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Optimal decision analysis of PV supply chain considering power structure

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Abstract: As a clean energy source, photovoltaic power generation is most in line with the current demand for energy transformation. Therefore, China's PV industry has developed rapidly, among which, industrial distributed PV projects have developed particularly well and formed a mature market trading mechanism. However, the high-speed development has caused behavioral decision dysfunctions among PV companies and overall performance losses in the PV supply chain. Therefore, this paper integrates the actual demand preference characteristics of users and constructs a PV supply chain game model consisting of PV system manufacturers and service providers, and then, this paper studies the optimal decision analysis of PV supply chain firms in different situations from the perspective of different power structures.

Keywords: Photovoltaic supply chain; Game model; Power structure.

1. Introduction

Solar energy is widely regarded as one of the most promising green renewable energy sources due to its huge resources, cleanliness and safety, and ease of access, and the photovoltaic industry is developing rapidly. At the same time, the construction of ecological civilization with Chinese characteristics requires sustainable development, coupled with the proposed "double carbon" strategic goal, so photovoltaic power generation is the main trend of China's future new energy development. Although the future development of China's PV market is vast, there are opportunities and challenges. Although government subsidies at the beginning of the industry's development have stimulated the rapid development of the PV industry, they have also caused the dependence of PV enterprises on decision-making. PV companies ignore their core competencies and blindly produce, leading to poor decision-making relationships upstream and downstream in the PV supply chain and an imbalanced supply and demand structure that undermines the overall performance of the supply chain. At the same time, different power structures will inevitably affect the decision-making process of each member of the PV supply chain, and there are differences in the operational decisions made by each member to maximize benefits. Therefore, it is worthy of attention and research to consider different power structures to optimize the decision making of each member of the PV supply chain to coordinate the upstream and downstream decision-making relationships and obtain the optimal economic benefits.

At present, the PV industry as an emerging industry has been studied and analyzed by many scholars for the game decision research of PV supply chain. nash non-cooperative game as one of the mainstream methods can realize that each game party is to maximize personal interests for equilibrium decision. In the PV supply chain for PV system demand and supply inconsistency problem, the optimal solution under equilibrium decision can be obtained by establishing Gounod model [1]; or in the dual-channel supply chain composed of PV enterprises can also model and use numerical analysis to obtain the optimal pricing and demand of PV system products to balance the supply and demand relationship upstream and downstream of the supply chain [2]. Depending on the bargaining power of PV firms, unequal positions of supply chain members can occur in the Stackelberg game model [3]. The business performance of an enterprise depends not only on its business strategy but also on its position in the market, and the strength of bargaining power affects the decision-making process of supply chain members [4]. Competitor relationships with different power structures and levels in vertical supply chains have become an important factor in decision making and profitability [5].

2. Model assumptions

This paper constructs a PV supply chain game model consisting of PV system manufacturers and service providers. The specific process is as follows: the PV system manufacturer produces the PV system products, and then the PV system service provider orders the products and installs them in the industrial user's premises for free; the industrial user can directly use the PV power and absorb it by itself, and only needs to pay the service provider for consuming the corresponding power generation.

Based on the above analysis and based on the modeling needs, the following basic assumptions are made.

(1) Quality technology level k_1 and effort performance level k_2 . k_1 is used to indicate the quality level of the products produced by the PV system manufacturer, and k_2 is used to indicate the guarantee level of the PV system service provider in product promotion and product maintenance.

(2) The PV product market demand function can be expressed as

$$Q = a - b\theta + d_1k_1 + d_2k_2$$

Where, $a > 0$ denotes the market size of PV system products, $b > 0$ denotes the discount sensitivity, θ denotes the discount for industrial customers using PV power, $d_1 > 0$ denotes the customer quality preference factor, and $d_2 > 0$ denotes the customer product guarantee preference factor.

(3) Quality technology cost and effort performance cost. Referring to the cost model proposed by Ghosh et al [6], based

on the principle of increasing marginal cost of the firm, the quality innovation cost of the PV system manufacturer is denoted by $\frac{1}{2}\lambda_1 k_1^2$, and the effort performance cost of the PV system service provider is denoted by $\frac{1}{2}\lambda_2 k_2^2$, where $\lambda_1 > 0$ denotes the quality innovation cost coefficient and $\lambda_2 > 0$ denotes the effort performance cost coefficient.

(4)Define c as the production cost of PV products, use w to denote the sales price of PV products, use μ to denote the photovoltaic conversion efficiency of PV products, use t to denote the effective service life of PV products, and use p to denote the price of electricity per industrial unit set by the national grid.

3. Model construction and solution

The target profit function for PV system manufacturers and service providers can be obtained as

Photovoltaic system manufacturer objective function:

$$\pi_M = (w-c)Q - \frac{1}{2}\lambda_1 k_1^2$$
$$= (w-c)(a - b\theta + d_1 k_1 + d_2 k_2) - \frac{1}{2}\lambda_1 k_1^2$$

Photovoltaic system service provider objective function:

$$\pi_S = \theta p\mu t Q - wQ - \frac{1}{2}\lambda_2 k_2^2$$
$$= (\theta p\mu t - w)(a - b\theta + d_1 k_1 + d_2 k_2) - \frac{1}{2}\lambda_2 k_2^2$$

3.1. The Nash equilibrium game between PV system manufacturers and service providers

The power parity between PV system manufacturers and service providers represents a type of power structure in which both parties are medium-sized firms and cannot dominate the market individually, so that both parties' own behavioral decisions depend on each other's decisions and both parties make decisions that are in their own best interest at the same time, considering their power parity.

The optimal sales price w_1^*, optimal discount θ_1^*, optimal quality and technology level k_{11}^*, optimal effort performance level k_{21}^*, and optimal demand Q_1^* for PV system products can be obtained by the inverse solution method as follows

$$w_1^* = \frac{\lambda_1\lambda_2 ap\mu t + c[2b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]}{3b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t}$$

$$\theta_1^* = \frac{2\lambda_1\lambda_2 ap\mu t + c[b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]}{[3b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]p\mu t}$$

$$k_{11}^* = \frac{d_1\lambda_2(ap\mu t - bc)}{3b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t}$$

$$k_{21}^* = \frac{d_2\lambda_1(ap\mu t - bc)}{3b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t}$$

$$Q_1^* = \frac{bd_1 d_2(ap\mu t - bc)}{[3b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]p\mu t}$$

we obtain the optimal profit for PV system manufacturers and service providers as

$$\pi_{M1}^* = \frac{\lambda_1\lambda_2^2(ap\mu t - bc)^2(2b\lambda_1 - d_1^2 p\mu t)}{2p\mu t[3b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]^2}$$

$$\pi_{S1}^* = \frac{\lambda_1^2\lambda_2(ap\mu t - bc)^2(2b\lambda_2 - d_2^2\mu t)}{2p\mu t[3b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]^2}$$

3.2. The Stackelberg master-slave game dominated by PV system manufacturers

The Stackelberg game market structure dominated by PV system manufacturers represents a channel power structure consisting of a few larger PV system manufacturers and many relatively small PV system service providers, which results in an unequal status of manufacturers and service providers. The decision-making behavior of the service provider is dependent on the manufacturer's decision, and the discourse is controlled by the manufacturer, who has a relative leadership position, while the service provider is a follower, and both parties make decisions according to the master-slave relationship.

The optimal sales price w_2^*, the optimal discount θ_2^*, the optimal quality and technology level k_{12}^*, the optimal effort and performance level k_{22}^*, and the optimal demand Q_2^* for PV system products can be obtained as follows

$$w_2^* = \frac{\lambda_1 ap\mu t(2b\lambda_2 - d_2^2 p\mu t) + bc[2b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]}{b[4b\lambda_1\lambda_2 - (d_1^2\lambda_2 + 2d_2^2\lambda_1)p\mu t]}$$

$$\theta_2^* = \frac{bc[b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t] + a\lambda_1 p\mu t(3b\lambda_2 - d_2^2 p\mu t)}{bp\mu t[4b\lambda_1\lambda_2 - (d_1^2\lambda_2 + 2d_2^2\lambda_1)p\mu t]}$$

$$k_{12}^* = \frac{d_1\lambda_2(ap\mu t - bc)}{4b\lambda_1\lambda_2 - (d_1^2\lambda_2 + 2d_2^2\lambda_1)p\mu t}$$

$$k_{22}^* = \frac{d_2\lambda_1(ap\mu t - bc)}{4b\lambda_1\lambda_2 - (d_1^2\lambda_2 + 2d_2^2\lambda_1)p\mu t}$$

$$Q_2^* = \frac{b\lambda_1\lambda_2(ap\mu t - bc)}{[4b\lambda_1\lambda_2 - (d_1^2\lambda_2 + 2d_2^2\lambda_1)p\mu t]p\mu t}$$

we obtain the optimal profit for PV system manufacturers and service providers as

$$\pi_{M2}^* = \frac{\lambda_1\lambda_2(ap\mu t - bc)^2}{2p\mu t[4b\lambda_1\lambda_2 - (d_1^2\lambda_2 + 2d_2^2\lambda_1)p\mu t]}$$

$$\pi_{S2}^* = \frac{\lambda_1^2\lambda_2(ap\mu t - bc)^2(2b\lambda_2 - d_2^2 p\mu t)}{2p\mu t[4b\lambda_1\lambda_2 - (d_1^2\lambda_2 + 2d_2^2\lambda_1)p\mu t]^2}$$

3.3. The Stackelberg master-slave game dominated by PV system service providers

The Stackelberg game market structure dominated by PV system service providers represents a channel power structure consisting of a few larger PV system service providers and relatively small PV system manufacturers, which makes the PV system manufacturers' decision-making behavior dependent on the service providers' decisions, and the discourse is controlled in the hands of the service providers, who have a relatively leading position, while the manufacturers are in the role of followers, and both parties make decisions in accordance with the master-slave relationship.

The optimal sales price w_3^*, the optimal discount θ_3^*, the optimal quality and technology level k_{13}^*, the optimal effort and performance level k_{23}^*, and the optimal demand Q_3^* for PV system products can be obtained as follows

$$w_3^* = \frac{\lambda_1\lambda_2 ap\mu t + c[3b\lambda_1\lambda_2 - (2d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]}{4b\lambda_1\lambda_2 - (2d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t}$$

$$\theta_3^* = \frac{bc[b\lambda_1\lambda_2 - (d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t] + a\lambda_2 p\mu t(3b\lambda_1 - d_1^2 p\mu t)}{bp\mu t[4b\lambda_1\lambda_2 - (2d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]}$$

$$k_{13}^* = \frac{d_1\lambda_2(ap\mu t - bc)}{4b\lambda_1\lambda_2 - (2d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t}$$

$$k_{23}^* = \frac{d_2\lambda_1(ap\mu t - bc)}{4b\lambda_1\lambda_2 - (2d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t}$$

$$Q_3^* = \frac{b\lambda_1\lambda_2(ap\mu t - bc)}{[4b\lambda_1\lambda_2 - (2d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]p\mu t}$$

we obtain the optimal profit for PV system manufacturers and service providers as

$$\pi_{M3}^* = \frac{\lambda_1\lambda_2^2(ap\mu t - bc)^2(2b\lambda_1 - d_1^2 p\mu t)}{2p\mu t[4b\lambda_1\lambda_2 - (2d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]^2}$$

$$\pi_{S3}^* = \frac{\lambda_1\lambda_2(ap\mu t - bc)^2}{2p\mu t[4b\lambda_1\lambda_2 - (2d_1^2\lambda_2 + d_2^2\lambda_1)p\mu t]}$$

4. Equilibrium solution conclusion analysis

Theorem 1 The optimal profit of the manufacturer in the manufacturer-dominated Stackelberg case of PV systems is greater than the Nash equilibrium case, which in turn is greater than the service-provider-dominated Stackelberg case.

Theorem 2 The optimal profit of the service provider in the PV system service provider-dominated Stackelberg case is greater than the Nash equilibrium case, which in turn is greater than the manufacturer-dominated Stackelberg case.

Theorem 3 The optimal selling price of PV system products in the Stackelberg case dominated by PV system manufacturers is higher than that in the Nash equilibrium case, while the Nash non-cooperative game case is higher than that in the Stackelberg case dominated by service providers.

Theorem 4 The optimal discount for the PV system product in the two-party Nash equilibrium case is better than the Stackelberg case. When $\frac{d_1^2}{\lambda_1} > \frac{d_2^2}{\lambda_2}$, the optimal discount for the PV system service provider-dominated Stackelberg case is better than the manufacturer-dominated Stackelberg case; when $\frac{d_1^2}{\lambda_1} < \frac{d_2^2}{\lambda_2}$, the optimal discount for the PV system manufacturer-dominated Stackelberg case is better than the service provider-dominated Stackelberg case; when $\frac{d_1^2}{\lambda_1} = \frac{d_2^2}{\lambda_2}$, the optimal discounts for the two cases discounts are equal in both cases.

Theorem 5 The optimal quality technology level, effort performance level, and demand in the Nash equilibrium case of both parties are greater than those in the Stackelberg case. When $\frac{d_1^2}{\lambda_1} > \frac{d_2^2}{\lambda_2}$, the optimal quality technology level, effort performance level, and demand in the Stackelberg case dominated by the PV system service provider is greater than that in the Stackelberg case dominated by the manufacturer; when $\frac{d_1^2}{\lambda_1} < \frac{d_2^2}{\lambda_2}$, the opposite is true; when $\frac{d_1^2}{\lambda_1} = \frac{d_2^2}{\lambda_2}$, the optimal quality technology level, effort performance level, and demand in both cases are equal.

5. Conclusion

The above theorem shows that the profits of different power structure PV system manufacturers and service providers differ, the manufacturer's profits are the largest in the three cases when the manufacturer dominates, while the service provider's profits are the smallest in the three cases; on the contrary, the service provider's profits are the largest when the service provider dominates, while the manufacturer's profits are the smallest, it can be seen that manufacturers and service providers will try to expand their influence, so that they can be in the leading position in the PV supply chain to achieve maximum benefits.

The next three scenarios are compared, when both parties are in the Nash equilibrium game with equal status, the demand, discount, quality technology level and effort performance level of PV system products are optimal; while in the Stackelberg game two scenarios, the magnitude depends on the positive and negative case of $d_1^2\lambda_2 - d_2^2\lambda_1$, when $d_1^2\lambda_2 - d_2^2\lambda_1 > 0$, that is, $\frac{d_1^2}{\lambda_1} > \frac{d_2^2}{\lambda_2}$, indicates that the quality intensity of the product is greater than the guarantee intensity. The demand, discount, quality technology and effort performance of PV system products in the Stackelberg game dominated by PV system service providers are better than those in the manufacturer dominated case, and vice versa.

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