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Incentive Mechanism of Micro-grid Project Development

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Abstract: Due to the issue of cost and benefit, the investment demand and consumption demand of micro-grids are insufficient in the early stages, which makes all parties lack motivation to participate in the development of micro-grid projects and leads to the slow development of micro-grids. In order to promote the development of micro-grids, the corresponding incentive mechanism should be designed to motivate the development of micro-grid projects. Therefore, this paper builds a multi-stage incentive model of micro-grid project development involving government, grid corporation, energy supplier, equipment supplier, and the user in order to study the incentive problems of micro-grid project development. Through the solution and analysis of the model, this paper deduces the optimal subsidy of government and the optimal cooperation incentive of the energy supplier, and calculates the optimal pricing strategy of grid corporation and the energy supplier, and analyzes the influence of relevant factors on optimal subsidy and incentive. The study reveals that the cost and social benefit of micro-grid development have a positive impact on micro-grid subsidy, technical level and equipment quality of equipment supplier as well as the fact that government subsidies positively adjust the level of cooperation incentives and price incentives. In the end, the validity of the model is verified by numerical analysis, and the incentive strategy of each participant is analyzed. The research of this paper is of great significance to encourage project development of micro-grids and to promote the sustainable development of micro-grids.

Keywords: micro-grid; project development; incentive mechanism; investment demand; consumption demand

1. Introduction

The micro-grid as one of the most important utilization forms of renewable energy and clean energy, and as a result, it has received much attention. The characteristics of the micro-grid using renewable energy to generate electricity can improve the utilization rate of renewable energy and clean energy, reduce power system carbon emissions [1]. The characteristics of the local generation and consumption of electricity in the micro-grid can make full use of scattered renewable energy, increase the utilization of renewable energy and increased the opportunity of renewable energy accessing the large power grid. At the same time, as an important form of the smart grid, the micro-grid conforms to the intelligent trend of the power system, which can meet the differentiated demand of the electricity market. In order to promote energy conservation, carbon emissions reduction as well as structural reform of energy supply, many countries in the European Union, as well as the United States, Japan and other countries have issued relevant policies and supportive plans to promote the development of micro-grid projects [2–4]. At the same time, China's Thirteenth Five Year Plan for Electricity Development also incorporated micro-grids as an important way of energy restructuring and power system reform to encourage the development of micro-grids [5,6]. As a result, the issue of how to promote the development of micro-grids has become an important topic.

With the development of the micro-grid, the research on micro-grids has also increased each year. Some research has focused on the technological field of micro-grids, such as, power generation technology [7,8], energy storage technology [9,10], control and protection technology [11,12], energy exchange technology [13,14], micro-grid system optimization [15,16] and other key technologies. Other research has focused on micro-grids from the perspective of economy and management, including costs and benefits of investment [17], the market operation mechanism [18], social benefits and social welfare effects [19], auction mechanism [20], and cooperation between stakeholders of micro-grid [21]. However, compared with other aspects of micro-grid research, the research on the incentive of micro-grid project development is relatively scarce. In the development of micro-grid projects, due to the technical difficulty and high cost in the early stages, the economic benefits of project development are low and the investment demand is insufficient. Low profits generated from developing micro-grid projects also demotivate other participants and decrease their effort level. The high cost of micro-grid project development leads to a high electricity price, which in turn leads to insufficient consumption demand of micro-grids. Therefore, during the development of micro-grids, the externality characteristic of micro-grids requires government participation in the development of micro-grids to compensate for the social value and environmental protection value of micro-grids, improve the investment returns of micro-grids, and attract more investments in micro-grids. The characteristics of micro-grid project development such as technical difficulty and high cost, need micro-grid investors to share profits to motivate the participation of other parties, and then to work together to construct micro-grids through sharing risk and professional efficiency. The characteristics of the user demand side in micro-grids requires that investors provide the corresponding price and quality to stimulate users' consumption demand. The efficiency and quality of these incentives directly affect the initiative and effort level of participants involved in micro-grid project development, so these aspects are important for the development of the micro-grid. However, at present, the corresponding incentive mechanisms of micro-grid project development are all still relatively scarce. The incentive mechanism of micro-grid now is mainly borrowed from the large power grid. For example, the subsidy mechanism and price incentive mechanism of micro-grid are mainly borrowed from the system for renewable energy generation in large power grid. Due to the difference of technology system and market feature between large power grid and micro-grid, the existing mechanism cannot effectively agree with the micro-grid, which is not beneficial for the micro-grid development and resources allocation. The socio-technical systems approach argues that the organization's technical system determines the management of the organization [20]. The micro-grid's technology system is different from that of the large power grid, thus its industry chain and interest transmission chain are also different from the large grid. Therefore, the development of the micro-grid requires different incentive 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 [21]. In the development of micro-grid projects, the technical system and marketization characteristics of micro-grid projects therefore involve many participants. Different participants have different interests. If the incentive mechanism does not balance the interests of all parties, it will seriously affect the quality and efficiency of micro-grid project development. Therefore, in the development of micro-grid projects, the corresponding incentive mechanism is required to motivate the participation of all parties and balance their interests. However, the characteristics of the micro-grid such as market inefficiency and externality make it so that the micro-grid market cannot automatically generate effective incentive mechanism to realize the Pareto Optimality. The lack of incentive mechanism seriously affects the investment demand and consumption demand of micro-grid projects. In order to promote the investment and consumption of micro-grid projects, it is necessary to study the incentive of micro-grid project development, so as to design the corresponding incentive mechanism to promote the development of the micro-grid.

Therefore, in order to study the incentive of micro-grid project development, this paper constructs a multi-stage incentive model reflecting the interest transmission of micro-grid project development. From the perspective of the interest transmission chain and stakeholder interest, this article builds a subsidy incentive model that government subsidies for grid corporation and energy suppliers, and designs a cooperation incentive model for cooperation between energy supplier and equipment supplier, and also constructs a price incentive model for stimulating user consumption. The three-stage incentive game model developed by a two-nested leader–follower model, involved five participants (government, grid corporation, energy investor, equipment supplier and user). We solve the optimal subsidy incentive and cooperative incentive, calculate the optimal price incentive of grid corporation and energy investor for user, and analyze the impact of relevant factors on these incentives. At the same time, we analyze the impact of government subsidy, cooperation incentive and related factors on competition and cooperation among grid corporation, energy supplier and equipment supplier. Analysis of the results of the model have important reference for how to stimulate the investment demand and consumption demand of micro-grid projects and how to encourage all parties to actively and efficiently participate in micro-grid project development.

The rest of the paper is arranged as follows: in Section 2, we introduce the literature review; in Section 3, we introduce the assumptions, build the models, and analyze incentive mechanisms based on multi-player games; in Section 4, we perform a numerical analysis to further analyze incentive strategy; and in Section 5, we draw the conclusions.

2. Literature Review

Scholars have studied incentives of micro-grid project development from different perspectives. Early research, mainly from the policy point of view, studied the policy incentive demand of the micro-grid, pointed out that the development of micro-grids needed corresponding policy support, and designed corresponding policy incentive mechanisms to support the development of micro-grids. For example, Urmee et al. [22] studied the photovoltaic micro-grid project in Bangladesh, analyzed the stakeholders and key factors of the micro-grid project, and pointed out that one of the key factors in the development of micro-grids is the support from corresponding energy policies. Long et al. [19] analyzed competitive cooperation relations between micro-grid and large power grid, and analyzed the influence of micro-grid development on social welfare, and pointed out that corresponding policy mechanisms should be designed to promote the development of the micro-grid. Palit et al. [23], through research on India's micro-grid, pointed out the contribution of construction of micro-grid projects to India's electrification, and proposed that corresponding policies needed to be built on to support the development of India's micro-grids. John et al. [24] analyzed the role of micro-grids on economic growth, energy demand and environmental demand, and put forward corresponding policy suggestions to promote the development of micro-grids.

With the development of the micro-grid project practice, scholars gradually paid attention to the incentive of the cooperative development of micro-grid. Due to the high cost and technical difficulty of micro-grid project development, the development of micro-grid projects requires cooperation among all parties. Therefore, based on the stakeholder theory, scholars discussed the characteristics and interest demand of different stakeholders and sought for the basis of cooperation among stakeholders, so as to establish the corresponding cooperation incentive mechanism to promote the cooperation of all parties. Nfah et al. [25] studied the micro-grid project in Cameroon, based on the analysis of interest demands of government, users, micro-lending institutions and project owners, and put forward corresponding cooperation incentives to promote the development of the micro-grid project. Zareen et al. [26] built an optimization model by using signal game to optimize the cooperation incentive mechanism of micro-grid, and to balance the interests of all stakeholders, formed new demand side strategies for micro-grid project development. Pan et al. [21], based on the analysis of the motivations and influencing factors of micro-grid cooperation with the conventional grid, analyzed game process of cooperation between them with evolutionary game theory, to balance the interests of the stakeholders, and to form a cooperative incentive for micro-grid and conventional grid. Borah et al. [27] pointed out that the development of the micro-grid needs the support of financial and technological innovation, and put forward corresponding motivation mechanisms to coordinate interests of different stakeholders and to promote technological improvement.

In recent years, the cost and benefit issues of the micro-grid in the early stages has lead to participants lacking motivation to participate in the development of micro-grids. In order to promote the development of micro-grids, scholars have begun to pay attention to the interior of micro-gird project development, and explore incentive and subsidy problems in the development of the micro-grid. Mainali et al. [28], based on the research of the remote mountainous micro-grid project in Nepal, pointed out that the government can balance the interests of micro-grid project stakeholders through credit and subsidy mechanisms, and can electrify remote mountainous areas through the development of micro-grid projects. Faber et al. [29] studied the influence of the pricing model for consumer preferences for investment in micro-grids, and emphasized that the construction of micro-grids must satisfy the preference of consumers and minimize the inefficiency of the economy. Ramchandran et al. [30] built the game model from the perspective of renewable energy corporation, analyzed the feasibility of the micro-grid driven by photovoltaic, biomass, and a hybrid of the two, and found that the photovoltaic micro-grid with subsidy mechanism was more stable in the scenario analysis. Lo Prete et al. [31] studied how micro-grids affect the price, costs and benefits of participants in the electricity market by cooperative game, and put forward corresponding measures to motivate the development of micro-grids. Zhang et al. [32] studied the financial model which supported micro-grid development with case studies, identified the advantage of crowdfunding in micro-grid project financing, and designed interactive scenarios for stakeholders and organizations in crowdfunding. The research results provided inspiration for the incentive and policy development of micro-grid financing.

Through the literature review, we can see that improving the investment demand and consumption demand of all participants in the micro-grid and promoting the development of the micro-grid project are the key trends of the current research. It is worth mentioning that the existing research on micro-grids is mainly written from the single aspect of incentive, and lacks the perspective of interest transmission of micro-grid project development. The process of micro-grid project development is also an interest-sharing process. Interests are constantly flowing and transmitting in all stages of micro-grid project development. Stakeholders and their interest demands in each stage of the interest chain have an important impact on the development of micro-grid projects. Although research on the individual incentive of the micro-grid is advantageous to deepen understanding of different incentive mechanisms, due to the characteristics of the micro-grid, such as technology system and multiple stakeholders, if incentive mechanisms cannot reflect the interest transmission chain and stakeholder interest, it will seriously affect the quality of incentive. Therefore, we take the perspective of interest transmission chain and stakeholder interest, and build a multi-stage incentive model reflecting interest transmission of the micro-grid, in order to study the incentive problems of micro-grid project development.

3. Multi-Stage Incentive for Micro-Grid Project Development

3.1. Problem Description

In micro-grid project development, the interest transmission includes four stages, which are decision-making, investment, construction, and consumption, and involves five participants, including government, grid corporation, energy supplier, equipment supplier and user. The interests of micro-grid project development are constantly flowing and transmitting through these four stages and among the five participants. Due to the cost and benefit issues of the micro-grid in the early stages, this leads to participants in each stage having insufficient investment demand and consumer demand for the micro-grid. In order to promote the development of the micro-grid, each stage of micro-grid project development requires corresponding mechanisms to motivate all parties to participate in the project development of micro-grids, actively and efficiently.

The incentive of micro-grid project development is divided into four stages. Firstly, at the government stage, the government, g, in order to promote the development of micro-grid, according to the social benefits of micro-grid, r, formulates subsidy policy, s, to encourage investor invest in micro-grid projects. Then, at the investment stage, grid corporation, m, for example, state grid corporation of China and China southern power grid, under the background of electric system reform and structure adjustment of energy, in order to improve the utilization of renewable energy and gain more market gains, grid corporation enter into the micro-grid market to develop micro-grid projects. Energy supplier e, such as the five major power generation companies of China, regional energy investment groups, regional gas groups, regional new energy companies, and crowdfunding. Under the background of electric system reform and energy structure adjustment, government gradually opens the right of access to the power grid market. So, the energy supplier has the opportunity to access the power grid construction field, and competes with grid corporations in the micro-grid market through development incremental distribution projects. In the micro-grid investment market, grid corporation and energy suppliers, according to government subsidy s, use their own construction cost c_m, c_e and revenues π_m, π_e to decide whether to invest in the construction of the micro-grid. If they decide to invest, they will start developing micro-grid projects. Then, at the construction stage, as the main builder and operator of the main power grid, grid corporation m is a monopolist in the power market and has advantages in resources and technology of power grid construction. Due to the system attributes and resource attributes, the grid corporation has a low degree of marketization in the development of micro-grid projects. While, owing to its rich resources of power grid construction, the grid corporation usually develops micro-grids independently. The system attribute and resource attribute of the energy supplier e is different from that of the grid corporation. The energy supplier has typical market characteristics, which can respond quickly to market changes and solve market problems innovatively. However, the grid construction technologies and resources of the energy supplier are weaker than that of the grid corporation. In order to improve the quality and efficiency of micro-grid construction and ensure the smooth progress of the micro-grid project development, the energy supplier needs to improve the capacity of micro-grid construction by cooperating with other participants, especially the key equipment supplier es of micro-grid, such as the power equipment supplier, and the energy storage equipment supplier. The energy supplier e encourages the equipment supplier es to participate in cooperation by providing cooperative incentive β, and the equipment supplier works together with the energy supplier by providing their own technology t and quality q. As for energy supplier, the cooperation with the equipment supplier can break through the constraints of resources and technicalities in micro-grid construction, and this market operation method can bring innovative and differentiated schemes and prices for micro-grid construction, which will help to satisfy the diversified demands of users and enable energy suppliers to compete with grid corporations in the micro-grid market. As for the equipment supplier, the key equipment of the micro-grid, such as the power equipment and energy storage equipment, belong to the strategic emerging industries, which are the key industries encouraged by the state. The cooperation between equipment supplier and energy supplier in micro-grid development can increase benefits of the equipment supplier by sharing the profits, so that the equipment supplier has sufficient funds for related equipment production and research and development (R&D), to promote the development of the equipment supplier and related industry. Then, at the consumption stage, grid corporation m and energy supplier e compete in the micro-grid market by setting prices p_m and p_e respectively, to stimulate users' consumption demand. Finally, the price competition between them will eventually form a balance in the micro-grid market. The incentive process of micro-grid project development is shown in Figure 1.

In summary, in micro-grid project development, the government is the first leader, grid corporations and energy suppliers are the followers to invest in micro-grid projects. Then, the energy supplier is the second leader, and the equipment supplier is follower. Energy suppliers and equipment suppliers cooperate in micro-grid development so that they can compete with grid corporations in the micro-grid market for price and quality. In the nested leader–follower cooperative development model, issues below are the focus in this article, namely, to address these questions: what is the optimal subsidy government can give to grid corporations and the energy suppliers for the construction of a micro-grid? What is the optimal incentive the energy supplier provides to the equipment supplier? What is the best price for the grid corporation and the energy supplier to motivate the consumer demand of the user? What are, and how do, the factors affect the government's subsidy strategy, the cooperation incentive strategy of the energy supplier and the market pricing strategy of the micro-grid? To explore these problems, we construct the following game model.

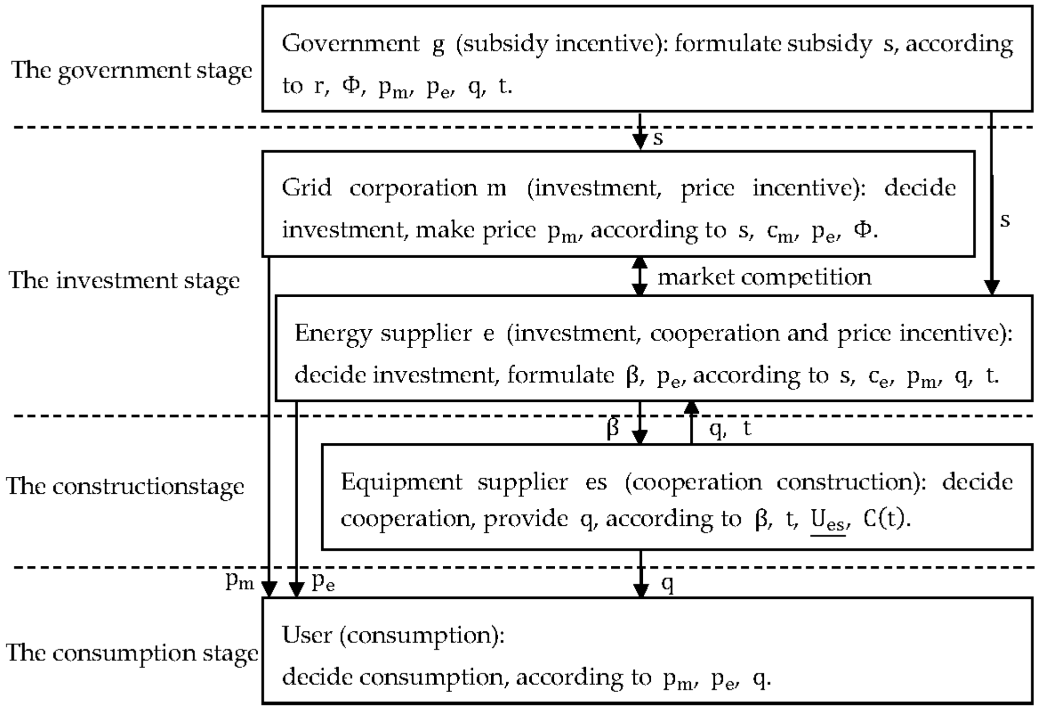


Figure 1. Multi-stage incentive of micro-grid project development.

3.2. Model Assumption

Hypothesis 1. *Micro-grids constructed by the grid corporation* (m) *and the energy supplier* (e) *are different. Namely, the market can make a distinction between the two types. Moreover, they can be substituted for each other to some extent, both of them carry out price competition in the micro-grid market, their market demand functions are associated with its unit price, and affected by the other party's price. The unit prices of them are* p_m, p_e, *the corresponding unit costs are* c_m, c_e, *the market demand functions are* $D_m = \Phi - bp_m + dp_e$, $D_e = \Phi - bp_e + dp_m (b \geq d > 0,\ p_e < p_m)$ *respectively. Among them,* Φ *is the overall market demand,* b *is price elasticity,* d *is elasticity of substitution.*

It is reasonable that under the condition of the power system reform, the micro-grid eliminates the intermediate link between power generation and power selling, so the micro-gird can compete with the grid corporation for price. The user can choose a suitable micro-grid supplier according to user demand and micro-grid price.

Hypothesis 2. *Energy supplier cooperates with equipment supplier to develop the micro-grid. On the one hand, the equipment supplier provides equipment to the energy supplier, and the quality attribute of equipment provided by the equipment supplier increases the price demand function of the energy supplier. On the other hand, the energy supplier motivates the participation of the equipment supplier by sharing part of the profits. So, the price demand function of the energy supplier becomes* $D_e = \Phi - bp_e + dp_m + \theta q$. q *is quality attribute,* θ *is quality attribute coefficient. The quality attributes of the equipment include the technical quality and configuration quality.*

Suppose that the incentive contract provided by the energy supplier to the equipment supplier for the incentive equipment supplier to participate in the development of micro-grid project is $I(\pi_{eo}) = \alpha + \beta\pi_{eo}$. α is the fixed income of the equipment supplier and is not affected by π_{eo}, π_{eo} is the profit generated by the equipment with different quality attributes provided by the equipment supplier in the micro-grid. β is profit sharing coefficient. The expression of π_{eo} is $\pi_{eo} = ht + \varepsilon$, h is the output coefficient of the technical level of equipment supplier, ε represents the influence of external uncertainties on output, satisfy $\varepsilon \sim N(0, \sigma^2)$.

It is reasonable that the higher the equipment quality attribute provided by the equipment supplier to the energy supplier in the micro-grid project, such as the higher technology quality and configuration quality of power generation and energy storage, the more likely it is to meet the diverse demand of users, which can effectively increase market demand of the micro-grid. At the same time, energy supplier shares profits to motivate the equipment supplier to participate in the micro-grid development and provide high quality equipment. The output of equipment provided by the equipment supplier is affected by its technical level and external uncertainty.

Hypothesis 3. *Suppose that the quality attribute of the equipment supplier is a function of its technical level* t, *the expression is* $q(t) = \gamma t$, γ *is technical coefficient,* $\gamma > 0$. *The technical cost of the equipment supplier satisfies the following relations* $C(t) = 1/2kt^2$, $k > 0$, k *is cost elasticity coefficient*.

It is reasonable that the higher the technical level of the equipment supplier, the higher the quality of the micro-grid equipment and corresponding solutions. With the improvement of the technology level of the equipment supplier, the cost increases incrementally.

Hypothesis 4. *In the decision-making process, government, grid corporation and energy investors are all risk-neutral rational economic entities, the equipment supplier is risk averse, the utility of equipment supplier satisfies utility function with invariant risk aversion characteristic* $U_{es} = -e^{-\rho\pi_{es}}$, ρ *is absolute risk aversion,* π_{es} *represents the revenue of the equipment supplier*.

It is reasonable from the perspective of role and information of each participant in the leader–follower model. Government, grid corporation and energy investor are the leaders in the construction of micro-grid projects. They have the ownership of the project and the distribution right of profits, while also having more project information. So, it is reasonable that they are risk-neutral. Equipment suppliers, as follow participants, are uncertain about project benefit and their own profit sharing, so it is reasonable that equipment suppliers are risk averse.

3.3. Model Establishment

In this paper, government is the first leader, and the grid corporation and the energy supplier as followers to invest in micro-grid project. The energy supplier is the second leader, and the equipment supplier as follower to participate in the development of the micro-grid project. Based on the revenue function theory and the utility theory, the decision-making functions of all participants are as follows.

3.3.1. Decision-Making Function of Government

The government, as a leader, supports and guides the development of the micro-grid by providing unit subsidy s according to the unit social benefit r brought by the micro-grid. We consider endogenous government decision-making into the decision-making model. We take the unit subsidy s as the decision-making variable, and take the micro-grid development and benefit maximization as the government's decision objectives to build the government's decision-making function. It is worth mentioning that government mainly subsidizes electricity price and cost according to generating capacity or installed capacity in practice. But no matter which way it chooses, subsidy is associated with generating capacity. Generating capacity is the index of the micro-grid supply side; according to the principle of supply–demand equilibrium, the demand quantity is equal to the amount of generating capacity in equilibrium. Therefore, we use the market demand quantity of the micro-grid as the agent for generating capacity and put it into the government's decision-making model. To sum up, the decision-making function of the government considering its own utility maximization is:

$$\max \pi_g = (r - s)(D_m + D_e) = (r - s)(\Phi - bp_m + dp_e + \Phi - bp_e + dp_m + \theta q) = (r - s)(2\Phi + (d - b)(p_m + p_e) + \theta q), \tag{1}$$

3.3.2. Decision-Making Function of Grid Corporation

The revenues of the grid corporation in constructing the micro-grid are mainly derived from two parts, namely the revenue of micro-grid development and government subsidy. The goal of the grid corporation's decision-making is to maximize its revenue, expressed as:

$$\max \pi_m = sD_m + (p_m - c_m)D_m = (s + p_m - c_m)(\Phi - bp_m + dp_e), \tag{2}$$

3.3.3. Decision-Making Function of Energy Supplier

The revenues of energy supplier in constructing the micro-grid mainly include three parts, the revenue of micro-grid development, government subsidy and the profits sharing to the equipment supplier, expressed as:

$$\pi_e = sD_e + (p_e - c_e)D_e - I(\pi_{e0}) = (\Phi - bp_e + dp_m + \theta q)(s + p_e - c_e) - I(\pi_{eo}), \tag{3}$$

Since $\varepsilon \sim N(0, \sigma^2)$, $E(\varepsilon) = 0$, the equation $E(\pi_{eo}) = ht$, $E\big(I(\pi_{eo})\big) = \alpha + \beta ht$ can be obtained. So, the expected return of energy supplier is:

$$E(\pi_e) = sD_e + (\Phi - bp_e + dp_m + \theta q)(p_e - c_e) - \beta ht - \alpha, \tag{4}$$

According to the decision-making function of the equipment supplier below, the premise of the energy supplier decision-making function is involving equipment supplier in the development of the micro-grid, satisfy the constraint:

$$\text{s.t. } U'_{es} = E(U_{es}) - 1/2\,\rho\beta^2\sigma^2 = \alpha + \beta ht - 1/2kt^2 - 1/2\,\rho\beta^2\sigma^2 \geq \underline{U_{es}}, \tag{5}$$

In equilibrium, the above constraint equation is established, thus:

$$\alpha = \underline{U_{es}} - \beta ht + 1/2\,kt^2 + 1/2\,\rho\beta^2\sigma^2, \tag{6}$$

By substituting above expression (6) in the decision-making function (4), the decision-making function of energy supplier becomes:

$$\text{Max } E(\pi_e) = sD_e + (\Phi - bp_e + dp_m + \theta q)(p_e - c_e) - \beta ht - \underline{U_{es}} + \beta ht - \tfrac{1}{2}kt^2 - \tfrac{1}{2}\rho\beta^2\sigma^2 = (\Phi - bp_e + dp_m + \theta q)(s + p_e - c_e) - \underline{U_{es}} - \tfrac{1}{2}kt^2 - \tfrac{1}{2}\rho\beta^2\sigma^2, \tag{7}$$

3.3.4. Decision-Making Function of Equipment Supplier

The equipment supplier is risk averse, and the revenues of the equipment supplier is as follows:

$$U_{es} = I(\pi_{eo}) - C(t) = \alpha + \beta(ht + \varepsilon) - 1/2kt^2, \tag{8}$$

where $\varepsilon \sim N(0, \sigma^2)$, we get $E(\varepsilon) = 0$, $Var(\varepsilon) = \sigma^2$. The expected return of the equipment supplier is:

$$E(U_{es}) = I(\pi_{eo}) - C(t) = \alpha + \beta ht - 1/2kt^2, \tag{9}$$

Since the equipment supplier is risk-averse, the theory of utility shows that there is a risk premium for its expected return. In order to make the decision, it is necessary to convert the uncertainty return into certainty return. It is known from the certainty equivalent theory that its certainty equivalent return is expected return minus the risk premium. From $Var(\varepsilon) = \sigma^2$, we obtain the risk premium of return as:

$$1/2\,\rho Var(I(\pi_{eo})) = 1/2\,\rho Var(\alpha + \beta(ht + \varepsilon)) = 1/2\,\rho\beta^2\sigma^2, \tag{10}$$

So, the certainty equivalent return of the equipment supplier is:

$$U'_{es} = E(U_{es}) - 1/2\,\rho\beta^2\sigma^2 = \alpha + \beta ht - 1/2kt^2 - 1/2\,\rho\beta^2\sigma^2, \tag{11}$$

There is a utility boundary of the equipment supplier participating in micro-grid development $\underline{U_{es}}$. Only if the utility is greater than the utility boundary $\underline{U_{es}}$, the equipment supplier will accept the incentive contract of energy supplier to participate in micro-grid development. Therefore, the participation constraints of equipment supplier are satisfied:

$$U'_{es} = E(U_{es}) - 1/2\,\rho\beta^2\sigma^2 = \alpha + \beta ht - 1/2kt^2 - 1/2\,\rho\beta^2\sigma^2 \geq \underline{U_{es}}, \tag{12}$$

The decision-making function of the equipment supplier is the maximized certainty equivalent return, that is:

$$\max U'_{es} = \alpha + \beta ht - 1/2kt^2 - 1/2\,\rho\beta^2\sigma^2, \tag{13}$$

3.4. Solution and Analysis of the Model

We start with the equilibrium of the equipment supplier in third phase by inverse method to calculate the equilibrium of the model. When the equipment supplier in equilibrium, from the first order condition, we have $\frac{\partial U'_{es}}{\partial t} = 0$. The expression of technical level t is:

$$t = \frac{h}{k}\beta, \tag{14}$$

By substituting Equation (14) in expression of q, $q(t) = \gamma t$, we get:

$$q = \frac{\gamma h}{k}\beta, \tag{15}$$

By substituting the expression of t and q in the decision-making expression of energy supplier, the decision-making function of energy supplier becomes:

$$\max E(\pi_e) = \left(\Phi - bp_e + dp_m + \frac{\gamma}{k}h\beta\theta\right)(s + p_e - c_e) - \underline{U_{es}} - \frac{1}{2}\frac{h^2\beta^2}{k} - \frac{1}{2}\rho\beta^2\sigma^2, \tag{16}$$

Energy supplier makes decisions based on price p_e and profit sharing for equipment supplier β, so from first order condition available in equilibrium we have $\frac{\partial E(\pi_e)}{\partial \beta} = 0$, $\frac{\partial E(\pi_e)}{\partial p_e} = 0$. Take the derivative of Equation (16) with respect to β and p_e, we get:

$$\beta^* = \frac{\gamma h\theta(s + p_e - c_e)}{h^2 + k\rho\sigma^2}, \tag{17}$$

$$p_e^* = \frac{1}{2b}\left(dp_m + \Phi + bc_e + \theta\frac{\gamma h}{k}\beta - bs\right), \tag{18}$$

Grid corporation makes decisions based on price p_m, so from first order condition available in equilibrium we have $\frac{\partial \pi_m}{\partial p_m} = 0$. Take the derivative of decision-making function of grid corporation Equation (2) with respect to p_m, we get:

$$p_m^* = \frac{1}{2b}(dp_e + \Phi + bc_m - bs), \tag{19}$$

Since expressions of p_e^* and p_m^* are nested each other, so simplify expressions of p_e^* and p_m^*, we get:

$$p_e^* = \frac{(2b + d)\Phi + 2b^2c_e + bdc_m + \frac{2b\gamma h\theta}{k}\beta - b(2b + d)s}{4b^2 - d^2}, \tag{20}$$

$$p_m^* = \frac{(2b + d)\Phi + 2b^2c_m + bdc_e + \frac{d\gamma h\theta}{k}\beta - b(2b + d)s}{4b^2 - d^2}, \tag{21}$$

Since Equations (20) and (21) contain β and Equation (17) β^* contains p_e, simplify the simultaneous equation group of Equations (17), (20) and (21), we have:

$$\beta^* = \frac{k\gamma h\theta\left((2b^2 - bd - d^2)s + (2b + d)\Phi + bdc_m - (2b^2 - d^2)c_e\right)}{k(h^2 + k\rho\sigma^2)(4b^2 - d^2) - 2bh\gamma^2\theta^2}, \tag{22}$$

$$p_e^* = \frac{(2b+d)\Phi + 2b^2c_e + bdc_m - b(2b+d)s}{4b^2 - d^2} + \frac{2b\gamma^2h^2\theta^2\left(\frac{1}{(2b-d)}\Phi + \frac{bd}{(4b^2-d^2)}c_m - \frac{(2b^2-d^2)}{(4b^2-d^2)}c_e\right) - 2b\gamma^2h^2\theta^2\frac{b-d}{(2b-d)}s}{k(h^2+k\rho\sigma^2)(4b^2-d^2) - 2bh\gamma^2\theta^2}, \quad (23)$$

$$p_m^* = \frac{(2b+d)\Phi + 2b^2c_m + bdc_e - b(2b+d)s}{4b^2 - d^2} + \frac{d\gamma^2h^2\theta^2\left(\frac{1}{(2b-d)}\Phi + \frac{bd}{(4b^2-d^2)}c_m - \frac{(2b^2-d^2)}{(4b^2-d^2)}c_e\right) - d\gamma^2h^2\theta^2\frac{b-d}{(2b-d)}s}{k(h^2+k\rho\sigma^2)(4b^2-d^2) - 2bh\gamma^2\theta^2}, \quad (24)$$

Theorem 1. *In equilibrium, the optimal unit subsidy of government for micro-grid s^* satisfies the following Equation (25), the optimal incentive of energy supplier for equipment supplier β^* satisfies following Equation (26).*

Proof. By substituting the expression of q, $q(t) = \gamma t$ and the simplified expression of β^* (Equation (22)) in the decision-making function of government, and seek the optimal decision-making of government. The government optimizes the endogenous decision-making according to s, satisfies $\frac{\partial \pi_g}{\partial s} = 0$ in equilibrium. Take the derivative of decision-making function of government with respect to s. We have,

$$s^* = \frac{(2b\Phi - b(b-d)(c_m+c_e) - 2b(b-d)r)\left(k(h^2+k\rho\sigma^2)(4b^2-d^2) - 2bh\gamma^2\theta^2\right)}{4b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2) - 2bh\gamma^2\theta^2) + 2(d-b)(2b+d)(3b-2d)\gamma^2h^2\theta^2} + \frac{\gamma^2h^2\theta^2\left(b(2b+d)\Phi + b^2dc_m - b(2b^2-d^2)c_e - r(b-d)(6b^2-bd-2d^2)\right)}{4b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2) - 2bh\gamma^2\theta^2) + 2(d-b)(2b+d)(3b-2d)\gamma^2h^2\theta^2}, \quad (25)$$

The optimal subsidy government provides for development of micro-grid is s^*, that is government subsidizes s^* can support and guide grid corporation and energy investors to invest and develop micro-grid effectively, and can ensure the quality of micro-grid development. Apply s^* into removable variables equation of β^* (Equation (22)), we have the optimal β^*:

$$\beta^* = \frac{(2b+d)\Phi + bdc_m - (2b^2-d^2)c_e)}{k(h^2+k\rho\sigma^2)(4b^2-d^2) - 2bh\gamma^2\theta^2} + \frac{k\gamma h\theta(b-d)(2b+d)}{k(h^2+k\rho\sigma^2)(4b^2-d^2) - 2bh\gamma^2\theta^2} * \left(\frac{(2b\Phi - b(b-d)(c_m+c_e) - 2b(b-d)r)\left(k(h^2+k\rho\sigma^2)(4b^2-d^2) - 2bh\gamma^2\theta^2\right)}{4b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2) - 2bh\gamma^2\theta^2) + 2(d-b)(2b+d)(3b-2d)\gamma^2h^2\theta^2} + \frac{\gamma^2h^2\theta^2\left(b(2b+d)\Phi + b^2dc_m - b(2b^2-d^2)c_e - r(b-d)(6b^2-bd-2d^2)\right)}{4b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2) - 2bh\gamma^2\theta^2) + 2(d-b)(2b+d)(3b-2d)\gamma^2h^2\theta^2}\right), \quad (26)$$

The best incentive energy supplier provides for equipment supplier is β^*. That is energy supplier provides incentive β^* can effectively motivate the initiative and effort of equipment supplier to participate in the cooperative development of micro-grid, and can ensure the efficiency and quality of cooperative development. Theorem 1 is proofed. □

By Theorem 1, the optimal subsidy and incentive exist in the interest chain of cooperative development of micro-grid. At the same time, from the solution process and expression of optimal subsidy and incentive, we can see the schemes' formulation of subsidy and incentive should take into account the influence of related factors. More concretely, the government should formulate a subsidy scheme in consideration of the influence of related factors, such as social benefits, market demand, market competition condition and the technical level of micro-grid to support and guide the investment of the micro-grid reasonably. The energy supplier should develop an incentive scheme taking into account the impact of related factors, such as subsidy, market return and technical level in order to promote the participation of the equipment supplier effectively.

Theorem 2. *The optimal pricing of the grid corporation p_e^* and optimal pricing of the energy supplier p_m^* in equilibrium are satisfying the following Equations (27) and (28).*

Proof. By substituting s^* in removable variables equation of p_e^* and p_m^* (Equations (23) and (24)), we get the optimal p_e^*:

$$p_e^* = \frac{(2b+d)\Phi + 2b^2c_e + bdc_m}{4b^2-d^2} + \frac{2b\gamma^2h^2\theta^2\left(\frac{1}{(2b-d)}\Phi + \frac{bd}{(4b^2-d^2)}c_m - \frac{(2b^2-d^2)}{(4b^2-d^2)}c_e\right)}{k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2} - \frac{b\left(k\left(h^2+k\rho\sigma^2\right)\left(4b^2-d^2\right)-2bh\gamma^2\theta^2\right)+2b(b-d)\gamma^2h^2\theta^2}{(2b-d)(k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2)} * \left(\frac{(2b\Phi - b(b-d)(c_m+c_e)-2b(b-d)r)\left(k\left(h^2+k\rho\sigma^2\right)\left(4b^2-d^2\right)-2bh\gamma^2\theta^2\right)}{4b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2)+2(d-b)(2b+d)(3b-2d)\gamma^2h^2\theta^2} + \frac{\gamma^2h^2\theta^2\left(b(2b+d)\Phi + b^2dc_m - b\left(2b^2-d^2\right)c_e - r(b-d)\left(6b^2-bd-2d^2\right)\right)}{4b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2)+2(d-b)(2b+d)(3b-2d)\gamma^2h^2\theta^2}\right), \quad (27)$$

We get the optimal p_m^*:

$$p_m^* = \frac{(2b+d)\Phi + 2b^2c_m + bdc_e}{4b^2-d^2} + \frac{d\gamma^2h^2\theta^2\left(\frac{1}{(2b-d)}\Phi + \frac{bd}{(4b^2-d^2)}c_m - \frac{(2b^2-d^2)}{(4b^2-d^2)}c_e\right)}{k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2} - \frac{b\left(k\left(h^2+k\rho\sigma^2\right)\left(4b^2-d^2\right)-2bh\gamma^2\theta^2\right)+d(b-d)\gamma^2h^2\theta^2}{(2b-d)(k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2)} * \left(\frac{(2b\Phi - b(b-d)(c_m+c_e)-2b(b-d)r)\left(k\left(h^2+k\rho\sigma^2\right)\left(4b^2-d^2\right)-2bh\gamma^2\theta^2\right)}{4b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2)+2(d-b)(2b+d)(3b-2d)\gamma^2h^2\theta^2} + \frac{\gamma^2h^2\theta^2\left(b(2b+d)\Phi + b^2dc_m - b\left(2b^2-d^2\right)c_e - r(b-d)\left(6b^2-bd-2d^2\right)\right)}{4b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2)+2(d-b)(2b+d)(3b-2d)\gamma^2h^2\theta^2}\right), \quad (28)$$

Theorem 2 is proofed. □

p_m^* and p_e^* are the optimal price of the grid corporation and the energy supplier, respectively. Due to obvious difference of user demand, the technical scheme and the cost in micro-grid construction by the grid corporation and the energy supplier, their competition price in the he micro-grid market also have obvious distinction. By Theorem 2, the grid corporation and the energy supplier should aim at the target market according to their own advantages and disadvantages to get the market and benefits matching themselves by means of differentiated competition in the micro-grid market. When the market in equilibrium, the grid corporation and the energy supplier provide the micro-grid at the price of p_m^* and p_e^* respectively, and construct the micro-grid according to the matching scheme.

Theorem 3. *As the social benefit of the micro-grid increases, the government subsidy increases. As the cost of the grid corporation in micro-grid construction increases, the government subsidy increases. As the cost of the energy supplier in micro-grid construction falls, the government subsidy reduces.*

Proof. Take the derivative of s^* with respect to r, we get:

$$\frac{\partial s^*}{\partial r} = \frac{\gamma^2h^2\theta^2(r(d-b)(6b^2-bd-2d^2))}{4b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2)+2(d-b)(2b+d)(3b-2d)\gamma^2h^2\theta^2} = \frac{\gamma^2h^2\theta^2(2b+d)(3b-2d)}{4b(k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2)+2(2b+d)(3b-2d)\gamma^2h^2\theta^2} > 0, \quad (29)$$

$\frac{\partial s^*}{\partial r} > 0$ indicates that the bigger the social benefit of the micro-grid, the higher the government's subsidy for the micro-grid. That is, the more social return such as environmental protection value, energy structure adjustment value and diversified user demands satisfaction are brought by micro-grid, the more subsidy government should provide to encourage the development of micro-grid project.

Take the derivative of s^* with respect to c_m, we get:

$$\frac{\partial s^*}{\partial c_m} = \frac{b(d-b)\left(k\left(h^2+k\rho\sigma^2\right)\left(4b^2-d^2\right)-2bh\gamma^2\theta^2\right)+bbd\gamma^2h^2\theta^2}{4b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2)+2(d-b)(2b+d)(3b-2d)\gamma^2h^2\theta^2} > 0, \quad (30)$$

Since the grid corporation has rich resources, advanced technology, and lower transaction costs, the grid corporation has a lower cost than the energy supplier in micro-grid construction. $\frac{\partial s^*}{\partial c_m} > 0$ indicates that the higher the construction cost of the grid corporation, the higher the subsidy the government will give to the micro-grid. That is, when the grid corporation spends a lot of costs in micro-grid construction, which reflects the huge construction costs of the micro-grid project at present, the government should provide more subsidies to balance the costs and benefits of the construction of the micro-grid to encourage the development of micro-grid.

Take the derivative of s^* with respect to c_e, we get:

$$\frac{\partial s^*}{\partial c_e} = \frac{b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2)+b(d^2-2b^2)\gamma^2h^2\theta^2}{4b(d-b)(k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2)+2(d-b)(2b+d)(3b-2d)\gamma^2h^2\theta^2} > 0, \tag{31}$$

$\frac{\partial s^*}{\partial c_e} > 0$ indicates that when the construction cost of the energy supplier descends, the subsidy of the government for the micro-grid reduces. That is, with the progress of technology and the development of relevant systems, the construction cost of the micro-grid decreases gradually under the condition of market-oriented operation, the micro-grid project can well balance the cost and benefit, so the subsidy provided by the government should be reduced as appropriate. Theorem 3 is proofed. □

By Theorem 3, social return and construction cost are positively affecting the unit subsidy. Therefore, the optimal subsidy scheme of the government should be reasonably designed according to the social return and construction cost of the micro-grid. Only considering these factors, the subsidy scheme can effectively balance the cost and benefit of construction, operation and implementation of the micro-grid. At the same time, through balancing cost and benefit of the micro-grid, optimized subsidy schemes can effectively support and guide the grid corporation and the energy supplier to invest and develop micro-grids, which is beneficial to promote reasonable and healthy development of the micro-grid.

Theorem 4. *As the energy supplier get more subsidies, the energy supplier will share more profits with the equipment supplier. As the technical level and equipment quality of the equipment supplier increase, the energy supplier will share more profits with the equipment supplier.*

Proof. Take the derivative of β^* with respect to s, we get:

$$\frac{\partial \beta^*}{\partial s} = \frac{k\gamma h\theta(b-d)(2b+d)}{k(h^2+k\rho\sigma^2)(4b^2-d^2)-2bh\gamma^2\theta^2} > 0, \tag{32}$$

$\frac{\partial \beta^*}{\partial s} > 0$ shows that as government subsidy increases, the energy supplier will share more profits to the equipment supplier. That is, the energy supplier can better balance cost and benefit under government subsidy, and have more profits to share with the equipment supplier.

From $\frac{\partial U}{\partial t} = 0$, we have $t = \frac{h}{k}\beta$. By substituting t in the Equation (15), we have $q = \gamma t = \frac{\gamma h}{k}\beta$. Organize the expressions of t and q, we have $\beta = \frac{k}{h}t$, $\beta = \frac{k}{\gamma h}q$. Take the derivative of β with respect to q and t, we get the equation $\frac{\partial \beta^*}{\partial q} = \frac{k}{\gamma h} > 0$, $\frac{\partial \beta^*}{\partial t} = \frac{k}{h} > 0$.

$\frac{\partial \beta^*}{\partial q} = \frac{k}{\gamma h} > 0$, $\frac{\partial \beta^*}{\partial t} = \frac{k}{h} > 0$ show that the higher the technical level of the equipment, the higher the quality of equipment provided by the equipment supplier. The energy supplier needs to allocate more profits to the equipment supplier. That is, the equipment supplier can gain more profits and returns by improving their technical level and quality of equipment. Theorem 4 is proofed. □

By Theorem 4, government subsidy, technology level and equipment quality of the equipment supplier positively affect the incentive level. Therefore, the optimal incentive of the energy supplier for the equipment supplier should be designed based on government subsidy, technology level and equipment quality of the equipment supplier. Only the incentive scheme considering these factors can effectively promote the participation of the equipment supplier in the development of the micro-grid and improve the participation motivation and effort of the equipment supplier. The equipment supplier can earn more profits in micro-grid construction from this optimal incentive scheme, and they have sufficient funds to carry out production and technological innovation, which will be conducive to the growth and development of the equipment supplier.

Theorem 5. *As government subsidy increases, the unit price of the micro-grid built by the grid corporation and the energy supplier descends. The unit price of the micro-grid built by the energy supplier increases along with the increase of quality and technical level of equipment provided by the equipment supplier.*

Proof. Take the derivative of p_e^* and p_m^* with respect to s respectively, we get:

$$\frac{\partial p_e^*}{\partial s} = -\frac{b\left(k\left(h^2 + k\rho\sigma^2\right)\left(4b^2 - d^2\right) - 2bh\gamma^2\theta^2\right) + 2b(b-d)\gamma^2h^2\theta^2}{(2b-d)\left(k\left(h^2 + k\rho\sigma^2\right)\left(4b^2 - d^2\right) - 2bh\gamma^2\theta^2\right)} < 0, \tag{33}$$

$$\frac{\partial p_m^*}{\partial s} = -\frac{b\left(k\left(h^2 + k\rho\sigma^2\right)\left(4b^2 - d^2\right) - 2bh\gamma^2\theta^2\right) + d(b-d)\gamma^2h^2\theta^2}{(2b-d)\left(k\left(h^2 + k\rho\sigma^2\right)\left(4b^2 - d^2\right) - 2bh\gamma^2\theta^2\right)} < 0, \tag{34}$$

$\frac{\partial p_e^*}{\partial s} < 0$, $\frac{\partial p_m^*}{\partial s} < 0$ show that the higher the government's subsidy to the micro-grid, the lower the price of the micro-grid. That is, as the government subsidy increases, it is beneficial to balance the cost and benefit of the micro-grid construction, which is conducive to lower the price of electricity.

From $p_e^* = \frac{1}{2b}(dp_m + \Phi + bc_e + \theta\frac{\gamma h}{k}\beta - bs)$and $q = \gamma t = \frac{\gamma h}{k}\beta$, we have:

$$p_e^* = \frac{1}{2b}(dp_m + \Phi + bc_e + \theta q - bs), \tag{35}$$

$$p_e^* = \frac{1}{2b}(dp_m + \Phi + bc_e + \theta\gamma t - bs), \tag{36}$$

Take the derivative of Equations (35) and (36) with respect to q and t respectively, we get the equations,

$$\frac{\partial p_e^*}{\partial q} = \frac{\theta}{2b} > 0,\ \frac{\partial p_e^*}{\partial t} = \frac{\theta\gamma}{2b} > 0$$

Theorem 5 is proofed. □

$\frac{\partial p_e^*}{\partial q} = \frac{\theta}{2b} > 0$, $\frac{\partial p_e^*}{\partial t} = \frac{\theta\gamma}{2b} > 0$ show that as the technology level and equipment quality from the equipment supplier improve, the price of the energy supplier also increases. That is, with the improvement of technology level and quality attribute of the micro-grid constructed by the energy supplier, it is helpful for the energy supplier to meet the diversified demands of users and compete with the grid corporation. Differences between the grid corporation and the energy supplier in resources and technology results in the difference between the user groups in the micro-grid. Due to rich power grid resources and technologies, the micro-grid users of the grid corporation are mainly users with large electricity consumption and large amount of engineering. The micro-grid users of the energy supplier are mainly users with small electricity consumption, diversified demand and remote geographical location. By Theorem 5, with the improvement of technology and resources of the energy supplier, the level of micro-grid construction of the energy supplier also increases, the energy supplier can better meet the diversity of user demands and help the energy supplier compete against with the grid corporation for quality users. In the micro-grid market, the grid corporation will be forced to change and adjust to cope with the competition of the energy supplier and gain more market and return, such as by improving the quality of service and shift to marketization. In summary, the change of technology level and quality level can lead to the change of market competition and price of the micro-grid, which will help to improve the efficiency of the micro-grid market. At the same time, from Theorem 5, we can see that through improving technology and quality, reducing cost and increasing subsidy, we can effectively reduce price and promote the consumption demand of the micro-grid.

Theorem 6. *The incentive mechanism of micro-grid project development is consistent with the principle of individual rationality and incentive compatibility, and is an effective incentive mechanism.*

Proof. The mechanism design theory holds that an effective mechanism must satisfy the principle of individual rationality and incentive compatibility. From the optimal subsidy, optimal incentive and optimal price in this article, we found that, not only the participants are in equilibrium, but also the competition in the market is in equilibrium, the individual return and collective return are at the optimal level, which satisfy the principle of individual rationality and incentive compatibility. Therefore, the incentive mechanism constructed in this paper is an effective incentive mechanism. □

4. Numerical Analysis

In this section, we use numerical analysis to further verify the validity of the model and further analyze the incentives of the micro-grid. Assume that there are five participants in the micro-grid market, government g, grid corporation m, energy supplier e, equipment supplier es and user. In the market, the grid corporation m, the energy supplier e and the equipment supplier es compete and cooperate to build the micro-grid. Based on the characteristics of the micro-grid industry, hypotheses and related economic theories, we assume that the overall demand, price elasticity and substitution elasticity of the micro-grid market are $\Phi = 10$, $b = 4$, $d = 2$ respectively. The social benefit of the micro-grid is $r = 5$. The construction cost of the grid corporation and the energy supplier are $c_m = 4$, and $c_e = 5$. The quality attribute the coefficient of the energy supplier is $\theta = 0.6$. The fixed income, technical coefficient, cost elasticity coefficient, output coefficient of technical level, variance of ε, absolute risk aversion and retention utility of equipment supplier are respectively $\alpha = 0.15$, $\gamma = 0.2$, $k = 0.2$, $h = 1$, $\sigma^2 = 0.2$, $\rho = 0.5$, $\underline{U_{es}} = 0.3$. In order to analyze the variation of related factors, we assumed that the technical level of the equipment supplier changed between (1,3), while the ratio of c_e/c_m changed in (0.75, 1.25). According to the previous formula and matlab, the numerical results are shown in Table 1. Then we analyze different incentive strategies and corresponding influence factors.

Table 1. The impact of technology and cost on optimal decision-making of participants.

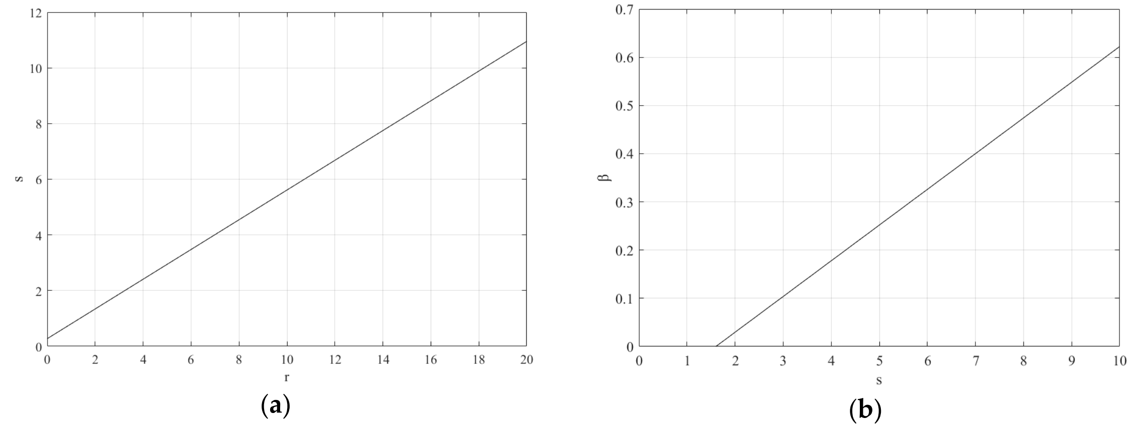
t	c_e/c_m	s^*	β^*	q	p_e^*	p_m^*	π_g	π_m	π_e	U'_{es}
1.000	1.250	4.998	0.474	0.200	9.377	6.631	3.779	101.975	63.800	0.225
1.100	1.225	4.902	0.482	0.220	9.393	6.786	7.811	100.999	64.398	0.323
1.200	1.200	4.806	0.489	0.240	9.408	6.940	12.090	100.024	64.992	0.415
1.300	1.175	4.711	0.496	0.260	9.424	7.095	16.632	99.048	65.582	0.503
1.400	1.150	4.615	0.504	0.280	9.439	7.250	21.420	98.072	66.168	0.585
1.500	1.125	4.519	0.511	0.300	9.455	7.404	26.460	97.097	66.750	0.663
1.600	1.100	4.424	0.519	0.320	9.470	7.559	31.752	96.121	67.328	0.735
1.700	1.075	4.328	0.526	0.340	9.486	7.714	37.296	95.146	67.902	0.803
1.800	1.050	4.232	0.533	0.360	9.501	7.868	43.092	94.170	68.472	0.865
1.900	1.025	4.137	0.541	0.380	9.517	8.023	49.140	93.194	69.038	0.923
2.000	1.000	4.041	0.548	0.400	9.532	8.177	55.440	92.219	69.600	0.975
2.100	0.975	3.945	0.556	0.420	9.548	8.332	61.992	91.243	70.158	1.023
2.200	0.950	3.850	0.563	0.440	9.563	8.487	68.796	90.268	70.712	1.065
2.300	0.925	3.754	0.570	0.460	9.578	8.641	75.852	89.292	71.262	1.103
2.400	0.900	3.658	0.578	0.480	9.594	8.796	83.160	88.316	71.808	1.135
2.500	0.875	3.563	0.585	0.500	9.609	8.951	90.720	87.341	72.350	1.163
2.600	0.850	3.467	0.593	0.520	9.625	9.105	98.532	86.365	72.888	1.185
2.700	0.825	3.372	0.600	0.540	9.640	9.260	106.596	85.389	73.422	1.203
2.800	0.800	3.276	0.607	0.560	9.656	9.415	114.912	84.414	73.952	1.215
2.900	0.775	3.180	0.615	0.580	9.671	9.569	123.480	83.438	74.478	1.223
3.000	0.750	3.085	0.622	0.600	9.687	9.724	126.000	82.463	75.000	1.225

4.1. Incentive Strategy of Investment Demand

In order to analyze the investment incentive strategy of the government for the grid corporation and the energy supplier, we drew Figure 2a according to previous formulae, and calculated t, s, π_g, π_m, π_e, as shown in Table 1. As shown in Figure 2a, as the social benefits of micro-grid projects increase, the government subsidy for micro-grid projects increase. As shown in Table 1, with the improvement of technical level and lower cost, the government subsidy decreases. At the same time, it can be seen that the subsidy changes between 3.08 and 4.96, which is slightly larger than that of the renewable energy subsidy standard 2–4.2 (0.1CNY/kW·h) adopted in practice. That is reasonable. Because it is different from renewable power generation constructs in renewable energy accumulation areas, the micro-grid can make full use of scattered resources and meet diversified demands of users, which makes the micro-grid have higher social benefits, so more subsidies are reasonable. It is assumed that the first line of Table 1 is the initial equilibrium level. It can be seen that the revenue is increasing, indicating that there is a revenue boundary. Only when the revenue reaches a certain level can the grid corporation and the energy supplier invest in the construction of the micro-grid. At the same time, it also can be seen from Table 1 that with the improvement of technology, the government's revenue also increases, but the subsidy decreases. This is reasonable. The basis on which the government formulates its subsidy is social benefit and market development levels—when the micro-grid investor can make profits on their own and the market efficiency improves, the government should reduce the corresponding economic incentives.

4.2. Incentive Strategy of Cooperative Development

To analyze the cooperation incentive strategy of the energy supplier to the equipment supplier, we drew Figure 2b according to previous formula, and calculated t, c_e/c_m, s, q, π_e, U'_{es}, as shown in Table 1. As can be seen from Table 1, as the revenue of energy supplier increases, the cooperation incentive increases. The increase of the equipment supplier's profit will help improve the enthusiasm of equipment suppliers to participate in cooperative development. As can be seen from Figure 2b, when technology and cost are constant, the energy supplier increases incentive for the equipment supplier as the subsidy increases. However, as shown in Table 1, with the reduction of technology and cost, the subsidy decreases, but cooperation incentive β increases rather than decreases. This is reasonable. When technology and cost change, although the reduction of subsidy reduces the incentive of cooperation, the improvement of technology and the decrease of cost are beneficial for increasing the incentive of cooperation. Because the improvement of technical level increases the contribution of the equipment supplier to the quality of the micro-grid project, the micro-grid project can obtain more market and profits and is conducive to improve the overall benefits, so the equipment supplier can also get more profit. From this we can see that the technology and quality of the equipment suppliers themselves have a stronger influence on the cooperation incentive than the government subsidy does. At the same time, it also can be seen that the profit of the equipment supplier participating in the cooperation is bounded, and this boundary increases with the improvement of the equipment supplier t and q.



(**a**) (**b**)

Figure 2. (**a**) The impact of social benefits on government subsidy; (**b**) The impact of government subsidy on cooperative incentive.

4.3. Incentive Strategy of Consumer Demand

In order to analyze the consumption incentive strategy of the grid corporation and energy supplier to the users, we calculated t, s, q, p_e, p_m, π_g, π_e and π_m according to previous formula, as shown in Table 1. As can be seen from Table 1, with the decrease of s, p_e and p_m increase. As t increases, q and the price of micro-grid p_e, p_m also increases. That is reasonable. Because, with the increase of t and q, the level at which the micro-grid meet users' demands will increase, so users will pay more fees to choose the micro-grid to replace the large power grid. As can be seen from Table 1, with the increase of t and q, the value of p_e changed from 9.38 to 9.69, and the value of p_m changed from 6.63 to 9.72, which is also reasonable. In reality, resident electricity price is generally between 5.2 and 10 (0.1 CNY/kW·h) and industrial electricity is between 8.6 and 18 (0.1 CNY/kW·h). In remote areas, electricity is generally between 9 and 34.7 (0.1 CNY/kW·h). It can be seen that micro-grid is suitable for residents with differentiated demand, some industrial electricity, as well as some remote areas and islands electricity. These places have a stronger consumer demand for micro-grid. As can be seen from Table 1, with the improvement of technology and quality, the cost of energy supplier is gradually lower than that of grid corporation, and finally the price of energy supplier is lower than that of grid corporation. It is shown that cooperation can bring professional efficiency and improve the quality and benefits of micro-grid. At the same time, it can be seen from Table 1 that with the improvement of technology and quality, not only the benefits of equipment suppliers are increased, but the profits of government, grid corporation and energy supplier are also increased. That is reasonable. Because, with the improvement of micro-grid technology and quality, it will make better use of renewable resources and will better meet the diversified demands of users, which is conducive to the improvement of overall social benefits. From numerical analysis, we can see that through providing differentiated solutions and market competition, improving the technology and quality of the micro-grid, and reducing the price of micro-grid, micro-grid investors can effectively stimulate consumers' consumption demand.

5. Conclusions

This paper studies the incentive mechanism of micro-grid project development and draws some interesting conclusions. Firstly, this paper puts forward that the government, the grid corporation, the energy supplier, the equipment supplier and the user are the main participants in the development of a micro-grid project, and analyzes and deduces the interest demands and return functions of the participants. Secondly, we derive the optimal subsidy and optimal cooperation incentive in equilibrium through the calculation of multi-player game of government, grid corporation, energy supplier and equipment supplier. Thirdly, the analysis concludes that the social benefits, the construction cost of the grid corporation and the construction cost of the energy supplier have a positive impact on the subsidy for the micro-grid project. It is also concluded that the government subsidy quota, the technical level of the equipment supplier and the quality level of the equipment have a positive influence on the cooperation incentive. Fourthly, through the proof and the numerical analysis, we conclude that the subsidy of government can reduce the optimal pricing of the grid corporation and the energy supplier, and the technical level and quality level of the equipment supplier have a positive effect on pricing. Finally, we point out that when the government, the grid corporation and the energy supplier are all risk neutral rational economic entities, and the equipment supplier is risk averse, then the incentive mechanism based on the transmission of interest is an effective incentive mechanism of micro-grid project development. Through an example analysis, we find government subsidy, cooperation incentive and the price of the micro-grid are inversely related. Although this result is contrary to intuition and earlier studies, it is nonetheless reasonable. Because, compared with the technology, subsidy has less influence on the cooperative profit sharing and micro-grid price; rather, it is the technical level and quality level of micro-grid that are the key factors in determining the cooperation of profit sharing and micro-grid pricing. At the same time, it can be seen from the example that with the improvement of technology level and quality level, the returns of all participants in the micro-grid show an increasing trend. Therefore, in order to obtain more benefits, we need to further improve the technology level and quality level of the micro-grid. These results form an incentive mechanism for micro-grid project development, which provide an important reference for the development of future micro-grid projects.

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Nomenclature

g	Government
r	Social benefits of micro-grid
s	Government subsidy
m	Grid corporation
e	Energy supplier
es	Equipment supplier
Φ	Overall market demand (billion kW·h)
D_m	Market demand of grid corporation (billion kW·h)
D_e	Market demand of energy supplier (billion kW·h)
b	Price elasticity
d	Elasticity of substitution
c_m	Unit construction cost of grid corporation (0.1CNY/kW·h)
c_e	Unit construction cost of energy supplier (0.1CNY/kW·h)
π_m	Revenue of grid corporation (0.1 billionCNY)
π_e	Revenue of energy supplier (0.1 billionCNY)
π_{es}	Revenue of equipment supplier (0.1 billionCNY)
β	Profit sharing coefficient provided by energy supplier
t	Technology level provided by equipment supplier
γ	Technical coefficient provided by equipment supplier
k	Cost elasticity coefficient
$C(t)$	Technical cost of the equipment supplier
q	Quality attribute provided by equipment supplier
θ	Quality attribute coefficient provided by equipment supplier
p_m	Unit price of micro-grid constructed by grid corporation(0.1CNY/kW·h)
p_e	Unit price of micro-grid constructed by energy supplier(0.1CNY/kW·h)
$I(\pi_{eo})$	Incentive contract provided by the energy supplier
π_{eo}	Profit generated by equipment with different quality attributes
h	Output coefficient of the technical level
α	Fixed income of equipment supplier
ε	Influence of external uncertainties on output
U_{es}	Utility of equipment supplier
$\underline{U_{es}}$	utility boundary of equipment supplier
ρ	Absolute risk aversion

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