

Article

# Research on a Microgrid Subsidy Strategy Based on Operational Efficiency of the Industry Chain

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**Abstract:** Government subsidy is a powerful tool to motivate the development of a new energy industry. At the early stage of microgrid development, for the sake of the cost and benefit issue, it is necessary for the government to subsidize so as to support and promote the development of microgrids. However, a big challenge in practice is how to optimize the operational efficiency of the microgrid industry chain with varying targets and methods of subsidy. In order to explore this problem, we construct a subsidy model based on the microgrid industry chain, involving government, investor, operator, equipment supplier, and user. Through calculation and solution of this model, we obtain price and return indicators of each microgrid industry chain participant when the subsidy target differs. Based on that, we contrast and compare the optimal subsidy strategy and influencing factors when operational efficiency indicators vary. Finally, we validate and analyze this model with numerical analysis and discuss the impact of development stage, technological level, and change in subsidy amount on the operational efficiency of the microgrid industry chain and on the returns of each participant. This result is of great significance to subsidy practice for microgrids and the development of microgrids.

**Keywords:** microgrid; industry chain; operational efficiency; subsidy strategy

## 1. Introduction

Optimizing energy structures and pursuing clean and low-carbon development are essential requirements for promoting energy revolution and social sustainable development, and are also urgently needed for economic and social transformation and development. Under the dual pressure of energy demand and environmental protection, governments are paying more and more attention to the development of clean energy fields [1–4]. As an important utilization forms of renewable energy and clean energy, microgrids have attracted wide attention. Although the development of microgrids plays an important role for the utilization of renewable energy, reducing carbon emissions of a power system, reformation of the power market, and the adjustment of the energy structure, the microgrid develops relatively slowly at the early stages due to technology immaturity and cost [5–7]. Financial subsidy is a powerful tool to promote the development of industries with low economic income, high environmental protection, and high external income. Therefore, government subsidies are critical and important to facilitating the development of microgrid projects at the early stages. However, a big challenge in practice is how to optimize the operational efficiency of the microgrid industry chain with varying targets and methods of subsidy. Therefore, the subsidy problem of microgrids has become an important topic in academic and practical circles.

One stream of research has focused on the technological field of microgrids, such as the power system [8], energy storage technology [9], control and protection technology [10,11], energy exchange

between the microgrid and a large grid [12], microgrid system scheduling [13,14], microgrid system optimization [15], and other key technologies. Another stream has studied the microgrid from the perspective of economy and management, including the costs and benefits of investment [16], the market operation mechanism [17], and cooperation between stakeholders of microgrids [18,19]. However, research on subsidies for microgrids is relatively scarce. At the early stage of the microgrid industry development, all issues of the microgrid industry are undergoing constant change and development, such as microgrid technology, type, performance, and user market. The uncertainty of these factors in the initial market of microgrids leads to high development costs and the high risk of microgrids as well as the high uncertainty of profits. High cost and high risk lead to insufficient investment demand for microgrids; this leads to the problem of quality instability and high prices at the early stages of the microgrids, which finally leads to insufficient consumption demand for the microgrids.

At the early stage of microgrid development, the industry is suffering from low maturity and insufficient investment and consumption demand [4,20]. High cost and high risk at the early stages of microgrid development require the government to provide an appropriate financial subsidy for the development and consumption of microgrids [21]. At the same time, compared with traditional coal-based power production, the production of microgrids can reduce the carbon emissions of the power system and correspond with external economy. Since the external economy has typical characteristics of public goods and externality, the microgrid cannot get corresponding benefits from these altruistic behaviors; the economic and environmental performance of the microgrid has not been fully demonstrated, thus leading to insufficient supply and investment demand. Attributes of the external economy and public goods of the microgrid require the government to develop subsidies and corresponding strategies to internalize the environmental value of the microgrid into microgrid project returns so as to improve the returns of the microgrid, and increase investment demand and consumption demand of microgrids.

The efficiency and quality of the subsidies in the microgrid industry chain directly affect the price and return of microgrids, which are very important for its development [22]. As an important economic means of the state, subsidy is critical to support or guide the development of industry at the early stages [23]. However, at the early stages of microgrid development, the market mechanism and corresponding policy mechanism are not perfect, and subsidy mechanisms for microgrids is still relatively scarce [19]. The subsidy mechanism for microgrids now is mainly borrowed from that for the large power grid. For example, the subsidy mechanism and price mechanism of microgrids are mainly borrowed from the system for renewable energy generation in the large power grid. Due to the difference in the technology system and market features between the large power grid and microgrids, the current mechanism cannot be effectively applied to microgrids, which is not beneficial to microgrid development and resource allocation. The socio-technical systems approach argues that the organization's technical system should determine the management of the organization. The microgrid technology system is different from the large power grid, which leads to a different industry chain for the microgrid, so the development of microgrids requires different subsidy mechanisms. At the same time, stakeholder theory holds that the organization involves many stakeholders, so the organizational system needs to balance the interests of all stakeholders [17]. In the microgrid industry chain, the technical system and marketization characteristics of the microgrid industry make it involve many participants. Different participants have different interests. If the subsidy mechanism does not balance the interests of all participants, it will seriously affect the operational efficiency and quality of the microgrid industry chain. Therefore, a corresponding subsidy mechanism is required to motivate the participation of all participants and balance the interests of all participants. However, the characteristics of microgrids such as monopoly and externality result in low efficiency of resource optimization and market failure in the microgrid market. Therefore, the microgrid market cannot automatically generate an effective subsidy mechanism to realize the Pareto Optimality. The lack of a subsidy mechanism largely affects all participants' investment demand and consumption

demand for microgrids. Therefore, in our article, it is necessary to study the subsidy of microgrids so as to design a corresponding subsidy mechanism to promote the sustainable development of the microgrid industry.

Game theory is an appropriate research method for studying the subsidy of microgrids [24]. The market characteristics of microgrids have determined that the construction of microgrids requires the participation of multiple partners. Especially at the early stages of microgrid construction, the government plays a very important role in coping with the problem of insufficient revenue generated by the property of public goods in microgrids [5]. In the government's incentive policy, subsidy is regarded as an effective way to promote the development of industry [25]. Subsidy will affect the decision of the participants involved in the construction of microgrids. In the cooperative development of microgrids, each participant has their own interest claims. Under the premise of rational decision-making, they all expect to maximize their own interests. Therefore, how to achieve cooperative balance and optimal efficiency is the key issue of the cooperative development of microgrids. Game theory is a theory to study decision-making and the decision-making equilibrium between two or more decision-makers. Since there are cooperation and competition between the entities in the market, game theory is widely used in the field of economy and management. For example, game theory is used to study issues of service pricing decisions [26], supply chain management [27,28], intelligent transportation [29], and network risk control [30]. Different from the simple two-player game, a multiplayer game coincides with the cooperation practice in different fields, and its research conclusion is more useful for practice. For instance, Taleizadeh et al. [31] considered the reference price effect in a three-level supply chain under five different channel power structures, such as vertical Nash, manufacturer Stackelberg, and retailer Stackelberg, and proposed a joint optimization model of pricing strategies, quality levels, effort decisions, and return policies. Argoneto et al. [32] constructed the Gale–Shapley model, and analyzed the cooperative game problem of sharing common infrastructure resources between manufacturing companies. They designed the allocation rules to minimize the unallocated capacity when all information was identifiable, and put forward a Gale–Shapley model which could guide all companies to report their real private information, regardless of the reporting decisions of other companies. In addition, game theory is used to study energy issues. For example, Karavas et al. [33] designed a multi-agent decentralized energy management system. Studies showed that applications based on game theory control could ensure better operation and economic benefits than known distributed intelligent energy management methods. Therefore, this paper uses game theory to construct a subsidy model for the cooperative development of microgrids involving five participants. Based on the analysis of subsidy strategies for different subsidy objects, the subsidy strategy that optimizes the operational efficiency of the microgrid industrial chain is explored.

The goal of this article is to construct a subsidy model to enhance the operational efficiency of the microgrid industry chain. Our contribution lies in taking stakeholders of the microgrid industry chain into consideration at each stage. We construct a multiplayer game model involving government, investor, operator, equipment supplier, and user, and create subsidy models under which the government subsidizes different participants in the microgrid industrial chain. In particular, when the user is being subsidized, we design model C. When the investor is being subsidized, we design model I. When the operator is being subsidized, we design model O. When the equipment supplier is being subsidized, we design model E. We find pricing and returns through solving models of different subsidy objects. Then, we analyze differences between subsidies and the corresponding influencing factors under different operational efficiencies. Finally, we further verify by numerical analysis the price and returns of microgrids when the subsidy object varies, and analyze the influence of the technological level and subsidy amount on the microgrid subsidy. The analysis results of this model have important implications for the formulation of microgrid subsidy strategies and for guiding and regulation of the development of the microgrid industrial chain.

The rest of the article is organized as follows: In Section 2, we introduce the literature review. In Section 3, we introduce the assumptions, build the models, and analyze the subsidy strategy for

different subsidy objects. In Section 4, we discuss how to optimize the operational efficiency of the microgrid industry chain with varying targets of subsidy. In Section 5, we perform a numerical analysis to further analyze subsidy strategy. In Section 6, we draw the conclusions.

## 2. Literature Review

Scholars have done a lot of research on the subsidy of microgrids. At the initial stage of study of microgrids, scholars analyzed the environmental and social value of microgrid projects as well as the economy of microgrid development at its early stage, and suggested that government subsidy and relevant policies should be required to encourage the development of microgrids. For instance, Blasques et al. [34] designed a prepaid metering system for Brazil's hybrid renewable energy microgrid for user demand-side management. Study has shown that the government must subsidize renewable energy systems to maintain the operation of hybrid renewable energy microgrids. Valer et al. [35] found that SMGs (Solar Microgrids) could meet the needs of consumers in remote areas in Brazil, but because of the high cost of photovoltaic power generation, many rural consumers could not afford it. At the same time, the effect of market-based solutions was limited. The continuous power supply of SMGs and an affordable price for consumers has become a huge challenge for electricity demand in remote areas. Study has also shown that the government must have clear, workable rules to ensure the provision of electricity services when the company is less profitable or unprofitable. Pereira et al. [36] used the Monte Carlo method to assess the risk of investment in renewable energy projects in the Brazilian Amazon. Research found that in the Amazon, energy demand was growing, but operation costs remained high. In order to reduce the risk of investment in renewable energy projects in Brazil, subsidies or incentives must be provided. By evaluating the social and economic characteristics, availability of renewable energy, and energy demand, Ramchandran et al. [37] found that cost saving was the main driving force for consumers to turn to clean energy. After comparing three models of a solar photovoltaic system, a biomass gasification system, and a solar biomass hybrid system, we found that the model with a subsidized solar photovoltaic system was the most reliable.

Along with the development of the study of microgrids, considering the value of microgrids in renewable energy utilization and in the reduction of pollution and carbon emissions, scholars began to consider the environmental and social benefits of microgrids as part of its economic performance, which enabled them to evaluate the resource value of environmental protection brought about by microgrids. Thus, the issue of microgrid subsidy could be further explored. For example, by cost-benefit analysis (CBA), Han et al. [38] constructed a new-generation planning model for microgrids with a goal of low carbon economy and maximum net profit over the life cycle, and incorporated government subsidies for photovoltaic power generation and the low carbon benefit of the microgrid into it. Liang et al. [39] studied the generation conditions and load characteristic of biomass power generation and photovoltaic power generation in rural areas of Guangxi, China. According to different climate characteristics of summer and winter, on the basis of subsidy for the renewable energy price, Liang et al. built a biomass power generation dynamic economic dispatch model with on-grid and off-grid modes aiming at the lowest cost for power generation. Chen et al. [22] investigated a government incentives plan provided to private investors to motivate support for the development of renewable energy microgrids. Chen built a principal-agent model between the government and private investors, revealed the conflict of interest between policy-maker and private investor, and investigated the impact of these parameters on the government's target in the case of information asymmetry, analyzed the optimal subsidy, and maximized the expected policy benefit for the government.

At present, with the development of microgrids, the cost-benefit issue and externality issue of microgrid development at early stages are becoming more and more outstanding. A corresponding subsidy mechanism is needed to promote the development of microgrids. For this purpose, scholars have designed appropriate microgrid subsidy mechanisms to promote the development of microgrids. For example, Srinivasan et al. [25] found that India federal Ministry of New and

Renewable Energy provides an interest subsidy for solar thermal systems through mainstream banking channels, which is superior to the capital subsidy for solar photovoltaic systems in the intention and the result. Couture et al. [40] pointed out that in terms of accelerating the development of renewable energy, the most widely used policy in the world is electricity price subsidy (Feed-in Tariffs, FITs). This policy accounts for a greater proportion than the tax preference or renewable portfolio standard policy (REN21 2009). In Germany, FITs are an effective policy tool to promote the development of renewable energy and contribute to achieving energy security and emission reduction targets (Germany BMU 2007). Tamás et al. [41] analyzed the effect of FITs based on UK data. Their study found that FITs will make renewable energy producers ignore the high cost of renewable energy, and provide no incentive to develop efficient renewable energy technologies and reduce costs. Although the electricity price subsidy has its own advantages, it will also bring difficulties in controlling the overall policy cost and the distortion of the wholesale price in the electricity market [25]. Taha et al. [42], based on the physical properties of microgrids, demand, and energy price fluctuation, proposed Quasi-Feed-in Tariffs (QFITs) from a technical point of view. Through QFIT policy, time-varying price subsidy that relies on grid and demand conditions can be realized for microgrids, which will increase the social welfare of microgrids. Palit et al. [43] found that the challenges to enhancing electricity access in South Asia are manifold, including technical, financial, institutional, and governance barriers. They also observe that all rural electrification (RE) programs in the region have a substantial subsidy component either to improve the infrastructure or through cross subsidization of tariffs for poor consumers.

To sum up, it can be seen that the trend of current research is to study the subsidy strategy of microgrids in order to design a corresponding microgrid subsidy mechanism to promote the development of microgrids and the utilization of renewable energy. Existing research on subsidies for microgrids mainly considers subsidy as a unilateral factor, or takes subsidy as part of the model. However, there is a shortage of research studying this issue from the perspective of the industrial chain of microgrid project development. However, the interests and prices of various stakeholders in the microgrid industrial chain have an important influence on investment in and consumption of microgrids. Subsidy for different objects in the microgrid industry chain will have a significant influence on operational efficiency of the microgrid industry chain. Although research on individual subsidies is helpful to understanding the resource value of microgrid projects and promoting the development of microgrid projects, if the subsidy policy of microgrids cannot reflect the interests of all participants in the microgrid development industry chain, it will seriously affect the development of the microgrid industry. Therefore, we construct a multiplayer game subsidy model of microgrids to study the subsidy strategy of microgrids, with consideration of the interests of all stakeholders and the operational efficiency of the industrial chain of the microgrid.

### 3. Subsidy Strategy for Different Subsidy Objects

#### 3.1. Problem Description

Against the background of energy structure adjustment and power system reform, the government subsidizes  $\delta l$  for participants in the development of microgrid projects so as to reduce the development cost of microgrids, improve the project returns of microgrids, and stimulate the investment and consumption demand of microgrid project development.

The microgrid industry chain mainly involves four stages—production, transmission, distribution, and consumption—and includes five participants—government, investor, operator, equipment supplier, and user. Through these four stages and five participants, the microgrid completes power generation and the consumption of clean and renewable energy sources. Therefore, these four stages and five participants constitute an important part of the microgrid industry chain. At the production stage of the microgrid industry chain, the investor, such as a grid company or new energy company, invests in microgrid construction, supplies project quality  $q$  of the microgrid, and sells electricity to the user for price  $p_2$  directly or sells electricity to the operator for price  $p_1$ . The equipment



supplier, based on their own technology  $t$ , provides equipment to the investor for price  $p_e$  and quality  $q$  to participate in development of microgrid projects. At the transmission and distribution stages, the operator—such as an electricity sale company, grid company, or investor-owned operating company—purchases electricity from the investor for price  $p_1$ , and sells electricity to the user for price  $p_o$ , competing with the investor electricity supply directly in the electricity sale market. At the consumption stage, the user, as the consumer of microgrid power, chooses whether to use microgrid power, the power mode, and microgrid company according to the quality  $q$ , and prices  $p_o$  and  $p_2$  of the microgrid project.

In the microgrid industry chain, what are the price and profits of each participant when the government subsidizes different objects? What are the factors affecting the microgrid subsidy strategy when the government subsidizes different objects? What is the optimal subsidy strategy with different operating efficiency indicators and under different situations in the microgrid industry chain? To answer those questions, we construct the following game model.

### 3.2. Model Assumption and Construction

In this paper, we construct a microgrid project development model based on a hybrid sales channel to study the impact of the choice of different subsidy objects on the pricing and returns of each participant in the microgrid industry chain, and which subsidy object can optimize the operational efficiency of the microgrid industrial chain, as shown in Figure 1. To make the research more scientific and targeted, we base microgrid subsidies on practice, starting from the key participants of microgrid subsidies to establish hypotheses, such as the sales method, subsidy method, participant characteristics, return characteristics, demand characteristics, and market characteristics of the microgrid. The specific hypotheses are as follows.

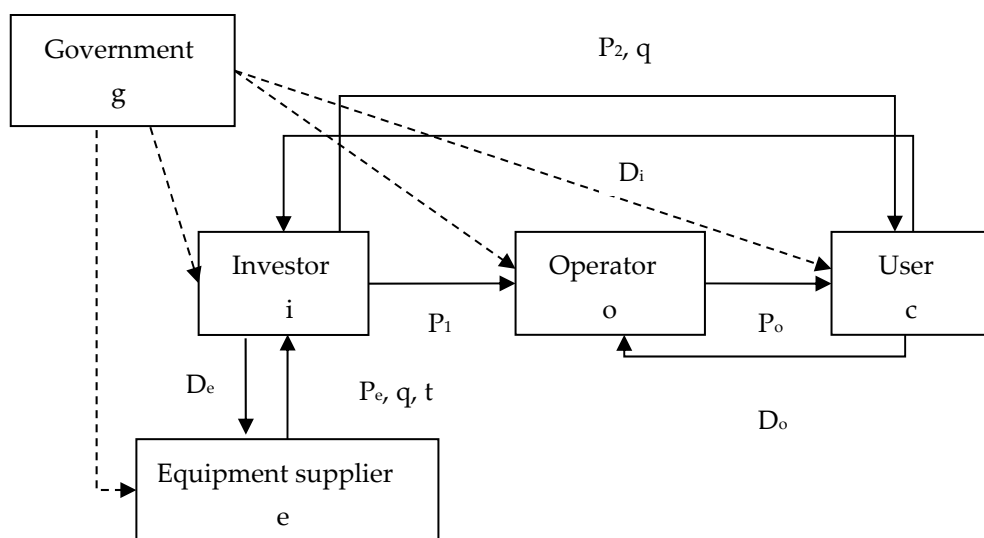


Figure 1. Subsidy model of the microgrid industrial chain.

**Hypothesis 1.** The microgrid sells electricity to users in two ways: one way is that the investor sells electricity to users directly; the other is that the investor sells electricity to an operator, who then sells electricity to users.

At the same time, according to the demand formula of hybrid sale channels and microgrid practice, we can set the demand functions of users for hybrid sales channels as follows.

User’s quantity demand for operator (refers to indirect quantity demand for investor):

$$D_o = r_0 - r_1 p_o - r_2 (p_o - p_2) = r_0 - (r_1 + r_2) p_o + r_2 p_2. \tag{1}$$

User's direct quantity demand for investor:

$$D_i = \begin{cases} r_2(p_o - p_2) + \theta q, & p_o - p_2 > 0 \\ 0, & p_o - p_2 \leq 0 \end{cases} \quad (2)$$

where  $r_0$  is the total market demand,  $r_1$  is the price elasticity of the user to electricity sold by the operator, and  $r_2$  is the elasticity coefficient of the user to price differences between the operator and investor, indicating the degree of competition in the two ways. It can be seen that when  $r_2$  gets larger, the difference between the two electricity selling ways increases and the competition accelerates. At the same time, the electricity demand of the user for the investor is also affected by the quality of the microgrid provided by investor, and  $\theta$  is the quality coefficient.

This is reasonable. A microgrid includes four aspects: generation, transmission, distribution, and sale of electricity. The microgrid can sell electricity to the operator under the background of electric power system reform. The operator is an entity such as an investor-owned operating company, electricity sale company, grid company, or other third-party operating company. The electricity price offered by an investor-owned operating company is different from that by the investor due to the existence of operating costs.

**Hypothesis 2.** *The subsidy coefficient of the government for the microgrid is  $\delta$ . The value of  $\delta$  is determined by factors such as social benefits and environmental protection values brought by the microgrid.  $l$  is the maximum amount of the unit microgrid subsidy. Therefore, the unit subsidy for the development of the microgrid is  $\delta l$ . Due to the differences in the effect of government subsidy on different objects, we assume that  $\varepsilon_i$ ,  $\varepsilon_e$ ,  $\varepsilon_o$ ,  $\varepsilon_c$  are the influence coefficients of subsidy on the microgrid investor cost, equipment supplier cost, operator cost, and user demand, respectively.*

This is reasonable. Microgrid subsidy funds come from renewable energy development funds. In practice, the amount of the microgrid subsidy is mainly decided by the social benefits such as the increase in renewable energy utilization, improvement of energy utilization efficiency, and environmental benefit. At the same time, when the government subsidizes different objects, the costs and benefits of different objects differ. Therefore, the influence coefficient of the subsidy on different objects is different.

**Hypothesis 3.** *Government and investors are the leaders in the development of microgrid projects; equipment suppliers, operators, and users are followers. Unlike the government, who leverage financial expenditure and policy to guide investment and development and to benefit the distribution of microgrids, this paper mainly studies financial subsidy strategy. The investor influences the electricity sale price of the operator and the electricity purchase price of the user through their electricity sale price. The equipment supplier influences the demand of the user, their own profit, and the profit of the investor through their own technology as well as the quality and price of equipment. All stakeholders make decisions based on maximizing their own interests.*

This is in line with reality. In the actual development process of microgrid projects, the roles and relationships of all participants are exactly as Hypothesis 3 describes, and all participants make decisions to maximize their own interests.

**Hypothesis 4.** *All stakeholders are rational economic people, and their risk preferences are neutral. They make decisions based on maximizing their own interests. The return for the investor mainly consists of three parts: the electricity sales to the user directly, the electricity sales to the user indirectly, and the profits shared by the equipment supplier. Therefore, the return function for the investor is a linear function of price, cost, and demand, expressed as*

$$\pi_i = (p_1 - c_i)D_o + (p_2 - c_i)D_i - p_e D_e. \quad (3)$$

The return for the operator mainly includes three parts: the electricity sales to the user directly, the cost payment to the investor, and their own operating cost. Therefore, we set the return function for the operator as a linear function of electricity sale price, price paid to investor, operating cost, and user demand, expressed as

$$\pi_o = (p_o - p_1 - c_o)D_o. \quad (4)$$

The return for the equipment supplier mainly includes two parts: the benefits from providing equipment and their own cost. Therefore, the return function for the equipment supplier is a linear function of price, cost, and demand, expressed as

$$\pi_e = (p_e - c_e)D_e. \quad (5)$$

This is reasonable. The return for the investor, operator, and equipment supplier are equal to their total revenue minus total cost. At the same time, based on the principle of balance between supply and demand, it is reasonable that we use quantity demanded to represent the sales volume for each participant. The return functions for all participants are obtained by differentiating the specific costs and benefits of each participant.

**Hypothesis 5.** *The investor's demand function for the equipment supplier is a function of the equipment supplier's price and quality, expressed as*

$$D_e = h_0 - h_1p_e + h_2q. \quad (6)$$

Among them, the quality attribute of the equipment supplier is a function of its technological level  $t$ ; the expression for this is set as  $q = \rho t$ , where  $\rho$  is a technological coefficient,  $\rho > 0$ . At the same time, the technological cost of the equipment supplier satisfies the relational expression  $c_e = 1/2kt^2$ , where  $k$  is the elasticity coefficient of the technological cost.

This is reasonable. When the equipment demand of the investor for the equipment supplier is not affected by equipment quality, it is determined only by price changes. When the equipment demand of the investor for the equipment supplier is affected by equipment quality, it is determined by the combined effect of price and quality. The equipment quality of the equipment supplier is affected by the technological level of the equipment supplier. The cost of the equipment supplier also increases exponentially with the increase of the technological level.

**Hypothesis 6.** *Assuming that the microgrid project development system is a sufficiently competitive system, government subsidy can be transferred freely among all stakeholders. With changes in environment and other factors, government subsidy has also changed accordingly.*

This is reasonable. In practice, the participation of all participants in the development of the microgrid is sufficient competition, for all participants target the maximization of their own interests. With the change of the specific situation, the government can adjust the subsidy object and the method of subsidy flexibly.

### 3.3. Solution of the Model

We design different government subsidy models based on different participants in each phase of the microgrid industrial chain to specifically study the operation of microgrid industrial chains. In particular, model C describes the government subsidizing the user. Model I describes the government subsidizing the investor. Model O describes the government subsidizing the operator. Model E describes the government subsidizing the equipment supplier. The solution of each model is as follows.



### 3.3.1. The Subsidy Object Is the User (Model C)

The user is the consumer of the microgrid. The ultimate goal of the microgrid is to satisfy the user's demand and improve the user's energy use. Only when a user adopts microgrid use can the environmental and social values of the microgrid be reflected. Due to the uncertainty of construction quality and power quality at the early stage of development of microgrids, the user is less willing to spend on microgrids. At the same time, compared with the low price of the traditional power grid, the price of the microgrid is high, which leads to insufficient consumption demand for microgrids. To stimulate consumption demand for microgrids, the government often subsidizes users directly. For example, in Yunyang county residential solar projects, the government subsidizes residents directly by installing solar power generation equipment to guide users' consumption. We establish model C to explore the situation of the government subsidizing users. For research convenience, we assume that the impact of the government subsidy on user demand is linear, and the demand function becomes

$$D_o = r_0 - r_1 p_o - r_2 (p_o - p_2) + \varepsilon_c \delta l = r_0 - (r_1 + r_2) p_o + r_2 p_2 + \varepsilon_c \delta l \quad (7)$$

$$D_i = \begin{cases} r_2 (p_o - p_2) + \theta q + \varepsilon_c \delta l, & p_o - p_2 > 0 \\ 0, & p_o - p_2 \leq 0. \end{cases} \quad (8)$$

We solve the equilibrium of the operator starting from the distribution stage by the inverse induction method. The operator makes a decision based on the price  $p_o$ . Therefore, the response function of the operator is

$$\frac{\partial \pi_o}{\partial p_o} = c_o = r_0 - 2(r_1 + r_2) p_o + (r_1 + r_2) p_1 + r_2 p_2 + \varepsilon_c \delta l + (r_1 + r_2) c_o. \quad (9)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_o}{\partial p_o} = 0$ , and we get

$$p_o = \frac{1}{2} p_1 + \frac{r_2}{2(r_1 + r_2)} p_2 + \frac{r_0 + \varepsilon_c \delta l + (r_1 + r_2) c_o}{2(r_1 + r_2)}. \quad (10)$$

The investor makes active decisions based on prices  $p_1$  and  $p_2$ . By substituting  $p_o$  in  $\pi_i$ , and taking the partial derivative of  $\pi_i$  with respect to  $p_1$  and  $p_2$ , we get the response function of the investor:

$$\frac{\partial \pi_i}{\partial p_1} = \frac{1}{2} r_0 - (r_1 + r_2) p_1 + \frac{1}{2} \varepsilon_c \delta l - \frac{1}{2} (r_1 + r_2) c_o + \frac{1}{2} r_1 c_i + r_2 p_2 \quad (11)$$

$$\frac{\partial \pi_i}{\partial p_2} = \frac{r_1 r_2}{2(r_1 + r_2)} c_i - \frac{2r_1 r_2 + r_2^2}{r_1 + r_2} p_2 + \frac{r_0 r_2 + r_2 \varepsilon_c \delta l + r_2 (r_1 + r_2) c_o}{2(r_1 + r_2)} + \theta q + \varepsilon_c \delta l + r_2 p_1. \quad (12)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_i}{\partial p_1} = 0, \frac{\partial \pi_i}{\partial p_2} = 0$ , and we get

$$p_1 = \frac{r_0}{2(r_1 + r_2)} + \frac{1}{2(r_1 + r_2)} \varepsilon_c \delta l - \frac{1}{2} c_o + \frac{r_1}{2(r_1 + r_2)} c_i + \frac{r_2}{r_1 + r_2} p_2 \quad (13)$$

$$p_2 = \frac{r_1}{2(2r_1 + r_2)} c_i + \frac{r_0 + (r_1 + r_2) c_o}{2(2r_1 + r_2)} + \frac{r_1 + r_2}{r_2(2r_1 + r_2)} \theta q - \frac{2r_1 + 3r_2}{2r_2(2r_1 + r_2)} \varepsilon_c \delta l + \frac{r_1 + r_2}{2r_1 + r_2} p_1. \quad (14)$$

Calculating simultaneous equations for  $p_1$  and  $p_2$ , we have

$$p_1 = \frac{r_0}{2r_1} - \frac{r_2}{2r_1(r_1 + r_2)} \varepsilon_c \delta l + \frac{1}{2} c_i - \frac{1}{2} c_o + \frac{1}{2r_1} \theta q \quad (15)$$

$$p_2 = \frac{r_0}{2r_1} + \frac{1}{2} c_i - \frac{r_1 + r_2}{2r_1 r_2} \varepsilon_c \delta l + \frac{r_1 + r_2}{2r_1 r_2} \theta q. \quad (16)$$

The equipment supplier makes active decisions with  $p_e$ . Therefore, the response function of the equipment supplier is

$$\frac{\partial \pi_e}{\partial p_e} = h_0 - 2h_1 p_e + h_2 q + h_1 c_e. \quad (17)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_e}{\partial p_e} = 0$ , and we have

$$p_e = \frac{h_0}{2h_1} + \frac{h_2}{2h_1} q + \frac{1}{2} c_e. \quad (18)$$

By substituting  $p_1$  and  $p_2$  in equation  $p_o$ , we get  $p_o$ . Thus, in equilibrium, the prices for which the government subsidizes the user are

$$p_1 = \frac{r_0}{2r_1} - \frac{r_2}{2r_1(r_1+r_2)} \varepsilon_c \delta l + \frac{1}{2} c_i - \frac{1}{2} c_o + \frac{1}{2r_1} \theta q \quad (19)$$

$$p_2 = \frac{r_0}{2r_1} + \frac{1}{2} c_i - \frac{r_1+r_2}{2r_1 r_2} \varepsilon_c \delta l + \frac{r_1+r_2}{2r_1 r_2} \theta q \quad (20)$$

$$p_e = \frac{h_0}{2h_1} + \frac{h_2}{2h_1} q + \frac{1}{2} c_e \quad (21)$$

$$p_o = \frac{r_0(3r_1+2r_2)}{4r_1(r_1+r_2)} + \frac{1}{2r_1} \theta q + \frac{r_1+2r_2}{4(r_1+r_2)} c_i + \frac{-2r_2+r_1}{4r_1(r_1+r_2)} \varepsilon_c \delta l + \frac{1}{4} c_o. \quad (22)$$

The obtained prices  $p_1$ ,  $p_2$ ,  $p_e$ , and  $p_o$  are the optimal prices of the model wherein the government subsidizes the user, and this price combination is the optimal set of decisions in Model C. In Model C, it is in the best interests of the investor, equipment supplier, and operator to adopt this set of decisions. By substituting  $p_1$ ,  $p_2$ ,  $p_e$ , and  $p_o$  into the returns function and demand function of each participant, the equilibrium returns of investor, operator, and equipment supplier under the optimal decision can be calculated.

Return of the investor:

$$\begin{aligned} \pi_i = & \left( \frac{r_0}{2r_1} - \frac{r_2}{2r_1(r_1+r_2)} \varepsilon_c \delta l - \frac{1}{2} c_i - \frac{1}{2} c_o + \frac{1}{2r_1} \theta q \right) \\ & * \left( \frac{r_0}{4} - \frac{r_1}{4} c_i - \frac{r_1+r_2}{4} c_o + \frac{1}{4} \varepsilon_c \delta l \right) \\ & + \left( \frac{r_0}{2r_1} - \frac{1}{2} c_i - \frac{r_1+r_2}{2r_1 r_2} \varepsilon_c \delta l + \frac{r_1+r_2}{2r_1 r_2} \theta q \right) \\ & * \left( \frac{r_0 r_2}{4(r_1+r_2)} + \frac{1}{2} \theta q + \frac{r_2}{4} c_o - \frac{r_2 r_1}{4(r_1+r_2)} c_i + \frac{4(2r_1+3r_2)}{4(r_1+r_2)} \varepsilon_c \delta l \right) \\ & - \left( \frac{h_0}{2h_1} + \frac{h_2}{2h_1} q + \frac{1}{2} c_e \right) * \left( \frac{1}{2} h_0 - \frac{h_1}{2} c_e + \frac{1}{2} h_2 q \right). \end{aligned} \quad (23)$$

Return of the operator:

$$\pi_o = \left( -\frac{1}{4} c_o + \frac{1}{4(r_1+r_2)} \varepsilon_c \delta l - \frac{r_1}{4(r_1+r_2)} c_i + \frac{r_0 r_1}{4r_1(r_1+r_2)} \right) * \left( \frac{r_0}{4} - \frac{r_1}{4} c_i - \frac{r_1+r_2}{4} c_o + \frac{1}{4} \varepsilon_c \delta l \right). \quad (24)$$

Return of the equipment supplier:

$$\pi_e = \left( \frac{h_0}{2h_1} + \frac{h_2}{2h_1} q - \frac{1}{2} c_e \right) \left( \frac{1}{2} h_0 - \frac{h_1}{2} c_e + \frac{1}{2} h_2 q \right). \quad (25)$$

### 3.3.2. The Subsidy Object Is the Investor (Model I)

The investor is the key participant in the production stage of the microgrid, and is responsible for the investment in and construction of the microgrid. There are many investors in microgrid development, such as the State Grid Corporation of China, China Southern Power Grid Corporation, the five major power generation companies of China, energy investment groups, gas groups,

new energy companies, crowdfunding, and other investors. With the background of power system reform and energy supply structure adjustment, the investor enters into the microgrid market to develop microgrid projects in order to increase the utilization rate of renewable energy and gain more market revenue. The investor invests in the development of microgrids through the integration of related resources. Therefore, at the early stage of microgrid development, the government often offers direct compensation to investors to encourage their participation in developing microgrids. For example, the government directly subsidizes investors to encourage the development of microgrids in Tianjin Binhai New District. We set up Model I to discuss the situation where the government subsidizes investors. The government directly subsidizes investors through tax breaks, subsidy costs, and benefits directly. For research convenience, we assume that subsidy brings about a reduction in the cost or an increase in the return of the investor, so the decision function for the investor becomes

$$\pi_i = (p_1 - c_i + \varepsilon_i \delta l) D_o + (p_2 - c_i + \varepsilon_i \delta l) D_i - p_e D_e. \quad (26)$$

We solve the equilibrium of the operator starting from the distribution stage by the inverse induction method. The operator makes a decision based on the price  $p_o$ . Therefore, the response function of the operator is

$$\frac{\partial \pi_o}{\partial p_o} = r_0 - 2(r_1 + r_2)p_o + (r_1 + r_2)p_1 + r_2 p_2 + (r_1 + r_2)c_o. \quad (27)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_o}{\partial p_o} = 0$ , and we get

$$p_o = \frac{1}{2} p_1 + \frac{r_2}{2(r_1 + r_2)} p_2 + \frac{r_0 + (r_1 + r_2)c_o}{2(r_1 + r_2)}. \quad (28)$$

The investor makes active decisions based on prices  $p_1$  and  $p_2$ . By substituting  $p_o$  in  $\pi_i$  and taking the partial derivative of  $\pi_i$  with respect to  $p_1$  and  $p_2$ , we get the response function of the investor:

$$\frac{\partial \pi_i}{\partial p_1} = \frac{1}{2} r_0 - (r_1 + r_2)p_1 - \frac{1}{2} (r_1 + r_2)c_o + \frac{r_1}{2} c_i - \frac{r_1}{2} \varepsilon_i \delta l + r_2 p_2 \quad (29)$$

$$\frac{\partial \pi_i}{\partial p_2} = \frac{r_1 r_2}{2(r_1 + r_2)} c_i + r_2 p_1 - \frac{r_2(2r_1 + r_2)}{r_1 + r_2} p_2 + \theta q - \frac{r_1 r_2}{2(r_1 + r_2)} \varepsilon_i \delta l + \frac{r_0 r_2}{2(r_1 + r_2)} + \frac{r_2}{2} c_o. \quad (30)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_i}{\partial p_1} = 0, \frac{\partial \pi_i}{\partial p_2} = 0$ , and we get

$$p_1 = \frac{1}{2(r_1 + r_2)} r_0 - \frac{1}{2} c_o + \frac{r_1}{2(r_1 + r_2)} c_i - \frac{r_1}{2(r_1 + r_2)} \varepsilon_i \delta l + \frac{r_2}{r_1 + r_2} p_2 \quad (31)$$

$$p_2 = \frac{r_1}{2(2r_1 + r_2)} c_i + \frac{r_1 + r_2}{2r_1 + r_2} p_1 + \frac{r_1 + r_2}{r_2(2r_1 + r_2)} \theta q - \frac{r_1}{2(2r_1 + r_2)} \varepsilon_i \delta l + \frac{r_0}{2(2r_1 + r_2)} + \frac{r_1 + r_2}{2(2r_1 + r_2)} c_o. \quad (32)$$

Calculating simultaneous equations for  $p_1$  and  $p_2$ , we have

$$p_1 = \frac{1}{2r_1} r_0 - \frac{1}{2} c_o + \frac{1}{2} c_i - \frac{1}{2} \varepsilon_i \delta l + \frac{1}{2r_1} \theta q \quad (33)$$

$$p_2 = \frac{1}{2r_1} r_0 + \frac{r_1 + r_2}{2r_1 r_2} \theta q + \frac{1}{2} c_i - \frac{1}{2} \varepsilon_i \delta l. \quad (34)$$

The equipment supplier makes active decisions with  $p_e$ . Therefore, the response function of the equipment supplier is

$$\frac{\partial \pi_e}{\partial p_e} = D_e + (p_e - c_e)(-h_1) = h_0 - h_1 p_e + h_2 q - h_1 p_e + h_1 c_e = h_0 - 2h_1 p_e + h_2 q + h_1 c_e. \quad (35)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_e}{\partial p_e} = 0$ , and we have

$$p_e = \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q + \frac{1}{2}c_e. \quad (36)$$

By substituting  $p_1$  and  $p_2$  into the equation for  $p_o$ , we get  $p_o$ . Thus, in equilibrium, the prices for which the government subsidizes the investor are

$$p_1 = \frac{1}{2r_1}r_0 - \frac{1}{2}c_o + \frac{1}{2}c_i - \frac{1}{2}\varepsilon_i\delta l + \frac{1}{2r_1}\theta q \quad (37)$$

$$p_2 = \frac{1}{2r_1}r_0 + \frac{r_1+r_2}{2r_1r_2}\theta q + \frac{1}{2}c_i - \frac{1}{2}\varepsilon_i\delta l \quad (38)$$

$$p_e = \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q + \frac{1}{2}c_e \quad (39)$$

$$p_o = \frac{3r_1+2r_2}{4r_1(r_1+r_2)}r_0 + \frac{1}{4}c_o + \frac{1}{2r_1}\theta q + \frac{r_1+2r_2}{4(r_1+r_2)}c_i - \frac{r_1+2r_2}{4(r_1+r_2)}\varepsilon_i\delta l. \quad (40)$$

The obtained prices  $p_1$ ,  $p_2$ ,  $p_e$ , and  $p_o$  are the optimal prices of the model in which the government subsidizes the investor, and this price combination is the optimal set of decisions for Model I. In Model I, it is in the best interests of the investor, equipment supplier, and operator to adopt this set of decisions. By substituting  $p_1$ ,  $p_2$ ,  $p_e$ , and  $p_o$  into the return function and demand function of each participant, the equilibrium returns of the investor, operator, and equipment supplier under the optimal decisions can be calculated.

Return of the investor:

$$\begin{aligned} \pi_i = & \left( \frac{1}{2r_1}r_0 - \frac{1}{2}c_o - \frac{1}{2}c_i + \frac{1}{2}\varepsilon_i\delta l + \frac{1}{2r_1}\theta q \right) * \left( \frac{1}{4}r_0 - \frac{r_1+r_2}{4}c_o - \frac{r_1}{4}c_i + \frac{r_1}{4}\varepsilon_i\delta l \right) \\ & + \left( \frac{1}{2r_1}r_0 + \frac{r_1+r_2}{2r_1r_2}\theta q - \frac{1}{2}c_i + \frac{1}{2}\varepsilon_i\delta l \right) \\ & * \left( \frac{r_2}{4(r_1+r_2)}r_0 + \frac{1}{2}\theta q - \frac{r_1r_2}{4(r_1+r_2)}c_i + \frac{r_2}{4}c_o + \frac{r_1r_2}{4(r_1+r_2)}\varepsilon_i\delta l \right) \\ & - \left( \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q - \frac{1}{2}c_e \right) * \left( \frac{1}{2}h_0 - \frac{h_1}{2}c_e + \frac{1}{2}h_2q \right). \end{aligned} \quad (41)$$

Return of the operator:

$$\pi_o = \left( \frac{1}{4(r_1+r_2)}r_0 - \frac{1}{4}c_o - \frac{r_1}{4(r_1+r_2)}c_i + \frac{r_1}{4(r_1+r_2)}\varepsilon_i\delta l \right) * \left( \frac{1}{4}r_0 - \frac{r_1+r_2}{4}c_o - \frac{r_1}{4}c_i + \frac{r_1}{4}\varepsilon_i\delta l \right). \quad (42)$$

Return of the equipment supplier:

$$\pi_e = \left( \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q - \frac{1}{2}c_e \right) \left( \frac{1}{2}h_0 - \frac{h_1}{2}c_e + \frac{1}{2}h_2q \right). \quad (43)$$

### 3.3.3. The Subsidy Object Is the Operator (Model O)

As the key participant in the distribution and sale stage of the microgrid system, the operator deals with the user directly. The quality and efficiency of the operator's work directly affect the experience of power consumption and the level of demand satisfaction of the user. In a traditional power grid, the grid company works as the operator and is in charge of the centralized operation and management of power grid transmission and distribution. With the reform of the power system, the state gradually opens the market of distribution and sale and allows private capital to enter into the market of distribution and sale of the power grid, which is conducive to improving the quality and efficiency of the distribution and sale of the power grid. For this purpose, the government often encourages the capital of all parties to participate in the distribution and sale of microgrids through preferential and subsidy policy. For example, preferential and subsidy policies have been introduced

to allow private capital to set up distribution and selling companies [44–46]. We set up Model O to discuss the situation of the government subsidizing the operator. For research convenience, we assume that the subsidy brings about a reduction in the cost or an increase in the return of the operator, so the decision function of the operator becomes

$$\pi_o = (p_o - p_1 - c_o + \varepsilon_o \delta l) D_o. \quad (44)$$

We solve the equilibrium of the operator starting from the distribution stage by the inverse induction method. The operator makes a decision based on the price  $p_o$ . Therefore, the response function of the operator is

$$\frac{\partial \pi_o}{\partial p_o} = r_0 - 2(r_1 + r_2)p_o + (r_1 + r_2)p_1 + r_2 p_2 + (r_1 + r_2)c_o - (r_1 + r_2)\varepsilon_o \delta l. \quad (45)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_o}{\partial p_o} = 0$ , and we get

$$p_o = \frac{1}{2}p_1 + \frac{r_2}{2(r_1 + r_2)}p_2 + \frac{r_0 - (r_1 + r_2)\varepsilon_o \delta l + (r_1 + r_2)c_o}{2(r_1 + r_2)}. \quad (46)$$

The investor makes active decisions based on prices  $p_1$  and  $p_2$ . By substituting  $p_o$  into  $\pi_i$  and taking the partial derivative of  $\pi_i$  with respect to  $p_1$  and  $p_2$ , we get the response function of the investor:

$$\frac{\partial \pi_i}{\partial p_1} = \frac{1}{2}r_0 - (r_1 + r_2)p_1 + r_2 p_2 + \frac{1}{2}(r_1 + r_2)\varepsilon_o \delta l - \frac{1}{2}(r_1 + r_2)c_o + \frac{r_1}{2}c_i \quad (47)$$

$$\frac{\partial \pi_i}{\partial p_2} = \frac{r_1 r_2}{2(r_1 + r_2)}c_i - \frac{r_2(2r_1 + r_2)}{r_1 + r_2}p_2 + r_2 p_1 + \frac{r_2}{2(r_1 + r_2)}r_0 - \frac{r_2}{2}\varepsilon_o \delta l + \frac{r_2}{2}c_o + \theta q. \quad (48)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_i}{\partial p_1} = 0, \frac{\partial \pi_i}{\partial p_2} = 0$ , and we get

$$p_1 = \frac{1}{2(r_1 + r_2)}r_0 + \frac{r_2}{r_1 + r_2}p_2 + \frac{1}{2}\varepsilon_o \delta l - \frac{1}{2}c_o + \frac{r_1}{2(r_1 + r_2)}c_i \quad (49)$$

$$p_2 = \frac{r_1}{2(2r_1 + r_2)}c_i + \frac{r_1 + r_2}{2r_1 + r_2}p_1 + \frac{1}{2(2r_1 + r_2)}r_0 - \frac{r_1 + r_2}{2(2r_1 + r_2)}\varepsilon_o \delta l + \frac{r_1 + r_2}{2(2r_1 + r_2)}c_o + \frac{r_1 + r_2}{r_2(2r_1 + r_2)}\theta q. \quad (50)$$

Calculating simultaneous equations for  $p_1$  and  $p_2$ , we have

$$p_1 = \frac{1}{2r_1}r_0 + \frac{1}{2}\varepsilon_o \delta l - \frac{1}{2}c_o + \frac{1}{2r_1}\theta q + \frac{1}{2}c_i \quad (51)$$

$$p_2 = \frac{1}{2}c_i + \frac{1}{2r_1}r_0 + \frac{r_1 + r_2}{2r_1 r_2}\theta q. \quad (52)$$

The equipment supplier makes active decisions with  $p_e$ . Therefore, the response function of the equipment supplier is

$$\frac{\partial \pi_e}{\partial p_e} = h_0 - h_1 p_e + h_2 q - h_1 p_e + h_1 c_e = h_0 - 2h_1 p_e + h_2 q + h_1 c_e. \quad (53)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_e}{\partial p_e} = 0$ , and we have

$$p_e = \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q + \frac{1}{2}c_e. \quad (54)$$

By substituting  $p_1$  and  $p_2$  into the equation for  $p_o$ , we get  $p_o$ . Thus, in equilibrium, the prices for which the government subsidizes the operator are

$$p_1 = \frac{1}{2r_1}r_0 + \frac{1}{2}\varepsilon_0\delta l - \frac{1}{2}c_o + \frac{1}{2r_1}\theta q + \frac{1}{2}c_i \quad (55)$$

$$p_2 = \frac{1}{2}c_i + \frac{1}{2r_1}r_0 + \frac{r_1+r_2}{2r_1r_2}\theta q \quad (56)$$

$$p_o = \frac{3r_1+2r_2}{4r_1(r_1+r_2)}r_0 - \frac{1}{4}\varepsilon_0\delta l + \frac{1}{4}c_o + \frac{1}{2r_1}\theta q + \frac{r_1+2r_2}{4(r_1+r_2)}c_i \quad (57)$$

$$p_e = \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q + \frac{1}{2}c_e. \quad (58)$$

The obtained prices  $p_1$ ,  $p_2$ ,  $p_e$ , and  $p_o$  are the optimal prices of the model where in the government subsidizes the operator, and this price combination is the optimal set of decisions for Model O. In Model O, it is in the best interests of the investor, equipment supplier, and operator to adopt this set of decisions. By substituting  $p_1$ ,  $p_2$ ,  $p_e$ , and  $p_o$  into the return and demand functions of each participant, the equilibrium returns of the investor, operator, and equipment supplier under the optimal decisions can be calculated.

Return of the investor:

$$\begin{aligned} \pi_i = & \left( \frac{1}{2r_1}r_0 + \frac{1}{2}\varepsilon_0\delta l - \frac{1}{2}c_o + \frac{1}{2r_1}\theta q - \frac{1}{2}c_i \right) \\ & * \left( \frac{1}{4}r_0 + \frac{r_1+r_2}{4}\varepsilon_0\delta l - \frac{r_1+r_2}{4}c_o - \frac{r_1}{4}c_i \right) \\ & + \left( -\frac{1}{2}c_i + \frac{1}{2r_1}r_0 + \frac{r_1+r_2}{2r_1r_2}\theta q \right) \\ & * \left( \frac{r_2}{4(r_1+r_2)}r_0 - \frac{r_2}{4}\varepsilon_0\delta l + \frac{r_2}{4}c_o + \frac{1}{2}\theta q - \frac{r_1r_2}{4(r_1+r_2)}c_i \right) \\ & - \left( \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q - \frac{1}{2}c_e \right) * \left( \frac{1}{2}h_0 - \frac{h_1}{2}c_e + \frac{1}{2}h_2q \right). \end{aligned} \quad (59)$$

Return of the operator:

$$\pi_o = \left( \frac{1}{4(r_1+r_2)}r_0 + \frac{1}{4}\varepsilon_0\delta l - \frac{1}{4}c_o - \frac{r_1}{4(r_1+r_2)}c_i \right) * \left( \frac{1}{4}r_0 + \frac{r_1+r_2}{4}\varepsilon_0\delta l - \frac{r_1+r_2}{4}c_o - \frac{r_1}{4}c_i \right). \quad (60)$$

Return of the equipment supplier:

$$\pi_e = \left( \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q - \frac{1}{2}c_e \right) \left( \frac{1}{2}h_0 - \frac{h_1}{2}c_e + \frac{1}{2}h_2q \right). \quad (61)$$

### 3.3.4. The Subsidy Object Is the Equipment Supplier (Model E)

The equipment supplier is an important participant in the microgrid production stage. They are crucial to the development of the microgrid. For example, the key equipment suppliers, such as the microgrid motor supplier and energy storage supplier, provide equipment and technical support for the development of microgrids. The equipment supplier constructs a microgrid with the investor by providing their own technology and equipment quality. The uncertainty of the technology and the user's demand are high at the early stages of the microgrid industry. The participation of the equipment supplier allows them to exert their specialized ability to improve the technology and construction quality of the microgrid, bringing innovative and differentiated construction plans and prices for the microgrid, and helping to meet the diverse demand of users to promote the development of microgrids. To this end, the state has introduced corresponding preferential policies to encourage the development of the equipment supplier industry. We set up Model E to discuss the situation of the government subsidizing the equipment supplier. For research convenience, we assume that the



subsidy brings about a reduction in the cost or an increase in the return of the equipment supplier, so the decision function of the equipment supplier becomes

$$\pi_e = (p_e - c_e + \varepsilon_e \delta l) D_e. \quad (62)$$

We solve the equilibrium of the operator starting from the distribution stage by the inverse induction method. The operator makes a decision based on the price  $p_o$ . Therefore, the response function of the operator is

$$\frac{\partial \pi_o}{\partial p_o} = r_0 - 2(r_1 + r_2)p_o + (r_1 + r_2)p_1 + r_2 p_2 + (r_1 + r_2)c_o. \quad (63)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_o}{\partial p_o} = 0$ , and we get

$$p_o = \frac{1}{2}p_1 + \frac{r_2}{2(r_1 + r_2)}p_2 + \frac{r_0 + (r_1 + r_2)c_o}{2(r_1 + r_2)}. \quad (64)$$

The investor makes active decisions based on prices  $p_1$  and  $p_2$ . By substituting  $p_o$  into  $\pi_i$  and taking the partial derivative of  $\pi_i$  with respect to  $p_1$  and  $p_2$ , we get the response function of the investor:

$$\frac{\partial \pi_i}{\partial p_1} = \frac{1}{2}r_0 - (r_1 + r_2)p_1 - \frac{1}{2}(r_1 + r_2)c_o + r_2 p_2 + \frac{r_1}{2}c_i \quad (65)$$

$$\frac{\partial \pi_i}{\partial p_2} = \frac{r_1 r_2}{2(r_1 + r_2)}c_i - \frac{r_2(2r_1 + r_2)}{r_1 + r_2}p_2 + r_2 p_1 + \frac{r_2}{2(r_1 + r_2)}r_0 + \frac{r_2}{2}c_o + \theta q. \quad (66)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_i}{\partial p_1} = 0$ ,  $\frac{\partial \pi_i}{\partial p_2} = 0$ , and we get

$$p_1 = \frac{1}{2(r_1 + r_2)}r_0 - \frac{1}{2}c_o + \frac{r_2}{r_1 + r_2}p_2 + \frac{r_1}{2(r_1 + r_2)}c_i \quad (67)$$

$$p_2 = \frac{r_1}{2(2r_1 + r_2)}c_i + \frac{r_1 + r_2}{2r_1 + r_2}p_1 + \frac{1}{2(2r_1 + r_2)}r_0 + \frac{r_1 + r_2}{2(2r_1 + r_2)}c_o + \frac{r_1 + r_2}{r_2(2r_1 + r_2)}\theta q. \quad (68)$$

Calculating simultaneous equations for  $p_1$  and  $p_2$ , we have

$$p_1 = \frac{1}{2r_1}r_0 + \frac{1}{2}c_i - \frac{1}{2}c_o + \frac{1}{2r_1}\theta q \quad (69)$$

$$p_2 = \frac{1}{2}c_i + \frac{1}{2r_1}r_0 + \frac{r_1 + r_2}{2r_1 r_2}\theta q. \quad (70)$$

The equipment supplier makes active decisions with  $p_e$ . Therefore, the response function of the equipment supplier is

$$\frac{\partial \pi_e}{\partial p_e} = h_0 - 2h_1 p_e + h_2 q + h_1 c_e - h_1 \varepsilon_e \delta l. \quad (71)$$

In equilibrium, the first-order condition satisfies  $\frac{\partial \pi_e}{\partial p_e} = 0$ , and we have

$$p_e = \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q + \frac{1}{2}c_e - \frac{1}{2}\varepsilon_e \delta l. \quad (72)$$

By substituting  $p_1$  and  $p_2$  into the equation for  $p_o$ , we get  $p_o$ . Thus, in equilibrium, the prices for which the government subsidizes the equipment supplier are

$$p_o = \frac{3r_1 + 2r_2}{4r_1(r_1 + r_2)}r_0 + \frac{r_1 + 2r_2}{4(r_1 + r_2)}c_i + \frac{1}{4}c_o + \frac{1}{2r_1}\theta q \quad (73)$$

$$p_1 = \frac{1}{2r_1}r_0 + \frac{1}{2}c_i - \frac{1}{2}c_o + \frac{1}{2r_1}\theta q \quad (74)$$

$$p_2 = \frac{1}{2}c_i + \frac{1}{2r_1}r_0 + \frac{r_1+r_2}{2r_1r_2}\theta q \quad (75)$$

$$p_e = \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q + \frac{1}{2}c_e - \frac{1}{2}\varepsilon_e\delta l. \quad (76)$$

The obtained prices  $p_1$ ,  $p_2$ ,  $p_e$ , and  $p_o$  are the optimal prices of the model in which the government subsidizes the equipment supplier, and this price combination is the optimal set of decisions for Model E. In Model E, it is in the best interests of the investor, equipment supplier, and operator to adopt this set of decisions. By substituting  $p_1$ ,  $p_2$ ,  $p_e$ , and  $p_o$  into the return and demand functions of each party, the equilibrium returns of the investor, operator, and equipment supplier under the optimal decisions can be calculated.

Return of the investor:

$$\begin{aligned} \pi_i = & \left( \frac{1}{2r_1}r_0 - \frac{1}{2}c_i - \frac{1}{2}c_o + \frac{1}{2r_1}\theta q \right) \left( \frac{1}{4}r_0 - \frac{r_1}{4}c_i - \frac{r_1+r_2}{4}c_o \right) \\ & + \left( -\frac{1}{2}c_i + \frac{1}{2r_1}r_0 + \frac{r_1+r_2}{2r_1r_2}\theta q \right) \left( \frac{r_2}{4(r_1+r_2)}r_0 - \frac{r_1r_2}{4(r_1+r_2)}c_i + \frac{r_2}{4}c_o + \frac{1}{2}\theta q \right) \\ & - \left( \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q + \frac{1}{2}c_e - \frac{1}{2}\varepsilon_e\delta l \right) \left( \frac{h_0}{2} - \frac{h_2}{2}q - \frac{h_1}{2}c_e + \frac{h_1}{2}\varepsilon_e\delta l \right). \end{aligned} \quad (77)$$

Return of the operator:

$$\pi_o = \left( \frac{1}{4(r_1+r_2)}r_0 - \frac{r_1}{4(r_1+r_2)}c_i - \frac{1}{4}c_o \right) \left( \frac{1}{4}r_0 - \frac{r_1}{4}c_i - \frac{r_1+r_2}{4}c_o \right). \quad (78)$$

Return of the equipment supplier:

$$\pi_e = \left( \frac{h_0}{2h_1} + \frac{h_2}{2h_1}q - \frac{1}{2}c_e + \frac{1}{2}\varepsilon_e\delta l \right) * \left( \frac{h_0}{2} + \frac{h_2}{2}q - \frac{h_1}{2}c_e + \frac{h_1}{2}\varepsilon_e\delta l \right). \quad (79)$$

#### 4. Comparative Analysis of the Models and Discussion of Results

By calculating the models in which the government subsidizes the user, investor, operator, and equipment supplier, we find that as a result of the government subsidizing different objects, there are significantly different operational efficiencies of the microgrid industrial chain. In the microgrid development process, when the government takes different price and return indicators as the optimization objects for coordination development of microgrid projects, the operational efficiency of the microgrid project development industry chain differs markedly. In this section, we discuss the choice of subsidy objects which can optimize the operational efficiency of the microgrid project development industry chain through comparison and analysis of pricing and returns with different subsidy object models.

##### 4.1. Comparison of Price Indicators

###### 4.1.1. Electricity Price Indicator $p_2$

$$p_{i2} - p_{c2} = -\frac{1}{2}\varepsilon_i\delta l + \frac{r_1+r_2}{2r_1r_2}\varepsilon_c\delta l = \frac{(r_1+r_2)\varepsilon_c - r_1r_2\varepsilon_i}{2r_1r_2}\delta l \quad (80)$$

When  $\varepsilon_i \leq \frac{r_1+r_2}{r_1r_2}\varepsilon_c$ ,  $p_{i2} - p_{c2} \geq 0$ ,  $p_{i2} \geq p_{c2}$ , we have  $p_{e2} = p_{o2} > p_{i2} \geq p_{c2}$ ; that is,  $E = O > I \geq C$ ;

When  $\varepsilon_i > \frac{r_1+r_2}{3r_1+2r_2}\varepsilon_c$ ,  $p_{i2} - p_{c2} < 0$ ,  $p_{i2} < p_{c2}$ , we have  $p_{e2} = p_{o2} > p_{c2} > p_{i2}$ ; that is,  $E = O > C > I$ .

4.1.2. Electricity Price Indicator  $p_1$ 

Where  $p_{o1} > p_{e1}$ ,  $O > E$ ,

$$p_{c1} - p_{i1} = -\frac{r_2}{2r_1(r_1 + r_2)} \varepsilon_c \delta l + \frac{1}{2} \varepsilon_i \delta l = \frac{r_1(r_1 + r_2) \varepsilon_i - r_2 \varepsilon_c}{2r_1(r_1 + r_2)} \delta l. \quad (81)$$

When  $\varepsilon_i > \frac{r_2}{r_1(r_1 + r_2)} \varepsilon_c$ ,  $p_{c1} - p_{i1} > 0$ ,  $p_{c1} > p_{i1}$ , we have  $p_{o1} > p_{e1} > p_{c1} > p_{i1}$ ; that is,  $O > E > C > I$ ;

When  $\varepsilon_i \leq \frac{r_2}{r_1(r_1 + r_2)} \varepsilon_c$ ,  $p_{c1} - p_{i1} \leq 0$ ,  $p_{c1} \leq p_{i1}$ , we have  $p_{o1} > p_{e1} > p_{i1} \geq p_{c1}$ ; that is,  $O > E > I \geq C$ .

4.1.3. Electricity Price Indicator  $p_o$ 

$$p_{oo} - p_{io} = -\frac{1}{4} \varepsilon_o \delta l + \frac{r_1 + 2r_2}{4(r_1 + r_2)} \varepsilon_i \delta l = \frac{(r_1 + 2r_2) \varepsilon_i - (r_1 + r_2) \varepsilon_o}{4(r_1 + r_2)} \delta l \quad (82)$$

$$p_{oo} - p_{co} = -\frac{1}{4} \varepsilon_o \delta l + \frac{2r_2 - r_1}{4r_1(r_1 + r_2)} \varepsilon_c \delta l = \frac{(2r_2 - r_1) \varepsilon_c - r_1(r_1 + r_2) \varepsilon_o}{4r_1(r_1 + r_2)} \delta l \quad (83)$$

When  $\frac{2r_2 - r_1}{r_1(r_1 + r_2)} \varepsilon_c < \varepsilon_o \leq \frac{r_1 + 2r_2}{r_1 + r_2} \varepsilon_i$ ,  $p_{io} \leq p_{oo} < p_{co}$ , we have  $p_{eo} > p_{co} > p_{oo} \geq p_{io}$ ; that is,  $E > C > O \geq I$ ;

When  $\frac{r_1 + 2r_2}{r_1 + r_2} \varepsilon_i < \varepsilon_o \leq \frac{2r_2 - r_1}{r_1(r_1 + r_2)} \varepsilon_c$ ,  $p_{co} \leq p_{oo} < p_{io}$ , we have  $p_{eo} > p_{io} > p_{oo} \geq p_{co}$ ; that is,  $E > I > O \geq C$ .

4.1.4. Equipment Price Indicator  $p_e$ 

$$p_{ie} = p_{oe} = p_{ce} \quad (84)$$

$$p_{ee} - p_{ie} = -\frac{1}{2} \varepsilon_e \delta l \quad (85)$$

Thus, we get  $I = O = C > E$ .

Conclusion: The four price indicators of operational efficiency of the microgrid industry chain are all determined by five parameters. They are the subsidy impact coefficient on investment cost  $\varepsilon_i$ , the subsidy impact coefficient on operating cost  $\varepsilon_o$ , the subsidy impact coefficient on user demand  $\varepsilon_c$ , the elasticity coefficient of microgrid price demand  $r_1$ , and the elasticity coefficient of price substitutability  $r_2$ . The specific value of the price with different subsidy objects is determined by the specific values of the parameters such as  $\varepsilon_i$ ,  $\varepsilon_o$ ,  $\varepsilon_c$ ,  $r_1$ ,  $r_2$ , and so on.

For the electricity price indicator that the investor sells to the user directly, the price where the government subsidizes the investor and user is obviously lower than the price where they subsidize the equipment supplier and operator. This is mainly because the government subsidizes the investor and user directly and indirectly reduces the cost of the microgrid, resulting in a drop in the direct electricity sale price in the microgrid. For the electricity price indicator that the investor sells to the operator, we get the highest price when the government subsidizes the operator, and a lower price when subsidizing the equipment supplier and investor. The main reason for this is that when the government subsidizes the operator, the cost of the operator reduces and the sell quantity of the operator increases, resulting in the increase of the price of electricity sold by the investor to the operator. For the electricity price indicator that the operator sells to the user, we get the highest price when the government subsidizes the equipment supplier, and a lower price when subsidizing the operator, investor, and user. This is mainly because subsidizing the operator, investor, and user can reduce the cost of electricity purchases of the operator and increase the demand of the operator, resulting in a reduction of the electricity price for the operator.

## 4.2. Comparison of Return Indicators

### 4.2.1. Return Indicator for Investor $\pi_i$

$$\begin{aligned} \pi_{ii} - \pi_{oi} = & \left( \frac{r_1}{4} \varepsilon_i \delta l - \frac{r_1+r_2}{4} \varepsilon_o \delta l \right) * \left( \frac{1}{2r_1} r_0 - \frac{1}{2} c_o + \frac{1}{2r_1} \theta q - \frac{1}{2} c_i \right) + \left( \frac{1}{2} \varepsilon_i \delta l - \frac{1}{2} \varepsilon_o \delta l \right) \\ & * \left( \frac{1}{4} r_0 - \frac{r_1+r_2}{4} c_o - \frac{r_1}{4} c_i \right) + \left( \frac{1}{2} \varepsilon_i \delta l * \frac{r_1}{4} \varepsilon_i \delta l - \frac{1}{2} \varepsilon_o \delta l * \frac{r_1+r_2}{4} \varepsilon_o \delta l \right) \\ & + \left( \frac{r_1 r_2}{4(r_1+r_2)} \varepsilon_i \delta l + \frac{r_2}{4} \varepsilon_o \delta l \right) * \left( -\frac{1}{2} c_i + \frac{1}{2r_1} r_0 + \frac{r_1+r_2}{2r_1 r_2} \theta q \right) + \frac{1}{2} \varepsilon_i \delta l \\ & * \left( \frac{r_2}{4(r_1+r_2)} r_0 + \frac{1}{2} \theta q - \frac{r_1 r_2}{4(r_1+r_2)} c_i + \frac{r_2}{4} c_o \right) + \frac{1}{2} \varepsilon_i \delta l * \frac{r_1 r_2}{4(r_1+r_2)} \varepsilon_i \delta l > 0 \end{aligned} \quad (86)$$

$$\begin{aligned} \pi_{oi} - \pi_{ci} = & \left( \frac{r_1+r_2}{4} \varepsilon_o \delta l - \frac{1}{4} \varepsilon_c \delta l \right) * \left( \frac{1}{2r_1} r_0 - \frac{1}{2} c_o + \frac{1}{2r_1} \theta q - \frac{1}{2} c_i \right) + \left( \frac{1}{2} \varepsilon_o \delta l + \frac{r_2}{2r_1(r_1+r_2)} \varepsilon_c \delta l \right) \\ & * \left( \frac{1}{4} r_0 - \frac{r_1+r_2}{4} c_o - \frac{r_1}{4} c_i \right) + \left( \frac{1}{2} \varepsilon_o \delta l * \frac{r_1+r_2}{4} \varepsilon_o \delta l + \frac{r_2}{2r_1(r_1+r_2)} \varepsilon_c \delta l * \frac{1}{4} \varepsilon_c \delta l \right) \\ & + \left( -\frac{r_2}{4} \varepsilon_o \delta l - \frac{4(2r_1+3r_2)}{4(r_1+r_2)} \varepsilon_c \delta l \right) * \left( -\frac{1}{2} c_i + \frac{1}{2r_1} r_0 + \frac{r_1+r_2}{2r_1 r_2} \theta q \right) + \frac{r_1+r_2}{2r_1 r_2} \varepsilon_c \delta l \\ & * \left( \frac{r_2}{4(r_1+r_2)} r_0 + \frac{1}{2} \theta q - \frac{r_1 r_2}{4(r_1+r_2)} c_i + \frac{r_2}{4} c_o \right) + \frac{4(2r_1+3r_2)}{4(r_1+r_2)} \varepsilon_c \delta l * \frac{r_1+r_2}{2r_1 r_2} \varepsilon_c \delta l \\ & > 0. \end{aligned} \quad (87)$$

The amount of the investor's return is affected by the values of parameters, such as  $\varepsilon_c$ ,  $\varepsilon_i$ ,  $\varepsilon_o$ ,  $\delta l$ ,  $r_0$ ,  $r_1$ ,  $r_2$ ,  $c_o$ ,  $c_i$ , and  $\theta q$ .

When the influence of parameters  $\varepsilon_c$ ,  $\varepsilon_i$ , and  $\varepsilon_o$  is smaller than that of  $r_0$ ,  $r_1$ , and  $r_2$ , we get  $I > O > C > E$ .

When the influence of parameters  $\varepsilon_c$ ,  $\varepsilon_i$ , and  $\varepsilon_o$  is bigger than that of  $r_0$ ,  $r_1$ , and  $r_2$ , the return indicator of the investor depends on the specific values of  $\varepsilon_c$ ,  $\varepsilon_i$ ,  $\varepsilon_o$ ,  $\delta l$ ,  $r_0$ ,  $r_1$ ,  $r_2$ ,  $c_o$ ,  $c_i$ ,  $\theta$ , and  $q$ .

### 4.2.2. Return Indicator for Equipment Supplier $\pi_e$

Because the parameter values  $\frac{1}{2} \varepsilon_e \delta l$ ,  $\frac{h_1}{2} \varepsilon_e \delta l$  are both greater than 0, we get  $\pi_{ee} > \pi_{ce} = \pi_{ie} = \pi_{oe}$ ; that is,  $E > C = I = O$ .

### 4.2.3. Return Indicator for Operator $\pi_o$

$$\begin{aligned} \pi_{oo} - \pi_{io} = & \left( \frac{1}{4} \varepsilon_o \delta l - \frac{r_1}{4(r_1+r_2)} \varepsilon_i \delta l \right) \left( \frac{1}{4} r_0 - \frac{r_1+r_2}{4} c_o - \frac{r_1}{4} c_i \right) + \left( \frac{r_1+r_2}{4} \varepsilon_o \delta l - \frac{r_1}{4} \varepsilon_i \delta l \right) \\ & * \left( \frac{1}{4(r_1+r_2)} r_0 - \frac{1}{4} c_o - \frac{r_1}{4(r_1+r_2)} c_i \right) + \left( \frac{1}{4} \varepsilon_o \delta l * \frac{r_1+r_2}{4} \varepsilon_o \delta l - \frac{r_1}{4(r_1+r_2)} \varepsilon_i \delta l \right. \\ & \left. * \frac{r_1}{4} \varepsilon_i \delta l \right) > 0 \end{aligned} \quad (88)$$

$$\begin{aligned} \pi_{io} - \pi_{co} = & \left( \frac{r_1}{4(r_1+r_2)} \varepsilon_i \delta l - \frac{1}{4(r_1+r_2)} \varepsilon_c \delta l \right) \left( \frac{1}{4} r_0 - \frac{r_1+r_2}{4} c_o - \frac{r_1}{4} c_i \right) + \left( \frac{r_1}{4} \varepsilon_i \delta l - \frac{1}{4} \varepsilon_c \delta l \right) \\ & * \left( \frac{1}{4(r_1+r_2)} r_0 - \frac{1}{4} c_o - \frac{r_1}{4(r_1+r_2)} c_i \right) + \left( \frac{r_1}{4(r_1+r_2)} \varepsilon_i \delta l * \frac{r_1}{4} \varepsilon_i \delta l - \frac{1}{4(r_1+r_2)} \varepsilon_c \delta l \right. \\ & \left. * \frac{1}{4} \varepsilon_c \delta l \right) > 0. \end{aligned} \quad (89)$$

The amount of the operator's return is affected by the values of parameters, such as  $\varepsilon_c$ ,  $\varepsilon_i$ ,  $\varepsilon_o$ ,  $\delta l$ ,  $r_0$ ,  $r_1$ ,  $r_2$ ,  $c_o$ ,  $c_i$ , and  $\theta q$ .

When the influence of parameters  $\varepsilon_c$ ,  $\varepsilon_i$ , and  $\varepsilon_o$  is smaller than that of  $r_0$ ,  $r_1$ , and  $r_2$ , we get  $O > I > C > E$ .

When the influence of parameters  $\varepsilon_c$ ,  $\varepsilon_i$ , and  $\varepsilon_o$  is bigger than that of  $r_0$ ,  $r_1$ , and  $r_2$ , the return indicator of the operator depends on the specific values of  $\varepsilon_c$ ,  $\varepsilon_i$ ,  $\varepsilon_o$ ,  $\delta l$ ,  $r_0$ ,  $r_1$ ,  $r_2$ ,  $c_o$ ,  $c_i$ ,  $\theta$ , and  $q$ .

Conclusion: The return distribution for each participant in the operation of the microgrid industrial chain is significantly related to the above parameters; that is, the subsidy amount of the

microgrid  $\delta l$ , the subsidy impact coefficient on investment cost  $\varepsilon_i$ , the subsidy impact coefficient on operating cost  $\varepsilon_o$ , the subsidy impact coefficient on user demand  $\varepsilon_c$ , the elasticity coefficient of microgrid price demand  $r_1$ , the elasticity coefficient of price substitutability  $r_2$ , and the quality coefficient of the microgrid  $\theta$ . The specific value of the return with different subsidy objects is determined by the specific values of the parameters such as  $\delta l$ ,  $\varepsilon_i$ ,  $\varepsilon_o$ ,  $\varepsilon_c$ ,  $r_1$ ,  $r_2$ ,  $\theta$ , and so on.

When the impact of the subsidy is less than that of price, the return of the investor is larger when the government subsidizes the investor over other participants. This is mainly because when the government subsidizes investors, it reduces the costs and risks of investors and increases their returns. The return for the equipment supplier is larger when subsidizing the equipment supplier than other parties. This is mainly because when the government subsidizes the equipment supplier, it reduces the R&D and technological costs of the equipment supplier, and increases the profit of the equipment supplier. The return of the operator is larger when the government subsidizes the operator over other participants. The main reason for this is that when the government subsidizes the operator, it reduces the cost of the operator and thus increases the profit of the operator. In summary, when the impact of the subsidy is less than that of price, it can be seen that different subsidy objects all have an important influence on the return distribution of the microgrid industrial chain. When the impact of subsidy is greater than that of price, the return of all participants will be determined according to the specific circumstances. Subsidies will have more significant impact on return of all participants in the microgrid industry chain.

## 5. Numerical Analysis

We further explore the subsidy issue of the microgrid industrial chain through numerical analysis. Assume that there are five participants in the microgrid market: government, equipment supplier, investor, operator, and user. Since the microgrid is of great significance to the utilization of renewable energy, electricity market reform, and energy structure adjustment, in order to encourage the early stages of development of microgrids, the government motivates the participation of all parties in the development of microgrids through financial subsidy.

Based on the characteristics of the microgrid industry, related model hypothesis, and economic theories, we assume that the total demand, price elasticity, price difference elasticity, and quality demand elasticity of the microgrid market are  $r_0 = 200$ ,  $r_1 = 2$ ,  $r_2 = 3$ , and  $\theta = 6$ , respectively. The microgrid subsidy coefficient, the maximum subsidy amount, and the influence coefficients of subsidy on each participant are  $\delta = 0.2$ ,  $l = 100$ ,  $\varepsilon_i = 2.4$ ,  $\varepsilon_e = 0.4$ ,  $\varepsilon_o = 2.2$ , and  $\varepsilon_c = 2$ , respectively. The costs for investor, operator, and equipment supplier are  $c_i = 40$ ,  $c_o = 10$ , and  $c_e = 10$ , respectively. The total demand, price demand elasticity, and quality demand elasticity coefficient of the investor for the equipment supplier are  $h_0 = 40$ ,  $h_1 = 2$ , and  $h_2 = 4$ , respectively. The technological level, technological coefficient, and technological cost elasticity coefficient of the equipment company are  $t = 1$ ,  $\rho = 5$ , and  $k = 2$ , respectively.

We calculate the price and return of the market equilibrium with each subsidy model through Matlab, as shown in Table 1. Then, we further analyze the operational efficiency of the microgrid industrial chain and the impact of technological level and subsidy change on returns of all participants with each subsidy model.

**Table 1.** Indicators for different subsidy objects in the microgrid industry chain.

Indicator	Subsidize Energy Investor (Model I)	Subsidize Equipment Supplier (Model E)	Subsidize Operator (Model O)	Subsidize User (Model C)
$p_o$	66.80	86.00	75.00	82.00
$p_1$	48.50	72.50	94.50	66.50
$p_2$	58.50	82.50	82.50	65.83
$p_e$	20.00	16.00	20.00	20.00
$\pi_o$	344.45	61.25	1051.30	151.25
$\pi_i$	5117.60	2162.00	4070.00	4061.70
$\pi_e$	200.00	392.00	200.00	200.00

### 5.1. The Operational Efficiencies for Different Subsidy Objects in the Microgrid Industrial Chain

Since the main issues and conflicts vary at different stages of microgrid development, the government should adopt different subsidy policies. The selection of different subsidy objects will help achieve the goal of the government and improve the operational efficiency of the microgrid industrial chain. In order to further analyze the impact of different subsidy objects on the microgrid industrial chain, we examine Table 1 to analyze the operational efficiency or situation for different subsidy objects in the microgrid industrial chain. When government subsidizes the investor, the investor has the lowest direct electricity sale price of 58.50 (0.01 CNY/kW·h) and the lowest wholesale price of 48.50 (0.01 CNY/kW·h) among the four subsidy models, which in turn leads to the lowest price for electricity sale by the operator of 66.80 (0.01 CNY/kW·h) among the four subsidy models; this maximizes the return of the investor at 5117.60 (0.001 billion CNY) among the four subsidy models. This is mainly because when the government subsidizes investors, it can reduce the costs of investors and increase the demand for investors, thus increasing the profits of investors. When the government subsidizes equipment suppliers, equipment suppliers have the lowest price at 16.00 (0.01 CNY/kW·h) and highest returns at 392.00 (0.001 billion CNY) among the four subsidy models, while the investor and operator have the highest electricity sale prices and the lowest returns at 2162.00 (0.001 billion CNY) and 61.25 (0.001 billion CNY), respectively, among the four subsidy models. This is mainly due to the fact that when the government subsidizes equipment suppliers, in spite of the reduction of the costs of the equipment supplier and increase of the returns of the equipment supplier, the returns of the equipment supplier have less impact on the operation return of the entire microgrid industry chain, which causes other participants and the microgrid industrial chain to see less returns from subsidies. When the government subsidizes operators, the operator has a higher price of 75.00 (0.01 CNY/kW·h), the investor has the highest direct electricity sale price of 82.50 (0.01 CNY/kW·h) and wholesale price of 94.50 (0.01 CNY/kW·h), and the equipment supplier has the highest price of 20.00 (0.01 CNY/kW·h) among the four subsidy models; the operator has the highest return of 1051.30 (0.001 billion CNY), and the equipment supplier and investor have higher returns of 200.00 (0.001 billion CNY) and 4070.00 (0.001 billion CNY), respectively, among the four subsidy models. This is mainly because the subsidy reduces the cost of the operator, decreasing the electricity sale price of the operator and increasing the user's demand and demand for the investor, resulting in increasing returns for the operator. When the government subsidizes users, it increases the demand of the users. The electricity sale price of microgrid investors is relatively low at 65.83 (0.01 CNY/kW·h), thus increasing the demand for microgrid investors and equipment suppliers. In conclusion, when the microgrid market shows different characteristics, the government can influence the microgrid market through the adjustment of subsidy objects and subsidy methods, and promote the development of reasonable and healthy microgrids.

### 5.2. Impact of Microgrid Technology Change on Returns of All Participants

Microgrids are a technology-intensive industry, and the technological levels of microgrids in different stages of development present significant differences. The technological level of a microgrid system does not only affect the quality of microgrid construction and user requirements of the microgrid, but also affects the enthusiasm and benefit of all parties in the development of the microgrid. Therefore, the technological level of the microgrid has an important impact on the microgrid system. In order to further analyze impact of technology on the microgrid industrial chain, we draw Figure 2a,b and Figure 3a to analyze the impact of technology changes on the return of each participant of the microgrid. From Figure 2a, it can be seen that when the technological level changes from 1 to 3, with the improvement of technological level, the returns of the microgrid investor all gradually increase with different subsidy objects. The return of the investor rises fastest when the government subsidizes users. It is possible that as the technological level of the investor in microgrid construction improves, the microgrid can better guarantee the security and reliability of the power supply, and can better meet the demand of users; this increases the demand of users, so the return of the microgrid



investor shows a rising trend. As can be seen from Figure 2b, when the technological level changes from 1 to 3, with the improvement of technological level, the return of the operator under each subsidy model remains unchanged; that is, the return of operator is not affected by technology change. This is mainly because the operator is an intermediate stage of the microgrid industrial chain. As an operator of the microgrid, it has fixed income, which is less affected by changes in microgrid technology. From Figure 3a, it can be seen that when the technological level changes from 1 to 3, with the improvement of technological level, the return of the equipment supplier also increases. When the subsidies are paid to the investor, operator, and user, the return of the equipment supplier is equal. When the government subsidizes the investor, operator, and user, the returns of the equipment supplier are less than that when the equipment supplier is subsidized, and the growth rate of former is also less than that of latter. This is mainly due to the fact that the indirect impact of subsidizing other participants on the equipment supplier is less than the direct impact of subsidizing the equipment supplier. In summary, the improvement of the technological level in the microgrid system is conducive to improving the construction quality of the microgrid system and satisfying the demand of users, thereby enhancing the return of all participants of the microgrid, facilitating the participation of all participants, and promoting the development of the microgrid. At the same time, with the improvement of the return level of participants, all participants in the microgrid can balance their own costs and benefits, and thus the demand for subsidies will be weakened. When the technological level of the microgrid is mature, subsidies for the microgrid can be gradually canceled.

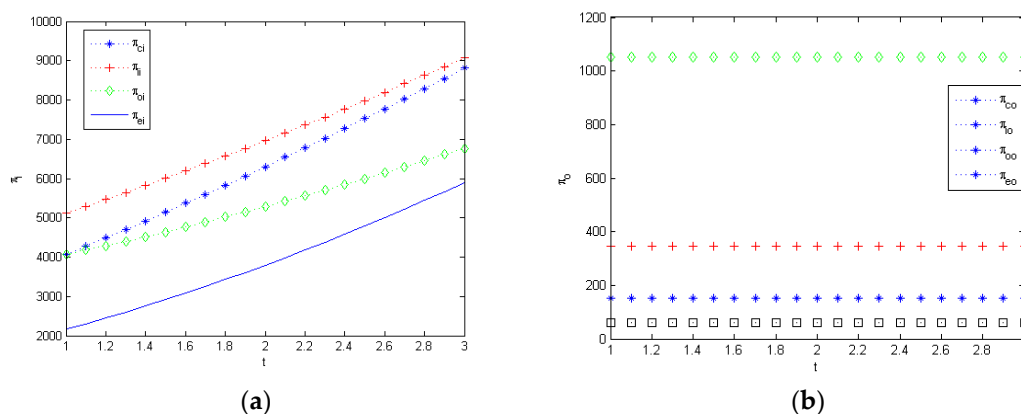


Figure 2. (a) The impact of change in  $t$  on  $\pi_i$ ; (b) the impact of change in  $t$  on  $\pi_o$ .

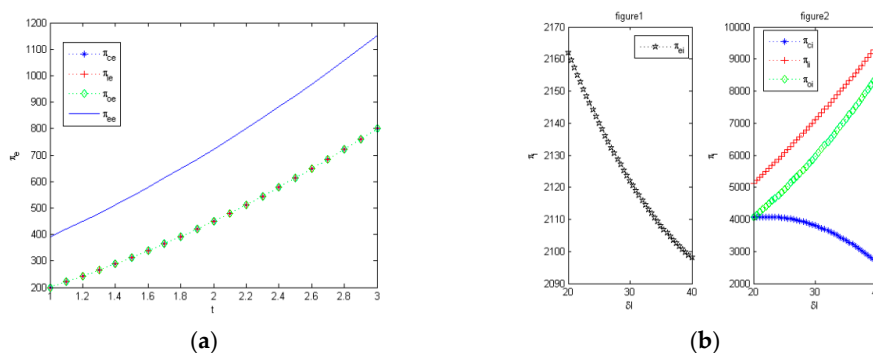


Figure 3. (a) The impact of change in  $t$  on  $\pi_e$ ; (b) the impact of change in  $\delta l$  on  $\pi_i$ .

### 5.3. Impact of Subsidy Change on Returns of All Participants

Not only does the object of subsidy affect the operational efficiency of the microgrid, but changes in the amount and method of subsidy also have an important impact on the microgrid industry chain. To this end, we draw Figures 3b and 4a,b to analyze the impact of subsidy change on the returns

of all participants in the microgrid. It can be seen from Figure 3b that when the amount of subsidy changes from 20 (0.01 CNY/kW·h) to 40 (0.01 CNY/kW·h), with the increase of subsidy, the return of the investor decreases when the user and equipment supplier are subsidized, and the return of the investor increases when the investor and operator are subsidized. This is mainly due to the fact that the returns of the investor are more affected by the investor and operator and less affected by the user and equipment supplier. From Figure 4a, it can be seen that when the amount of subsidy changes from 20 (0.01 CNY/kW·h) to 40 (0.01 CNY/kW·h), with the increase of subsidy, the return of the operator increases when the operator, user, and investor are subsidized. The operator enjoys a larger range of return when the subsidy goes to the operator than when it goes to the investor, and the operator enjoys the smallest range of return when the subsidy goes to users. The return of the operator is unchanged when the equipment supplier is subsidized. This is mainly because the return of the operator is greatly affected by the operator and investor, and less affected by the user. From Figure 4b, it can be seen that when the amount of subsidy changes from 20 (0.01 CNY/kW·h) to 40 (0.01 CNY/kW·h), with the increase of subsidy, the returns of the equipment supplier are equal and constant when the user, investor, and operator are subsidized, and the returns of the equipment supplier increase when the equipment supplier is subsidized. In summary, we can see that the subsidy is not “the higher the better”, and there is an optimal boundary. For example, in fact, through the methods of quota limit subsidy, price limit subsidy, and gradual elimination of subsidy, the development of the microgrid will be promoted as well as the adjustment of the subsidy amount to promote market-oriented operation and development of the microgrid.

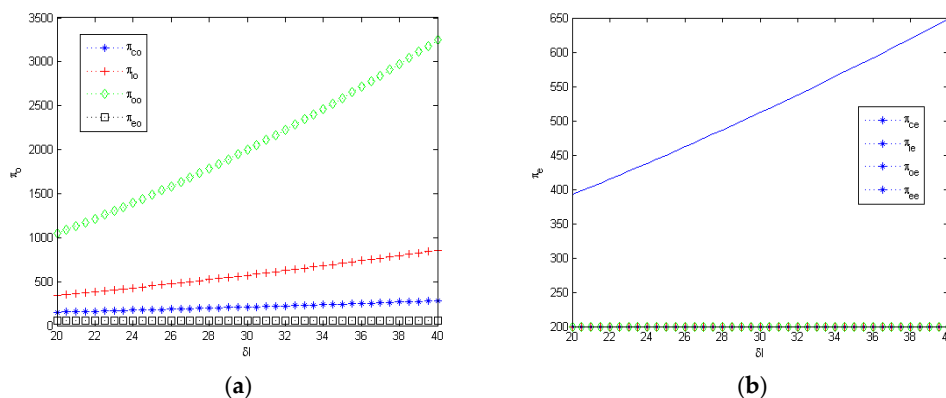


Figure 4. (a) The impact of change in  $\delta l$  on  $\pi_o$ ; (b) The impact of change in  $\delta l$  on  $\pi_e$ .

## 6. Conclusions

This article studied the subsidy issue of the microgrid industrial chain and obtained some interesting conclusions. Firstly, this article proposed and analyzed industrial chain subsidy models involving the government, investor, equipment supplier, operator, and user, and analyzed the interests of all participants. Secondly, we calculated the equilibrium price and equilibrium returns of each participant for different subsidy objects. Then, we analyzed and compared the optimal subsidy strategy and relevant influencing factors when different prices and return indicators are taken as the optimal goals of the microgrid industrial chain. The study finds that when the equipment supplier and investor are subsidized, the price indicator of the microgrid industry chain channel is lower. When the operator and user are subsidized, the price indicator of the microgrid industry chain channel is higher. It can be concluded that the government should subsidize microgrid equipment suppliers and investors to promote the investment in and development of microgrids in the early stages of microgrids or when the microgrid market is in a downturn. When microgrids develop to a certain extent or the microgrid market is saturated, the government should subsidize microgrid operators and users to improve the microgrid operation quality and stimulate the demand of users for microgrids, further promoting the development of microgrids. Finally, we verified the model in this paper through numerical analysis,

and through analysis we found that a change in technological level of the microgrid has an important impact on the return of all participants in the microgrid. At the same time, this paper also finds that subsidy has an optimal boundary. On the one hand, when the technological level of the microgrid system develops to a certain degree, the return of each participant can balance its own costs and risks, so the government can gradually reduce subsidies for the microgrid with the improvement of the technological level. On the other hand, in order to raise the efficiency of subsidy, the amount and method of subsidy should be determined prudently.

This paper analyzed the demand of different stages of microgrid development, revealing the price and return of each microgrid participant when the subsidy target differs. It also explored the influence of the subsidy object, change in technology, and subsidy on the efficiency of the microgrid. These research results provide important implications for decision-making by all participants in the microgrid industrial chain and government subsidy decisions.

In the future, we intend to study subsidy methods, such as quota limit subsidy and price limit subsidy, and to analyze the effect of different subsidy methods on subsidy object and operational efficiency of the microgrid industry chain. Furthermore, through research on the subsidy object and subsidy methods, we can deepen the understanding of microgrid subsidy and choose the optimal subsidy object and subsidy method for the construction of microgrids.

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## Nomenclature

$p_0$	Electricity price of operator sales to user (0.01 CNY/kW·h)
$p_1$	Electricity price of investor sales to operator (0.01 CNY/kW·h)
$p_2$	Electricity price of investor sales to user directly (0.01 CNY/kW·h)
$p_e$	Equipment price—equipment supplier provides to investor (0.01 CNY/kW·h)
$D_0$	Electricity demand—quantity of users for operator (0.1 billion kW·h)
$D_i$	Electricity demand—quantity of users for investor (0.1 billion kW·h)
$D_e$	Investor's demand function for equipment supplier (0.1 billion kW·h)
$r_0$	Total demand for electricity in microgrid market (0.1 billion kW·h)
$r_1$	Price elasticity coefficient of user for electricity sold by operator
$r_2$	Elasticity coefficient of user for price difference between operator and investor
$\theta$	Quality coefficient of microgrid supplied by investor
$\delta$	Subsidy coefficient of microgrid from government
$l$	Maximum amount of unit microgrid subsidy
$\delta l$	Unit subsidy for the development of microgrid (0.01 CNY/kW·h)
$\varepsilon_i$	Influence coefficient of subsidy on investor cost
$\varepsilon_e$	Influence coefficient of subsidy on equipment supplier cost
$\varepsilon_o$	Influence coefficient of subsidy on operator cost
$\varepsilon_c$	Influence coefficient of subsidy on user demand
$c_i$	Investment cost of investor (0.01 CNY/kW·h)
$c_o$	Operating cost of operator (0.01 CNY/kW·h)
$c_e$	Technological cost of equipment supplier (0.01 CNY/kW·h)
$\pi_i$	Return of investor (0.001 billion CNY)
$\pi_o$	Return of operator (0.001 billion CNY)
$\pi_e$	Return of equipment supplier (0.001 billion CNY)

q	Microgrid project quality
$h_0$	Total demand of investor for equipment supplier (0.1 billion kW·h)
$h_1$	Price demand elasticity coefficient of investor for equipment supplier
$h_2$	Quality demand elasticity coefficient of investor for equipment supplier
$\rho$	Technological coefficient of equipment supplier
t	Technological level of equipment supplier
k	Technological cost elasticity coefficient

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