

# Capacity investment decision and coordination model research in distributed power generation

Wenhui Zhao, Xiaomei Wang

**Abstract**—Distributed power generation (DG) projects have the advantages of being close to load centers and easy to consumption. These characteristics, together with the incentive of subsidy policy, have led to the rapid development of DG projects in China. However, subsidies put a lot of fiscal pressure to the government. We need to explore other models that can encourage DG investment. Based on the supply chain coordination theory, both centralized and decentralized decision-making modes are discussed in the paper. The capacity investment and coordination models of profit distribution and risk allocation between the DG owners and investors are designed under the constraint of market demand. The research shows that the risk sharing model and the modified profit sharing model can achieve the optimal DG capacity in the centralized decision-making mode. Both of them can realize the coordination of the supply chain. The design and implementation of these mechanisms can promote the scientific and sustainable development of China's DG to some extent.

**Index Terms**—distributed generation, capacity investment, supply chain coordination, risk sharing; profit sharing.

## I. INTRODUCTION

In order to protect the environment and to realize transition in the energy portfolio, China attempts to boost the development of electricity from renewable energy source (RES-E). The third request for comment about the implementation of the renewable portfolio standards (RPS) have been issued by the National Energy Administration (NEA) in 2018. It stresses that power construction and operation management should be carried out in accordance with the principle of priority development and full consumption of the RES-E. RES-E trading should play a pivotal role in the future electricity market.

There exist centralized and distributed modes of renewable energy (RE) development. In recent years, China's centralized RE development waxed and waned. The north of China with concentrated wind and solar resources confronts the difficulty in RES-E consumption, since these regions are far away from the power load centers. The RES-E development and utilization in China is characterized by regional surplus and shortage in total amount. In particular, the eastern regions are close to the power load center, but it lacks high-quality RE generation projects. Compared with the traditional centralized development, distributed generation (DG) was strongly supported by policies because it has high consistency

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with the power grid and the load, and is adjacent to consumers. According to China's 13th Five-Year Plan for energy development, the aggregate capacity of installed distributed photovoltaic generation should reach 60 GW by 2020. However, there is still large room for distributed energy development. On March 20th, 2018, the NEA issued the DG Management Approach (Draft for Comment). It announces that the DG development and market trading will be the main contents of the electricity market reform. On the other hand, at the end of 2017, the aggregate capacity of installed distributed photovoltaic generation in China was 29.66 GW, by an increment of 190% in each year. Furthermore, at the end of 2018, China's capacity of installed distributed photovoltaic even reached 50.61 GW. Nevertheless, the DG projects have a low rate of return and high risk at the same time. With the rocketing development of wind power, photovoltaic and other REs, the government is confronted with a mammoth subsidy deficit. For sustainable development, it is particularly important to study the investment of DG projects against the unprecedented context. Moreover, we expand the capacity investment by designing reasonable incentive models under the constraint of market demand

## II. LITERATURE REVIEW

As for the development of DG, some scholars have carried out research from the technical aspects of reducing line loss [1], power forecast [2], energy storage and impacts on the grid [3]. The investment planning involves the location and construction scale of DG projects. Ref. [4] and [5] respectively obtain the optimal scale and site selection decision for investment and construction of DG projects through the cost-benefit analysis method and the Binary Particle Swarm Optimization method. Ref. [6] studies the influence of multiple uncertain factors on the location and scale of DG projects by genetic algorithm (GA) approach. In addition, the theory of real option is an important theory for project investment. Ref. [7] Researches the investment decision making of natural gas-fired distributed power generators with real options. The generators can choose to execute, delay or abandon long-term expansion plans based on new realities of electric power demand. The real option theory is also mainly applied to the analysis of investment model in case of variable factors. Ref. [7] studies that postponing or giving up the investment plan can save the capital cost in case of adverse power demand and help the DG project to reduce financial risks under the condition of limited capital acquisition. Ref. [8] draws a conclusion that high price volatility increases the value of investment opportunities in the condition of uncertain prices, and it is optimal to wait for higher prices than the net present value break-even price.

In addition to the above research results, the cooperative relationship between project participants and benefit

distribution analysis are also the research perspectives of DG project investment. Ref. [9] establishes a comprehensive benefit evaluation model based on different commercial operation modes and different distributed power/grid-connected methods. Ref. [10] proposes the fair distribution of profits among participants in distributed energy networks (DEN) based on the cooperative game theory. There are two types of DG investment modes: the owner's unilateral investment and the independent investor's investment (power grid enterprise, power generation enterprise or energy conservation enterprise). The two major types of investment modes are consistent with the division of centralized and decentralized decision-making in supply chain theory [11]-[12]. They all research the two-stage supply chain model composed of a generator and an electricity retailer and the one-stage supply chain model. There is also a cooperative game relationship between investors and DG owners. In the investment and generation activities, there will be a case that the investors invest in the construction of excessive capacity but it cannot be fully consumed by the market; there may also be another case that DG owners miss out on some of the profits from selling electricity due to insufficient investment. On the one hand, it is owners' demand for expanding the generation capacity; but on the other hand, it is investors' conservative investment. Based on this, effective capacity investment decision and coordination model should be designed to increase the confidence of investors. The model should promote the two sides to invest the optimal DG capacity to meet market demand and realize the maximization of the expected profits of both sides.

The complete DG project is divided into three parts: investment and construction, power generation and operation, and online sales, each of which corresponds to a different mode, as shown in Figure 1.

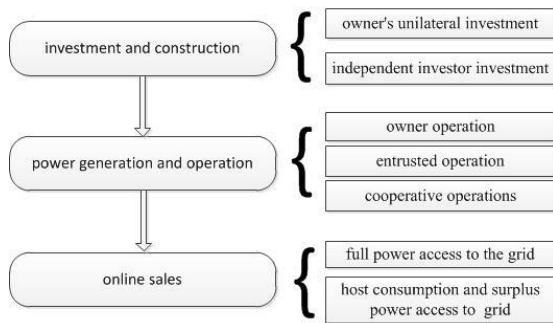


Figure.1 Model division of distributed power generation

The paper focuses on the distribution of the profits and coordination of both parties, including the owner's unilateral investment and independent investor investment in the case of owner operation and full power access to the grid. Firstly, construct the income functions of owners and investors from the two scenarios of centralized decision-making and decentralized decision-making, and obtain the optimal power generation capacity that needs to be invested in the coordination of supply chain. Then, based on the actual situation of decentralized decision-making of investors and owners, the risk sharing model is constructed from the perspective of risk, and the profit sharing model is constructed from the perspective of profit. The design of the two models is compared, and the model that cannot achieve supply chain coordination is improved.

### III. MATHEMATICAL MODEL

#### A. Model Description

This paper discusses the supply chain problem consisting of an investor and a DG owner. The investor provide production funds for the owner, and the latter conducts the construction, operation and power generation of the distributed project on the basis of the financial support from the investor. In the mode of full power access to the grid, the income of the owner comes from the electricity sales income plus the electricity price subsidy minus the various costs of power generation, and the income of the investor comes from the return from the DG owner.

#### B. Basic Parameters

The parameters and symbol definitions required by the model are shown in Table 1:

Table.1 Parameters and descriptions	
Parameters	Description
$Q$	Generation capacity of the DG project
$P$	A feed-in tariff per unit of electricity
$p_s$	Price subsidy per unit of on-grid electricity
$b$	Cost per unit of electricity of the owner (project investment cost, operation and maintenance cost, financial expense, etc.)
$c$	Costs per unit of electricity of the investor (The total investment funds are equally distributed to the average investment capital per unit of electricity.)
$h$	Loss to the investor when over-investment
$g$	Loss to the owner when the investment is insufficient
$S(Q)$	Expected sales volume

The amount of electricity generated by DG projects will be traded in the electricity market, so the model is constrained by the demand of the electricity market. In order to ensure the wide applicability of the model, it is assumed that the electricity market demand  $x$  is subject to IGFR distribution [13] (such as uniform distribution, normal distribution, exponential distribution, gamma distribution, etc.).  $f(x)$  and  $F(x)$  represent the probability density function and distribution function.  $F'(x) = f(x)$ ,  $f(x) > 0$ ,  $\bar{F}(x) = 1 - F(x)$ ,  $0 < \bar{F}(x) < 1$ .  $\mu$  is the mean value of this distribution,  $E(x) = \mu$ .

With the constraints of market demand,  $S(Q)$  is defined as the expected sales volume of  $Q$ .

$$S(Q) = E \min[x, D] = \int_0^Q xf(x)dx + \int_Q^{+\infty} Qf(x)dx \quad (1)$$

$$= Q - \int_0^Q F(x)dx = \int_0^Q \bar{F}(x)dx$$

The first and the second derivatives of  $S(Q)$  with respect to  $Q$

are  $S'(Q)$  and  $S''(Q)$ .  $S'(Q) = \bar{F}(Q) > 0$ ,  $S''(Q) = -f(Q) < 0$ . Therefore,  $S(Q)$  is a convex function of  $Q$ , and it has a unique local maximum.

### C. Model Establishment

This section studies the two modes of centralized and decentralized decision-making from the DG owner and the investor. We aim to analyze the optimal power generation capacity in different modes and compare them.

#### a) Centralized Decision-making Mode

If the DG investor and the owner belong to the same enterprise, a central decision maker will decide the amount of power generation capacity to be invested. The expected profit for the entire supply chain is described as

$$\Pi_1(Q) = E[(p + p_s) \min[Q, x] - bQ - h(Q - x)^+ - g(x - Q)^+] \quad (2)$$

Where,  $[x]^+ = \max\{x, 0\}$

In the formula, the first item is expected revenue of electricity sales, the second item is the production cost, the third and the fourth items are losses caused by over-investment and under-investment respectively. By the derivation process is shown in Appendix A, we get

$$\Pi_1(Q) = (p + p_s + h + g)S(Q) - (b + h)Q - g\mu \quad (3)$$

Where,  $\mu$  is the mean value demand of the power market  $x$ .

Since  $S(Q)$  is a convex function of  $Q$ ,  $\Pi_1(Q)$  is also a convex function of  $Q$ . It has a unique local maximum value. Let its first derivative be  $d\Pi_1(Q)/dQ = 0$ , we can get  $(p + p_s + h + g)\bar{F}(Q) - (b + h) = 0$ . The optimal DG capacity under the centralized decision-making mode can be obtained in Formula (4). (The value of  $\bar{F}(Q)$  is used to represent the investment capacity indirectly).

$$\bar{F}_1(Q^*) = \frac{b + h}{p + p_s + h + g} \quad (4)$$

#### b) Decentralized Decision-making Mode

As independent enterprises, the DG owner and the investor coordinate the capital flow through separate decisions. The owner pays the price  $w$  per unit electricity to the investor. The risk of excess investment is borne by the investor, while the loss caused by insufficient capacity is borne by the owner. The expected profit of the investor is shown as Formula (5). By the derivation process is shown in Appendix B, we get Formula (6).

$$\Pi_R^II(Q) = E[w \cdot \min[Q, x] - cQ - h(Q - x)^+] \quad (5)$$

$$\Pi_R^II(Q) = (w + h)S(Q) - (c + h)Q \quad (6)$$

$\Pi_R^II(Q)$  is a convex function of  $Q$ . Combining with Formula (7), there will be a local maximum value for  $\Pi_R^II(Q)$ .

When  $d\Pi_R^II(Q)/dQ = 0$ , we get Formula (8).

$$\frac{d\Pi_R^II(Q)}{dQ} = (w + h)\bar{F}(Q) - c - h \quad (7)$$

$$\bar{F}_II(Q^*) = (c + h)/(w + h) \quad (8)$$

The expected profit of the DG owner is indicated in Formula (9). The same as the derivation process in Appendix B, Formula (10) can be obtained. We now use Formula (8) to derive the result shown in Formula (11). With the derivative of  $w(Q_{II})$  with respect to  $Q$ , Formula (12) is achieved. Substitute Formula (11) and (12) into

Equation  $d\Pi_R^II(Q)/dQ = 0$  and get Formula (13), which is the expression of the optimal capacity in the decentralized decision-making mode.

$$\Pi_D^II(Q) = E[(p + p_s - w) \min[Q, x] - (b - c)Q - g(x - Q)^+] \quad (9)$$

$$\Pi_D^II(Q) = (p + p_s - w + g)S(Q) - (b - c)Q - g\mu \quad (10)$$

$$w(Q_{II}) = (c + h)/\bar{F}_II(Q^*) - h \quad (11)$$

$$dw(Q_{II})/dQ = (c + h)f(Q)/\bar{F}_II^2(Q^*) \quad (12)$$

$$\bar{F}_II(Q^*) = \frac{b + h}{p + p_s + h + g} + \frac{(c + h)f(Q)S(Q)}{(p + p_s + h + g)\bar{F}_II^2(Q^*)} \quad (13)$$

By Formula (13) we know  $\bar{F}_II(Q^*) > (b + h)/(p + p_s + h + g)$ . This also means  $\bar{F}_II(Q^*) > \bar{F}_I(Q^*)$ . Since  $\bar{F}'(Q) = -f(Q) < 0$ ,  $\bar{F}(Q)$  is a decreasing function of  $Q$ . The DG capacity in the decentralized decision-making mode is smaller than that in the mode of centralized decision-making. In other words, the investment ability of the investor does not reach the optimal level of the system. The reason is that the game between the investor and the owner reduces the input level of the capital supply chain and the profitability of the supply chain.

It can be inferred from the above that in theory, the mode of unilateral investment and operation of DG owners can achieve the optimal coordination of the whole supply chain, while the mode of independent investors' investment and operation of DG owners fails to reach the optimal level. However, most owners do not have sufficient financial strength in practice. They need to cooperate with investors who possess strong capital strength, so it involves the coordination of interests between them. As independent participants, they need to design effective coordination models to achieve the optimal effect on the basis of the centralized decision-making mode.

## IV. CAPACITY INVESTMENT AND COORDINATION MODEL

The analysis above points out that the DG capacity under the centralized decision-making mode is optimal. While the overall profit of the supply chain corresponding to the optimal generation capacity is certain, the respective profits of the DG owner and the investor are related to the profit allocation between them. We consider designing the profit sharing model. On the other hand, investment in capacity involves the situation of insufficient investment and excess investment. Investors tend to be conservative to avoid the risk of over-investment. This paper wants to design an incentive method to ensure that the investor invests in sufficient capacity. Through contract design, the DG owner promises to provide the investor with some risk compensation in the event of overcapacity.

Based on the above, the owner designs coordination models from the perspective of risk sharing and profit sharing. The object is to increase their profits and realize the coordination of the capital supply chain.

### A. Risk Sharing Model

Given that the risk of excess investment will result in losses, the investor tends to reduce capital input. It may lead to insufficient investment in power generation capacity. In

view of this, the DG owner should share part of the risk cost when real overcapacity losses happen. The contract can boost the confidence of the investor and help the DG owner to expand generating scale. This is the risk sharing model. The DG owner will provide compensation  $\phi(\phi < w)$  per unit of excess capacity to the investor. If the generating capacity invested cannot meet the demand of the electricity market, the investor will not be compensated.

The expected profit of the investor is represented by Formula (14) and Formula (15) can be derived. The expected profit of the DG owner is shown as Formula (16). Then we can derive Formula (17). The first and the second derivatives of  $\Pi_R(Q_\phi)$  with respect to  $Q$  are shown as Formula (18) and (19).

$$\Pi_R(Q_\phi) = E[w \cdot \min[Q, x] - cQ - h(Q-x)^+ + \phi(Q-x)^+] \quad (14)$$

$$\Pi_R(Q_\phi) = (w+h-\phi)S(Q) - (c+h-\phi)Q \quad (15)$$

$$\Pi_D(Q_\phi) = E[(p+p_s-w) \cdot \min[Q, x] - (b-c)Q - g(x-Q)^+ - \phi(Q-x)^+] \quad (16)$$

$$\Pi_D(Q_\phi) = (p+p_s-w+g+\phi) \cdot S(Q) - (b-c+\phi)Q - g\mu \quad (17)$$

$$\frac{d\Pi_R(Q_\phi)}{dQ} = (w+h-\phi)\bar{F}(Q) - c - h + \phi \quad (18)$$

$$\frac{d\Pi_R^2(Q_\phi)}{dQ^2} = -(w+h-\phi)f(Q) < 0 \quad (19)$$

The expected profit of the investor  $\Pi_R(Q_\phi)$  is a convex function of  $Q$ . Take  $d\Pi_R(Q_\phi)/dQ=0$ , the optimal DG capacity can be obtained,  $\bar{F}_R(Q_\phi^*) = (c+h-\phi)/(w+h-\phi)$ .

If the DG capacity wants to achieve the optimal value in the centralized decision-making mode, the following equation needs to be satisfied:

$$(c+h-\phi)/(w+h-\phi) = (b+h)/(p+p_s+h+g)$$

Define a parameter  $\lambda$ , then we can get  $c+h-\phi = \lambda(b+h)$  and  $w+h-\phi = \lambda(p+p_s+h+g)$ . Calculation produces the following results:

$$\begin{aligned} w &= \lambda(p+p_s+g-b) + c \\ \phi &= h+c-\lambda(b+h) \end{aligned} \quad (20)$$

Formula (20) is substituted into Formula (17) to give

$$\Pi_D(Q_\phi) = (1-\lambda)[(p+p_s+h+g)S(Q) - (b+h)Q] - cQ - g\mu \quad (21)$$

It can be known that only if  $\lambda < 1$ , the DG owner's profit is reasonable, and the value decreases with the increase of  $\lambda$ . Likewise, the expected profit of the investor shown as Formula (22).

$$\Pi_R(Q_\phi) = \lambda[(p+p_s+h+g)S(Q) - (b+h)Q] \quad (22)$$

It can be seen that the investor's profit increases as  $\lambda$  increases.  $\lambda$  is actually the profit allocation coefficient between the investor and the DG owner. The risk sharing model can achieve the optimal capacity under centralized decision making mode. The profits of both parties are distributed by the different values of  $\lambda$ . The size of  $\lambda$  is the result of the negotiation game between the two parties in cooperation.

## B. Profit Sharing Model

As the investor cannot share the profits of electricity sales, he keeps a conservative attitude towards the investment scale. In this case, the owner needs to transfer a certain proportion of the profit to the investor, so as to motivate the investor to expand investment and realize the purpose of maximizing the profits of the owner. This is the profit sharing model.

On the basis of the price  $w$  paid to the investor per unit of electricity, the owner shall pay the  $(1-\alpha)$  proportion of the electricity sales profit to the investor. The expected profits of the DG owners and the investor are given in Formula (23) and Formula (25). Calculation produces the following results in Formula (24) and (26). The first derivative of Formula (26) is shown in Formula (27).

$$\Pi_D(Q_\alpha) = E[(\alpha p + p_s - w) \min[Q, x] - (b-c)Q - g(x-Q)^+] \quad (23)$$

$$\Pi_D(Q_\alpha) = (\alpha p + p_s - w + g)S(Q) - (b-c)Q - g\mu \quad (24)$$

$$\Pi_R(Q_\alpha) = E[(1-\alpha)p + w] \min[Q, x] - cQ - h(Q-x)^+ \quad (25)$$

$$\Pi_R(Q_\alpha) = [(1-\alpha)p + w + h]S(Q) - (c+h)Q \quad (26)$$

$$\frac{d\Pi_R(Q_\alpha)}{dQ} = [(1-\alpha)p + w + h]\bar{F}(Q) - c - h \quad (27)$$

As  $d\Pi_R(Q_\alpha)/dQ=0$ , we get the optimal DG capacity at this time.  $\bar{F}(Q_\alpha^*) = (c+h)/[(1-\alpha)p + w + h]$ .

When the optimal DG capacity reaches that of the centralized decision-making mode, the coordination of the power supply chain can be realized, that is:

$$\bar{F}(Q_\alpha^*) = \frac{c+h}{(1-\alpha)p + w + h} = \frac{b+h}{p + p_s + h + g} \quad (28)$$

The relationship between  $w$  and  $\alpha$  is derived as follows:

$$w = \frac{(c+h)(p + p_s + h + g)}{b+h} - (1-\alpha)p - h \quad (29)$$

Substituting Formula (29) into the expected profits of the owner and investor, and we get

$$\Pi_D(Q_\alpha) = (p + p_s + h + g) \frac{b-c}{b+h} S(Q) - (b-c)Q - g\mu \quad (30)$$

$$\Pi_R(Q_\alpha) = \frac{(c+h)(p + p_s + h + g)}{b+h} S(Q) - (c+h)Q \quad (31)$$

It can be seen from Formula (30) and (31) that there is no relationship between the profits and  $\alpha$ . The value of  $\alpha$  does not change the profits of both parties directly. So it is necessary to study whether  $\alpha$  can change them indirectly by changing the generation capacity  $Q$ .

According to Formula (28), the results can be given as follows:

$$w = \frac{c+h}{\bar{F}(Q_\alpha^*)} - (1-\alpha)p - h \quad (32)$$

$$\alpha = 1 - (c+h)/p / \bar{F}(Q_\alpha^*) + (w+h)/p \quad (33)$$

Supposed that  $w$  and  $\alpha$  are functions of  $Q$ , the following can be derived.

$$w'(Q) = \frac{(c+h)f(Q)}{\bar{F}^2(Q_\alpha^*)} + p\alpha'(Q) \quad (34)$$

$$\alpha'(Q) = -\frac{(c+h)f(Q)}{p \cdot \bar{F}^2(Q^*_\alpha)} + \frac{w'(Q)}{p} \quad (35)$$

Now the expected profit of the DG owner shown in Formula (24) is derived:

$$\partial \Pi_D(Q_\alpha) / \partial Q = [\alpha(Q)p + p_s - w(Q) + g] \bar{F}(Q^*_\alpha) + [\alpha'(Q)p - w'(Q)]S(Q) - b + c \quad (36)$$

Substitute the Formulas (34) and (35) into the above, then we get

$$\partial \Pi_D(Q_\alpha) / \partial Q = (p + p_s + h + g) \bar{F}(Q^*_\alpha) - \frac{(c+h)f(Q)S(Q)}{\bar{F}^2(Q^*_\alpha)} - b - h \quad (37)$$

When  $\partial \Pi_D(Q_\alpha) / \partial Q = 0$ , the result is

$$\bar{F}(Q^*_\alpha) = \frac{b+h + \frac{(c+h)f(Q)S(Q)}{\bar{F}(Q^*_\alpha)}}{p+p_s+h+g} = \bar{F}_{II}(Q^*) \quad (38)$$

The above shows that under the profit sharing model, the optimal DG capacity is the same as that of the decentralized decision-making mode. Parameter  $\alpha$  fails to change the profit of the DG owner and the investor indirectly. Compared with the traditional decentralized decision-making mode, this coordination model cannot reach the purpose of increasing the profits of the investor and the DG owner at the same time. It fails to meet the constraints of incentive compatibility and feasibility. Therefore, this simple profit sharing model cannot be implemented in practice. The model needs to be further improved.

### C. Modified Profit Sharing Model

In the modified profit sharing model, it is assumed that the DG owner not only shares the electricity income to the investor, but also bears a certain proportion of the investor's cost. Let the proportionality coefficient be  $\beta$ , and the profits of the DG owner and the investor are respectively shown in Formula (39) and (40).

$$\Pi_D(Q_{\alpha\beta}) = E[(\alpha p + p_s) \min[Q, x] - (b-c)Q - g(x-Q)^+ - \beta cQ] \quad (39)$$

$$\Pi_R(Q_{\alpha\beta}) = E[(1-\alpha)p \cdot \min[Q, x] - (1-\beta)cQ - h(Q-x)^+] \quad (40)$$

When  $d\Pi_R(Q_{\alpha\beta}) / dQ = 0$ , the optimal DG capacity can be obtained in Formula (41).

$$\bar{F}(Q^*_{\alpha\beta}) = \frac{(1-\beta)c+h}{(1-\alpha)p+h} \quad (41)$$

Substituting the above into Formula (39), we can get Formula (42). The derivative of  $\Pi_D(Q_{\alpha\beta})$  is represented by Formula (43). When  $d\Pi_D(Q_{\alpha\beta}) / dQ = 0$ , we can derive Formula (43). The result shows  $\bar{F}(Q^*_{\alpha\beta}) < \bar{F}_{II}(Q^*)$ .

$$\Pi_D(Q_{\alpha\beta}) = [p + p_s + h + g - \frac{(1-\beta)c+h}{\bar{F}(Q^*_{\alpha\beta})}]S(Q) - (b-c + \beta c)Q - g\mu \quad (42)$$

$$\frac{d\Pi_D(Q_{\alpha\beta})}{dQ} = (p + p_s + h + g) \bar{F}(Q^*_{\alpha\beta}) - b - h - \frac{(1-\beta)c+h}{\bar{F}^2(Q^*_{\alpha\beta})} f(Q)S(Q) \quad (43)$$

$$\bar{F}(Q^*_{\alpha\beta}) = \frac{b+h}{p+p_s+h+g} + \frac{(c+h)f(Q)S(Q)}{(p+p_s+h+g)\bar{F}^2(Q^*_{\alpha\beta})} - \frac{\beta c f(Q)S(Q)}{(p+p_s+h+g)\bar{F}^2(Q^*_{\alpha\beta})} \quad (44)$$

Because  $\bar{F}(Q)$  is a decreasing function of  $Q$ , so  $Q_{\alpha\beta}^* > Q_{II}^*$ . The DG capacity is greater in this model. It can achieve the goal of stimulating investment.

Take the partial derivative of Formula (42) with respect to  $\beta$  and we get

$$\frac{\partial \Pi_D(Q_{\alpha\beta})}{\partial \beta} = c \frac{S(Q) - Q \bar{F}(Q)}{\bar{F}(Q)} \quad (45)$$

Assuming  $H(Q) = S(Q) - Q \bar{F}(Q)$ , now we take the derivative of the function with respect to  $Q$  and get  $H'(Q) = \bar{F}(Q) - F(Q) + Q \cdot f(Q) = Q \cdot f(Q) > 0$ . As  $H(0) = 0$ , so  $H(Q) > 0$ . It means  $\partial \Pi_D(Q_{\alpha\beta}) / \partial \beta > 0$ . The owner's profit is an increasing function of  $\beta$ .

In the modified profit sharing model, the above has proved that the DG capacity is greater than that in the decentralized decision-making mode. If the DG owner wants to achieve coordination of the supply chain, the equation  $\bar{F}(Q^*_{\alpha\beta}) = \bar{F}_I(Q^*)$  needs to be satisfied.

$$\bar{F}(Q^*_{\alpha\beta}) = \frac{(1-\beta)c+h}{(1-\alpha)p+h} = \frac{b+h}{p+p_s+h+g} \quad (46)$$

$$\beta = 1 - \frac{(b+h)[(1-\alpha)p+h]}{c(p+p_s+h+g)} + \frac{h}{c} \quad (47)$$

$\alpha$  and  $\beta$  should satisfy the relation shown in Formula (47). Only if the ratio of the investment cost assumed by the owner satisfies the specific linear relationship with the proportion of the sales revenue shared with the investor, the optimal DG capacity under the centralized decision-making mode can be achieved.

In this mode, the selection of different  $\alpha$  and  $\beta$  can leads to different profit allocation. The modified model can be successfully implemented when the benefits of both parties are greater than those under traditional decentralized decision-making mode.

### V. SIMULATION AND ANALYSIS

In order to verify the analysis in this paper, we take a distributed photovoltaic power station in Shanghai as an example. All the electricity generated will be consumption by the grid. The demand of the electricity market is regarded as a uniform distribution of  $[0, 1000]$ .  $p=750$  CNY /MW h (data source: national benchmark feed-in tariff table for photovoltaic power generation),  $p_s=370$  CNY /MW h,  $b=800$  CNY /MW h,  $c=640$  CNY /MW h,  $h=0.5$  CNY /MW h,  $g=1$  CNY /MW h. According to the model analysis in the paper, the expected profits and the optimal capacity in different modes are calculated.

Table.2 Comparison of different models

	Centralized Decision-making	Decentralized Decision-making	Risk Sharing Model		Profit Sharing Model	
	-	-	$\lambda=0.2$	$\lambda=0.3$	$\alpha=0.1$	$\alpha=0.2$
TP	45500.00	37026.48	45500.00	45500.00	37026.48	37026.48
DGOP	-	29067.27	36312.58	31718.69	29067.27	29067.27
IP	-	7959.21	9187.78	13781.68	7959.21	7959.21
$Q$	286.22	163.59	286.22	286.22	163.59	163.59
$w$	-	750.00	704.20	736.30	-	-
$\phi$	-	-	480.40	400.35	-	-

Note. TP= total profit; DGOP = the DG owner’s profit; IP=the investor’s profit

It can be seen from Table 2 that the risk sharing model can achieve the coordination of the supply chain. The optimal production level  $Q$  is 286.22 which is consistent with the level of centralized decision-making mode. The decentralized decision-making mode and the profit-sharing model cannot coordinate the supply chain. The optimal DG capacities of these modes are both 163.59, which is lower than that of the centralized decision-making mode. In the profit sharing making model, the addition of complex design increases neither the level of capacity investment, nor the profits of the DG owner and the investor.

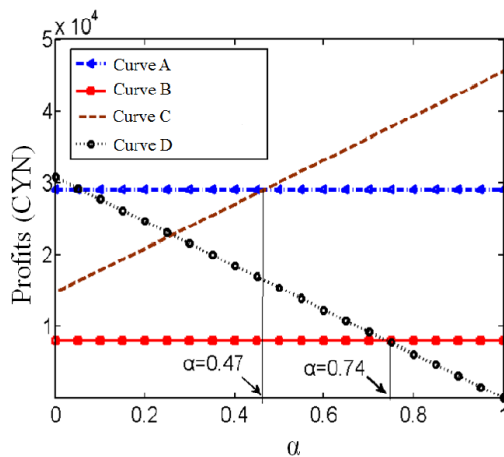


Fig. 2 Comparison of profits under two profit sharing models  
 Noted: Curve A: the original DG owner’s profit, Curve B: the original DG investor’s profit, Curve C: DG owner’s profit after modified, Curve D: DG investor’s profit after modified.

In Fig. 2, we compare the expected profits of the DG owner and the investor under the traditional profit sharing mode and the modified one. When  $\alpha$  and  $\beta$  satisfy the linear relationship  $\beta = 0.825\alpha + 0.1752$ , the modified profit sharing model can achieve the coordination of the power supply chain. As shown in Figure 2, when the value range of  $\alpha$  is  $[0.47, 0.74]$ , the profits of both the DG owner and investor of the modified model will be greater than that before improvement. The modified mechanism is feasible, and the corresponding value range of  $\beta$  is between  $[0.56, 0.79]$ . As long as the appropriate profit sharing coefficient  $\alpha$  and investment cost distribution coefficient  $\beta$  are selected according to the actual data, the mutual profits of both parties can be improved.

VI CONCLUSIONS

This paper studies how the DG owner designs coordination models to expand capacity investment and maximize the

profits under the constraint of market demand. We consider the centralized decision-making mode as the benchmark of supply chain coordination and the decentralized decision-making mode as the basis of comparison. Coordination models of risk sharing and profit sharing are designed respectively from the perspective of risk and profit. The implementation effect of the two models is analyzed. The model that fails to achieve the goal of supply chain coordination is further improved. The following conclusions are obtained through model derivation and calculation.

- 1) Under the risk-sharing model, the DG owner's contract design from sharing part of the risk cost is in line with the investor's mentality of avoiding the risk of over-investment. Therefore, the investment scale increases from the level of decentralized decision-making mode to that of centralized decision-making mode.
- 2) The design of profit sharing model cannot be put into practical application due to the violation of incentive compatibility and feasibility constraints because the owner is limited by his own profit space.
- 3) In the modified profit sharing model, the power generation capacity achieves the optimal DG capacity in the centralized decision-making mode and achieves the goal of coordinating the supply chain.

For the purpose of effectively expanding the DG capacity investment, this paper discusses the investment decision and coordination model design of DG projects. We find the new perspective for the research on DG investment. The research method of capacity investment and model design can also be extended to the study of different operation modes and grid access modes in DG projects. They are also applicable to the DG investment without subsidy policy in China in the future.

APPENDIX

Appendix A

In the centralized decision-making mode, the expected benefit for the entire supply chain is

$$\Pi_1(Q) = E[(p + p_s) \min[Q, x] - bQ - h(Q - x)^+ - g(x - Q)^+] \quad (A1)$$

Where,  $(Q - x)^+ = \max\{Q - x, 0\}$ ,  $(x - Q)^+ = \max\{x - Q, 0\}$

Calculation produces the following result:

$$\Pi_1(Q) = (p + p_s)E \min[Q, x] - b \cdot E(Q) - h \cdot E(Q - x)^+ - g \cdot E(x - Q)^+ \quad (A2)$$

$$\therefore E(Q) = Q ,$$

It is known from Formula (1) that:  $E \min[Q, x] = S(Q)$  , And

$$S(Q) = E[x - (x - Q)^+] = E(x) - E(x - Q)^+ \quad (A3)$$

$$\therefore E(x - Q)^+ = E(x) - S(Q) = \mu - S(Q)$$

As the same,

$$S(Q) = E[Q - (Q - x)^+] = E(Q) - E(Q - x)^+ \quad (A4)$$

$$\therefore E(Q - x)^+ = E(Q) - S(Q) = Q - S(Q)$$

Put the above derivation results into the expected benefit in Formula (A1), and get Formula (A5) and (A6).

$$\Pi_1(Q) = (p + p_s)E \min[Q, x] - b \cdot E(Q) - h \cdot E(Q - x)^+ - g \cdot E(x - Q)^+ \quad (A5)$$

$$\Pi_1(Q) = (p + p_s)S(Q) - bQ - h[Q - S(Q)] - g[\mu - S(Q)] \quad (A6)$$

With further derivation, the result is as follows:

$$\Pi_1(Q) = (p + p_s + h + g)S(Q) - (b + h) \cdot Q - g\mu \quad (A7)$$

### Appendix B

In the decentralized decision-making mode, the investor's expected benefit is

$$\Pi_R^I(Q) = E[w \cdot \min[Q, x] - cQ - h(Q - x)^+] \quad (B1)$$

Calculation produces the following result:

$$\Pi_R^I(Q) = w \cdot E \min[Q, x] - c \cdot E(Q) - h \cdot E(Q - x)^+ \quad (B2)$$

It is known from Formula (1) that:  $E \min[Q, x] = S(Q)$  ,  
and  $E(Q) = Q$  ,

It has been derived in Appendix A that:  $E(Q - x)^+ = Q - S(Q)$

With further derivation, the investor's expected benefit is as Formula (B3) and (B4)

$$\Pi_R^I(Q) = w \cdot S(Q) - cQ - h \cdot [Q - S(Q)] \quad (B3)$$

$$\Pi_R^I(Q) = (w + h) \cdot S(Q) - (c + h)Q \quad (B4)$$

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