weight mean score and objective weight of the  $m^{\text{th}}$  decision-making factor, respectively.

After the subjective/objective weights of decision-making factors are determined, their preference coefficients can be calculated by (43).

$$\begin{cases} \mu_{mk} = \frac{w_{mk}}{w_{mk} + g_m} \\ \lambda_{mk} = \frac{g_m}{w_{mk} + g_m} \end{cases} \quad (43)$$

where  $\mu_{mk}$  and  $\lambda_{mk}$  are the subjective and objective preference coefficients of the  $m^{\text{th}}$  decision-making factor in the  $k^{\text{th}}$  sharing mode, respectively.

Finally, the combination weight of each decision-making factor can be obtained by using (44).

$$\psi_{mk} = \frac{\mu_{mk} w_{mk} + \lambda_{mk} g_m}{\sum_{m=1}^v (\mu_{mk} w_{mk} + \lambda_{mk} g_m)} \quad (44)$$

where  $\psi_{mk}$  is the combination weight of the  $m^{\text{th}}$  decision-making factor in the  $k^{\text{th}}$  sharing mode.

### 3) Comprehensive Evaluation

The comprehensive evaluation values can be obtained according to the exact numerical values of decision-making factors and their combined weights, which can be expressed as:

$$C_k = \sum_{m=1}^v \psi_{mk} x_{mk} \quad (45)$$

where  $C_k$  is the comprehensive evaluation value of the  $k^{\text{th}}$  sharing mode. This value can reflect the comprehensive performance of three different sharing modes. By the comparison of the three evaluation values, the best sharing mode for the MMG system can be determined.

## IV. CASE STUDIES

A modified IEEE 33-bus system with nine MGs is used to verify the proposed method in this paper. Numerical results are performed using MATLAB R2016a and CPLEX 12.6 on a computer with 2.50 GHz CPU and 4 GB RAM.

### A. System Configuration and Basic Data

The nine MGs are numbered and divided into three categories, which are industrial MGs (MG1-MG3), commercial MGs (MG4-MG6) and residential MGs (MG7-MG9). Those nine MGs are located in the same area and connected to each other through transmission lines. The operation period  $T$  is 24 hours. The time interval  $\Delta t$  is 1 hour. The battery parameters are presented in Table I. The power forecasting curves of renewable energy and power load are shown in Fig. 7.

TABLE I  
BATTERY PARAMETERS

Parameter	Value	Parameter	Value
Charging/discharging efficiency	0.75	The minimum capacity (kWh)	80
The maximum charging/discharging power (kW)	100	Initial capacity (kWh)	80
The maximum capacity (kWh)	360	Self-discharging rate	0.02

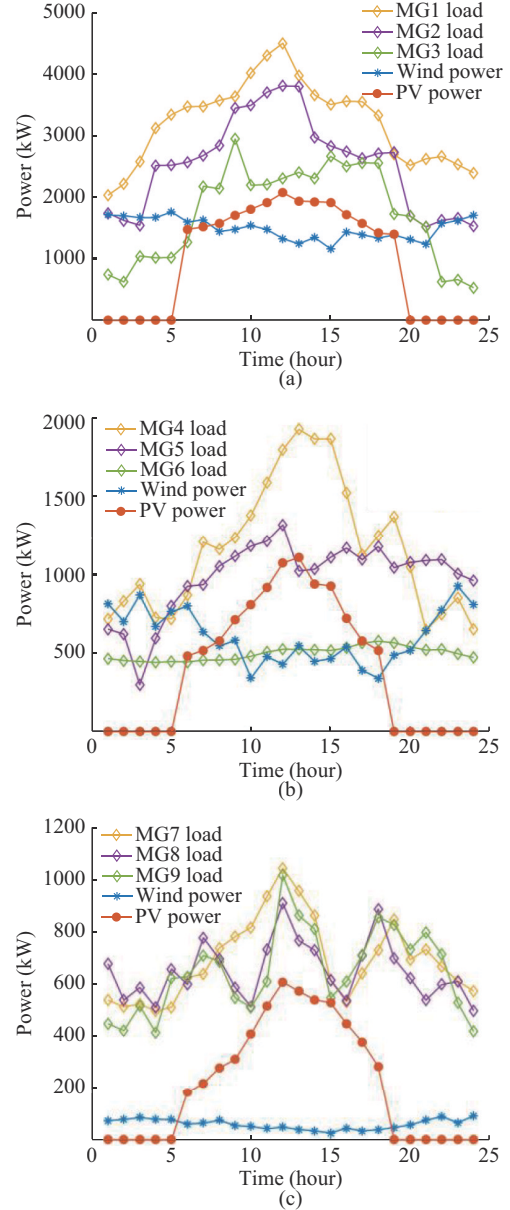


Fig. 7. Power forecasting curves of renewable energy and power load. (a) Industrial MGs. (b) Commercial MGs. (c) Residential MGs.

### B. Comparative Analysis

#### 1) Risk and Coordination Cost Analysis Among Three Sharing Modes

Figure 4 shows that the decision-making factor  $B_2$  is affected by three evaluation factors (e.g.,  $C_1$ ,  $C_2$ , and  $C_3$ ) in the criterion level. Specifically, the criterion  $C_1$  is composed



of four indexes ( $D_{11}$ ,  $D_{12}$ ,  $D_{13}$ , and  $D_{14}$ ). The criterion  $C_2$  is composed of two indexes ( $D_{21}$  and  $D_{22}$ ). The criterion  $C_3$  is composed of two indexes ( $D_{31}$  and  $D_{32}$ ). The above different subordination relations correspond to different pairwise comparison matrices. The pairwise comparison matrix corresponding to  $B_2$  is shown in Fig. 8, while three pairwise comparison matrices corresponding to  $C_1$ ,  $C_2$ , and  $C_3$  are expressed in Fig. 9(a), (b), and (c), respectively.

	$C_1$	$C_2$
$C_1$	(0.5, 0.5, 0.5)	(0.6, 0.7, 0.8)
$C_2$	(0.2, 0.3, 0.4)	(0.5, 0.5, 0.5)

Fig. 8. Matrix that shows relative importance of criteria corresponding to  $B_2$ .

	$D_{11}$	$D_{12}$	$D_{13}$	$D_{14}$
$D_{11}$	(0.5, 0.5, 0.5)	(0.5, 0.5, 0.6)	(0.6, 0.7, 0.7)	(0.6, 0.7, 0.7)
$D_{12}$	(0.4, 0.5, 0.5)	(0.5, 0.5, 0.5)	(0.5, 0.7, 0.7)	(0.6, 0.7, 0.7)
$D_{13}$	(0.3, 0.3, 0.4)	(0.3, 0.3, 0.5)	(0.5, 0.5, 0.5)	(0.4, 0.5, 0.5)
$D_{14}$	(0.3, 0.3, 0.4)	(0.3, 0.3, 0.4)	(0.5, 0.5, 0.6)	(0.5, 0.5, 0.5)

(a)

	$D_{21}$	$D_{22}$
$D_{21}$	(0.5, 0.5, 0.5)	(0.6, 0.7, 0.7)
$D_{22}$	(0.3, 0.3, 0.4)	(0.5, 0.5, 0.5)

(b)

	$D_{31}$	$D_{32}$
$D_{31}$	(0.5, 0.5, 0.5)	(0.5, 0.5, 0.5)
$D_{32}$	(0.5, 0.5, 0.5)	(0.5, 0.5, 0.5)

(c)

Fig. 9. Matrices that show relative importance of indexes corresponding to criteria. (a) Criterion  $C_1$ . (b) Criterion  $C_2$ . (c) Criterion  $C_3$ .

Triangular fuzzy numbers are measured by the fundamental scale of 0.1-0.9. The fundamental scale for the pairwise rating is shown in Table II. Note that if  $a_{pq}$  is the judgment value when  $p$  is compared with  $q$ , then  $a_{qp}=1/a_{pq}$  is the judgment value when  $q$  is compared with  $p$ .

Table III shows the evaluation results of privacy risk for sharing modes 1 and 2. The detailed information including installed device and load is shared among all MGs in mode 1 since the connected MGs in the system are treated as a large virtual MG managed by a coordinator. For mode 2, MGs make self-management and cooperate with each other by sharing the supply and demand information. But in mode 3, MGs are competitors rather than cooperators, which means their information is confidential to others. In this situation, the risk cost of MMG system is the highest in mode 1, while no risk exists in mode 3. Therefore, in terms of privacy protection, mode 3 shows advantages over the other

two modes.

TABLE II  
FUNDAMENTAL SCALE FOR PAIRWISE RATING

Scale	Meaning
0.1	Overwhelmingly less important
0.2	Very strongly less important
0.3	Strongly less important
0.4	Moderately less important
0.5	Equally important
0.6	Moderately more important
0.7	Strongly more important
0.8	Very strongly more important
0.9	Overwhelmingly more important

TABLE III  
EVALUATION RESULTS OF PRIVACY RISK FOR SHARING MODES 1 AND 2

Sharing mode	Criteria	Weight	Indicator	Indicator weight	Normalized weight	Score
Mode 1	Device information	0.69	Device type	0.311	0.215	270
			Device power	0.304	0.210	
			Device number	0.191	0.132	
			Device constraint	0.194	0.134	
	Load information	0.31	Load type	0.672	0.208	
			Load power	0.328	0.102	
Mode 2	Supply/demand information	1.00	Supply power	0.500	0.500	200
			Demand power	0.500	0.500	

The calculation results of coordination cost are listed in Table IV.

TABLE IV  
CALCULATION RESULTS OF COORDINATION COST

Sharing mode	Coordination coefficient	Coordination cost
Mode 1	$\delta_1 = 0.1$	173
Mode 2	$\delta_2 = 0.5$	1040
Mode 3	$\delta_3 = 0.9$	2700

For mode 1, the number of participants does not have an excessive impact on coordination cost. Meanwhile, the individual goal of a single MG is consistent with the overall goal of MMG system in the centralized management, which means MGs need not sacrifice personal interests for the overall benefits. As for mode 2, the coordinator performs energy matching and price setting after self-management of each MG in the hierarchical management. The pricing model based on supply and demand ratio aims to satisfy individual interest, which makes the coordination process relatively complex. Coordinator in mode 3 clears the market in terms of reservation price and quantity of each MG to achieve the maximum social welfare. MGs pursue their own economic benefit regardless of the interest of others in the distributed management, thus it poses a great challenge to the coordination. As analyzed above, mode 1 results in the lowest coordi-

nation cost among the three modes. So, in terms of coordination, mode 1 is superior to other two modes.

### 2) Economic Cost Analysis Among Three Sharing Modes

Figure 10 shows the power interaction of multiple MGs under different sharing modes. The output of flexible resource under different sharing modes is shown in Fig. 11. The calculation results of economic cost are shown in Table V. From Fig. 10(a) and (b), it is proven that the interactive power with the main grid reduces significantly in mode 1 compared with that in the independent operation mode. For mode 2, the internal transaction price is between the electricity price of the main grid and obtained after several iterations. It is able to incentivize MGs to participate in power sharing while guiding the regulation of flexible resources within MGs. As shown in Fig. 11(a) and (b), batteries have been charged or discharged more times in mode 2 than in mode 1. It may be because batteries tend to store some excess power for later use with the guidance of low price, and release power to make up for the shortage of power supply when the price is high. As a result, the overall interactive power of MMG system with the main grid in mode 2 is less than that in mode 1 (as shown in Fig. 10(b) and (c)). As shown in Fig. 10, the internal interactive power in mode 3 is the least among the three sharing modes.

According to the above analyses, the total economic cost is the highest in mode 3 while it is the least in mode 2. But all the three sharing modes are better than the independent operation mode in the perspective of economic benefits.

Table V shows that the total economic costs of MMG system in the three modes are reduced by 5%, 10.5%, and 3%, respectively, compared with those in the independent operation mode. Therefore, from the economics view, mode 2 is better than other two modes.

### 3) Weight Distribution and Comprehensive Evaluation for Three sharing modes

As shown in Fig. 4, three decision-making factors  $B_1$ ,  $B_2$ , and  $B_3$  are listed for the comprehensive evaluation. Their relative importance in three sharing modes are shown in Fig. 12(a), (b), and (c), respectively.

The expressions of the evaluation matrix  $X$  and the normalized matrix  $Y$  are shown in Fig. 13(a) and (b), respectively. The data in matrix  $X$  are obtained from simulation results about cost of economics, risk, and coordination in three sharing modes.

Table VI shows the subjective and objective weights of three decision-making factors. Figure 14 shows the combined weights of three decision-making factors and comprehensive evaluation values in three sharing modes.

In Table VI, the economics is set with the biggest subjective weight among three factors in any mode, which means the decision behavior is significantly affected. Besides, the risk accounts for the same proportion in modes 2 and 3. The results mentioned above are determined by the subjective experience of decision-makers. As for the objective weight, it is calculated based on objective data. Besides, the determination results of objective weight show that the risk is the most important among three factors.

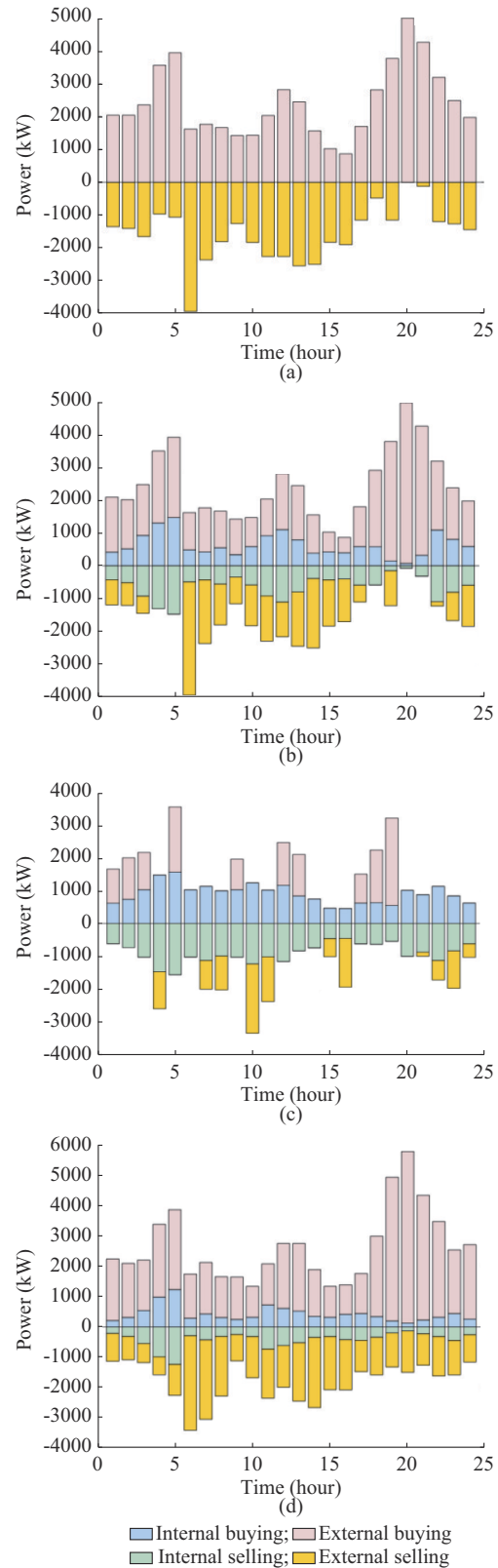


Fig. 10. Power interaction of multiple MGs in different sharing modes. (a) Independent operation mode. (b) Mode 1. (c) Mode 2. (d) Mode 3.

It can be observed from Fig. 14 that the comprehensive performance for three sharing modes is largely determined by the risk. Moreover, the economics accounts for a larger proportion than the coordination in any mode.

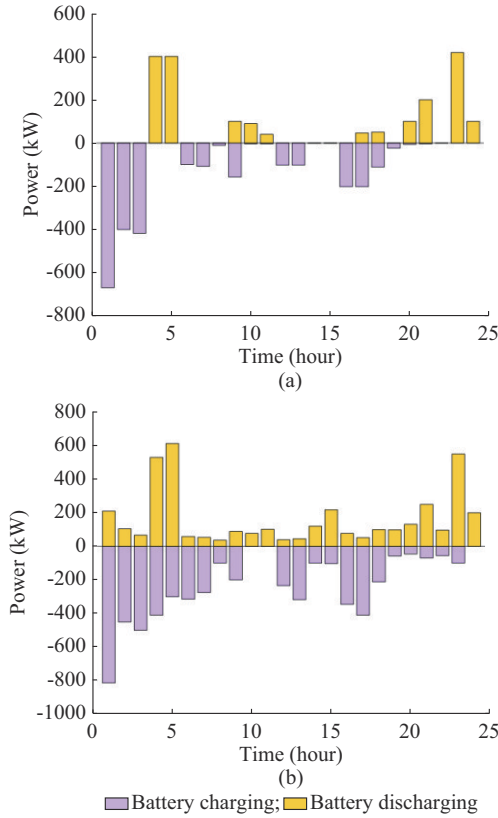


Fig. 11. Output of flexible resource under different sharing modes. (a) Total power of batteries in mode 1. (b) Total power of batteries in mode 2.

TABLE V  
CALCULATION RESULTS OF ECONOMIC COST

Operation mode	Cost (¥)
Independent operation	43900
Mode 1	41800
Mode 2	40200
Mode 3	42600

The evaluation values show that mode 2 achieves the best comprehensive performance among three sharing modes while mode 1 performs not as well as the other two modes.

### C. Decision Behavior Analysis

#### 1) Decision Behavior Analysis for Single MG

The analysis on the decision behavior of a single MG is carried out. Before the comprehensive evaluation for a single MG, a cost allocation method is introduced based on the interactive power contribution.

Considering that modes 1 and 2 express the cooperative game, the total economic cost of MMG system should be distributed in these two modes using (46). Other two costs such as costs of risk and coordination are supposed to be distributed in the three modes by (47) and (48). The definition of interactive power contribution is shown in (49).

$$C_{e,k,i} = C_{i,0} + \omega_i (C_{e,k} - C_0) \quad k=1,2 \quad (46)$$

$$C_{r,k,i} = \omega_i C_{r,k} \quad k=1,2,3 \quad (47)$$

$$C_{c,k,i} = \omega_i C_{c,k} \quad k=1,2,3 \quad (48)$$

	B <sub>1</sub>	B <sub>2</sub>	B <sub>3</sub>
B <sub>1</sub>	(0.5, 0.5, 0.5)	(0.5, 0.6, 0.6)	(0.6, 0.7, 0.7)
B <sub>2</sub>	(0.4, 0.4, 0.5)	(0.5, 0.5, 0.5)	(0.6, 0.7, 0.7)
B <sub>3</sub>	(0.3, 0.3, 0.4)	(0.3, 0.3, 0.4)	(0.5, 0.5, 0.5)

(a)

	B <sub>1</sub>	B <sub>2</sub>	B <sub>3</sub>
B <sub>1</sub>	(0.5, 0.5, 0.5)	(0.7, 0.8, 0.8)	(0.7, 0.7, 0.8)
B <sub>2</sub>	(0.2, 0.2, 0.3)	(0.5, 0.5, 0.5)	(0.3, 0.3, 0.4)
B <sub>3</sub>	(0.2, 0.3, 0.3)	(0.6, 0.7, 0.7)	(0.5, 0.5, 0.5)

(b)

	B <sub>1</sub>	B <sub>2</sub>	B <sub>3</sub>
B <sub>1</sub>	(0.5, 0.5, 0.5)	(0.7, 0.8, 0.8)	(0.6, 0.6, 0.7)
B <sub>2</sub>	(0.2, 0.2, 0.3)	(0.5, 0.5, 0.5)	(0.3, 0.3, 0.4)
B <sub>3</sub>	(0.3, 0.4, 0.4)	(0.6, 0.7, 0.7)	(0.5, 0.5, 0.5)

(c)

Fig. 12. Matrices that show relative importance of decision-making factors in different sharing modes. (a) Mode 1. (b) Mode 2. (c) Mode 3.

	Mode 1	Mode 2	Mode 3
B <sub>1</sub>	41800	40200	42600
B <sub>2</sub>	270	200	0
B <sub>3</sub>	173	1040	2700

(a)

	Mode 1	Mode 2	Mode 3
B <sub>1</sub>	0.333	1.000	0
B <sub>2</sub>	0	0.259	1
B <sub>3</sub>	1.000	0.657	0

(b)

Fig. 13. Matrices that show evaluation values of three decision-making factors in different sharing modes. (a) Evaluation matrix. (b) Normalized matrix.

TABLE VI  
SUBJECTIVE AND OBJECTIVE WEIGHTS OF THREE DECISION-MAKING FACTORS

Factor	Subjective weight			Objective weight
	Mode 1	Mode 2	Mode 3	
Economics	0.418	0.493	0.461	0.241
Risk	0.365	0.184	0.184	0.651
Coordination	0.216	0.323	0.355	0.107

$$\omega_i = \frac{\sum_{t \in T} P_{i,t}^{\text{ex}}}{\sum_{i \in N} \sum_{t \in T} P_{i,t}^{\text{ex}}} \quad (49)$$

where  $C_{e,k,i}$ ,  $C_{r,k,i}$ , and  $C_{c,k,i}$  are the economic cost, risk cost, and coordination cost of MG  $i$  in the  $k^{\text{th}}$  sharing mode, respectively;  $C_{i,0}$  is the economic cost of MG  $i$  in the independent operation mode;  $C_{e,k}$ ,  $C_{r,k}$ , and  $C_{c,k}$  are the total economic cost, total risk cost, and total coordination cost of MMG system in the  $k^{\text{th}}$  sharing mode, respectively; and  $C_0$  is the total economic cost of MMG system in the independent operation mode.

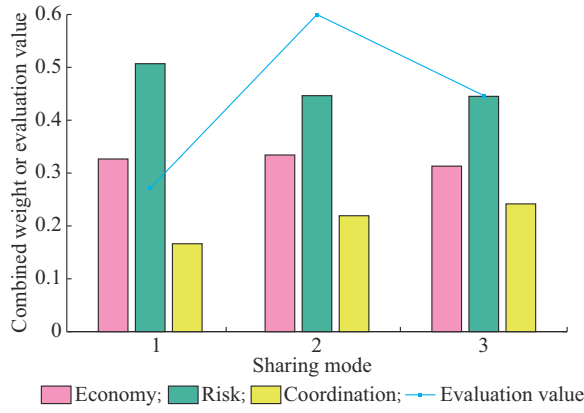


Fig. 14. Combined weights of three decision-making factors and comprehensive evaluation values in three sharing modes.

Based on the cost allocation method mentioned above, the allocated cost and comprehensive evaluation values of MG3, MG6, and MG7 are shown in Table VII, Table VIII, and Table IX, respectively.

TABLE VII  
ALLOCATED COST AND COMPREHENSIVE EVALUATION VALUE OF MG3

Sharing mode	Economic cost (¥)	Risk cost	Coordination cost	Evaluation value
Mode 1	-544	55	35	0.471
Mode 2	-638	28	147	0.745
Mode 3	-335	0	451	0.362

TABLE VIII  
ALLOCATED COST AND COMPREHENSIVE EVALUATION VALUE OF MG6

Sharing mode	Economic cost (¥)	Risk cost	Coordination cost	Evaluation value
Mode 1	-2430	35	22	0.559
Mode 2	-2640	26	136	0.804
Mode 3	-2170	0	19	0.162

TABLE IX  
ALLOCATED COST AND COMPREHENSIVE EVALUATION VALUE OF MG7

Sharing mode	Economic cost (¥)	Risk cost	Coordination cost	Evaluation value
Mode 1	5710	28	18	0.422
Mode 2	5550	20	105	0.617
Mode 3	5750	0	370	0.422

As shown in the above three tables, mode 2 still performs well for a single MG. This is owing to its better economics compared with other two modes and lower risk cost compared with mode 1.

## 2) Evolutionary Analysis of Decision Behavior of MMG System

The previous part has evaluated that mode 2 shows the best comprehensive performance for the MMG system as a whole. This part focuses on analyzing the evolutionary trend of decision behavior for the MMG system. When the number of MGs increases to a certain extent, the risk cost will

grow significantly due to the expansion of the scope of information dissemination. In the situation of large-scale power sharing, piecewise functions are defined to describe the risk cost using the following form.

$$C_{r,1} = \begin{cases} 479 & N \leq 20 \\ 479\sqrt{N} & N > 20 \end{cases} \quad (50)$$

$$C_{r,2} = \begin{cases} 200 & N \leq 20 \\ 200\sqrt[3]{N} & N > 20 \end{cases} \quad (51)$$

where  $C_{r,1}$  and  $C_{r,2}$  are the risk costs of sharing modes 1 and 2, respectively. In this paper, the turning point of the risk cost function is artificially set to be 20. Besides, the increasing number of MG will lead to the gradual increase of coordination cost. The evolutionary trends of the risk cost and coordination cost in the three sharing modes are shown in Figs. 15 and 16, respectively.

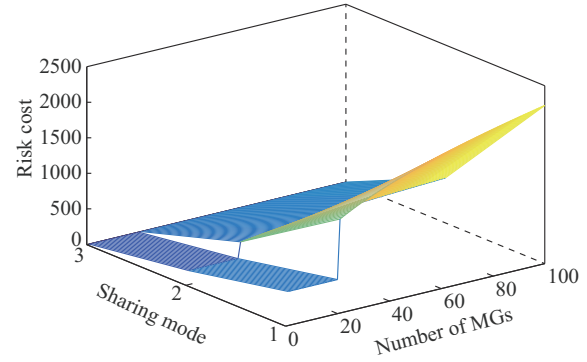


Fig. 15. Evolutionary trends of risk cost in three sharing modes.

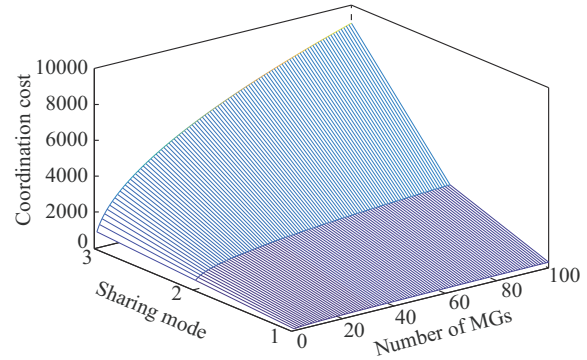


Fig. 16. Evolutionary trends of coordination cost in three sharing modes.

It can be observed from Fig. 15 that when the number of members in MMG system is more than 20, the risk cost in mode 1 is much greater than that in mode 2 since the sharing scale (number of participants) expands. Figure 16 shows that the coordination costs in modes 1 and 2 are much smaller than that in mode 3 in large-scale power sharing activity. Thus, the negative effect of the risk cost on the comprehensive evaluation value of mode 1 increases. It is also similar for the negative effect of the coordination cost on the comprehensive evaluation value of mode 3. As a result, the MMG system operator would tend to choose mode 2 for power sharing with the expansion of sharing scale.



## V. CONCLUSION

This paper focuses on several typical game-theory-based sharing modes of MMG system. Specifically, a method is developed to decide on the best sharing mode for general applications considering multiple influencing factors such as economics, risk, and coordination. The main conclusions are as follows.

1) According to the evaluation methods proposed in this paper, the risk cost of sharing mode based on the cooperative game with complete information is evaluated to be the highest, while the coordination cost of sharing mode based on the noncooperative game is calculated to be the highest. Besides, optimization results show that the economic cost in the mode of cooperative game with incomplete information is the minimal.

2) For the MMG system as a whole, the sharing mode based on cooperative game with incomplete information is proven to achieve the best comprehensive performance from evaluation results. For a single MG, its optimal choice for sharing mode is always consistent with that of the whole system.

3) With the expansion of sharing scale, the sharing mode based on cooperative game with incomplete information exhibits remarkable advantages over the other two modes.

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