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R&D Cost Sharing of Intelligent Upgrading of Photovoltaic Power Stations

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Abstract

The intelligent upgrading of photovoltaic (PV) power stations can improve their power-generating capacity, reduce operation and maintenance (O&M) costs, and effectively conserve energy and reduce emissions. However, the pressure of research and development (R&D) investment, as well as market demand uncertainty faced by PV technical suppliers, has become an obstacle to intelligent upgrading. From the perspective of R&D cost sharing between PV project operators and technical equipment suppliers in the PV supply chain, this study presents game models for suppliers and operators under the modes of R&D cost sharing and non-sharing, and compares the benefits to both parties under the cost-sharing contract. The results show that under the cost-sharing mode, the operators share a certain proportion of R&D costs with the suppliers, which can improve the effort level of R&D. The greater the impact of the power generation increased by intelligent products on market demand, the better the operator's maintenance efforts, and the more motivated the operator is to choose the cost-sharing strategy. By setting a reasonable wholesale price for products, both parties can balance their profits.

Keywords: PV power station; intelligent upgrading; R&D decision; cost sharing

1. Introduction

As the modern world moves towards a zero-emissions economy, with more than 120 countries globally declaring their commitment to 'carbon neutrality', countries are taking a variety of actions to reduce the share of fossil fuels in energy production, to drive renewable energy development, and to expand global energy markets [1,2]. Photovoltaic (PV) power is an important energy source. Compared to traditional sources of energy, the use of solar energy can continuously provide people with power, and the position of PV in the new energy industry has become irreplaceable [3]. As a clean energy source, PV energy has been widely applied in rooftops [4], water surfaces [5], agriculture [6], and other fields. By 2030, PV energy will meet 15% of all electricity demand in the European Union [7]. Meanwhile, the U.S. international PV energy storage market shows a trend of rapid development: as of the first quarter of 2025, solar power generation has accounted for 69% of the U.S. power grid's new generation, with the PV cumulative installed capacity reaching 266.2GW [8]. In China, central and local governments have issued a series of supporting policies for the PV power generation sector, and PV power stations have developed rapidly [9]. The generation of PV power increased from 8 billion kWh in 2013 to 26.05 billion kWh in 2020, representing a 32.6-fold increase [10]. By the end of April 2025, the installed

Check for updates

Academic Editor: Wen-Chyuan Chiang

Received: 20 January 2026
Revised: 24 February 2026
Accepted: 2 March 2026
Published: 4 March 2026

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capacity of PV power generation had reached 990 GW, ranking the first in the world [11]. However, in the early stage of China's PV industry, the focus was solely on the expansion of installed capacity. PV manufacturers mainly concentrated on processing and assembly processes with low added value and low technological sophistication. Deficiencies existed in core technological areas such as the preparation of energy-saving polysilicon materials, new technologies for solar cell manufacturing, high-end equipment manufacturing, and the grid connection of PV power generation [12]. Restricted by technological bottlenecks, the problems of traditional PV power stations have emerged, including the inability to determine the maximum power point, the inability to monitor and deal with various faults of PV power stations in a timely and effective manner, and the shortcomings of a high failure rate, large fire hazards, low efficiency, and high O&M costs. The actual capacity of a PV power station to generate power is far lower than its theoretical efficiency [13].

Due to the aforementioned reason, and in order to better promote the development of China's PV industry, in 2021, the State Council issued an action plan to develop the intelligent PV industry (2021–2025), which proposed the vigorous improvement of the intelligence level of the PV sector and shifting from pursuing scale and speed to focusing on efficiency and quality [14]. In 2022, China introduced over 10 policies to support and encourage the innovative development of the PV industry. With the support of government policies and advances in industrial technology, China is gradually developing into the world's most important PV application market [15]. Through intelligent upgrading, technologies such as the Internet, big data, and artificial intelligence (AI) can be deeply integrated into PV power stations to enhance the productivity of power generation and reduce O&M costs. We take the Yunnan Yuanmou Wumao PV Power Station as an example, which was put into operation in 2024 with a total installed capacity of 550 MW. In September 2025, the Huaneng Group, as the power station operator, collaborates with the upstream supplier Huayan Intelligent Technology Group. By leveraging 5G technology, they deploy an IoT fire-prevention cloud platform, a drone inspection system, and an AI big data analysis platform, thereby transforming traditional power stations into "smart power stations" that are perceivable, diagnosable, self-healing, and optimizable. However, in practice, the R&D for intelligent PV incurs high costs, and suppliers face significant capital pressure. Thus, in the case of market demand uncertainty, suppliers choose an R&D strategy only when funds are sufficient. This is the main factor hindering the intelligent upgrading of PV power stations.

With the development of the PV industry, most countries have basically completed the transition from protection to competition in this sector, meaning they have shifted from industrial protection policies to industrial competition policies. Under the guidance of these competition policies, how PV industry stakeholders make decisions to achieve optimal profits has become a practical issue facing the PV industry [16]. The intelligent upgrading of PV power stations involves upstream PV equipment suppliers and downstream PV project operators. In the PV supply chain, the relationship between the suppliers and the operators forms a typical principal–agent relationship. As the principal party, the operator builds, operates, and maintains the intelligent PV power station, expecting to obtain high-efficiency and reliable intelligent products through the suppliers' R&D investment to improve power generation efficiency and reduce O&M costs; the supplier, as the agent party, is responsible for developing intelligent products and manufacturing PV products with a higher level of intelligence.

This study intends to explore whether R&D cost sharing can promote the intelligent upgrading of PV projects and to analyze the impact of R&D cost-sharing contracts on the benefits of both parties. In practice, in order to improve the power generation efficiency of the power stations and reduce the O&M costs, the operators will put forward their own

demand for intelligent products. However, the operators usually do not have their own R&D departments and need to commission the suppliers to develop and manufacture intelligent PV products. The operator will provide funding to the supplier to share the R&D costs in order to motivate the supplier to choose an R&D strategy.

Hence, this study selected a typical phenomenon in the practice of the PV supply chain (upstream suppliers conduct intelligent R&D, while downstream operators perform O&M) to analyze the long-term cooperation within the principal–agent relationship between upstream and downstream firms. A Stackelberg differential game model was established for the supplier to invest in R&D and the operator to carry out intelligent maintenance. The impact of the R&D cost-sharing contract on the benefits of both parties was analyzed, with the aim of providing a theoretical basis for the intelligent upgrading of PV power stations.

The rest of this paper is structured as follows. Section 2 reviews the literature and proposes to analyze the cost-sharing problem in the PV supply chain from a dynamic perspective. A Stackelberg game model is constructed in Section 3, and model analysis is in Section 4. Section 5 conducts numerical simulations and sensitivity analysis. Section 6 discusses the findings, and Section 7 gives the conclusions.

The main contributions of this study are reflected in two ways. Firstly, we have addressed the issue of insufficient attention paid to the collaborative behavior of PV supply chain firms from R&D to O&M in existing studies, and we made a targeted analysis on the role of the cost-sharing contract in the intelligent upgrading. This enriches the application of differential game theory in the field of supply chain cooperation. Second, in the context of R&D cooperation within the PV supply chain, there exists information asymmetry between the operator (as the principal) and the supplier (as the agent), making it difficult to fully observe the supplier's R&D effort level. By deriving the optimal cost-sharing ratio and the marginal revenue functions of both parties, we designed a reasonable cost-sharing arrangement that effectively mitigates incentive inadequacy in principle–agent relationships. This provides a new pathway for PV suppliers and operators to achieve a balance of interests in R&D cooperation, further advancing the principal–agent theory in supply chain collaboration.

2. Literature Review

2.1. Supply Chain Cooperation

In terms of supply chain cooperation (SCC), to comply with low-carbon and environmental protection policies and satisfy consumers' pursuit of low-carbon living, manufacturers, retailers, and platforms have united to optimize supply chain resources [17]. Yu et al. [18] studied an R&D company cooperation alliance for the development of energy vehicles between automobile manufacturers (marketers) and battery manufacturers (innovators) to create and bring innovative green technologies to the market. Gao et al. [19] addressed the issue of channel selection for e-commerce enterprises under government green subsidy policies, proposing that utilizing platform franchise systems to collaborate with other enterprises can maximize supply chain benefits. Basiri and Heydari [20] compared non-green traditional products with green ones and found that the demand for the two products depended on the retail price, the green quality of the products, and the sales efforts of the retailers. They also analyzed the income of supply chain members in the three modes, showing that supply chain profit was the largest in the centralized control mode. Based on the resource-based view, De Luca [21] used the structural equation model to study the mediating effect of information integration on the hospital supply chain. The results show that the integration capability of external information not only directly impacts hospital resilience but also has a mediating role. Li et al. [22] considered the problem of information asymmetry between the government and firms, and constructed

single-layer and double-layer principal–agent models including suppliers. The results show that low-cost manufacturers can obtain additional income. Liu et al. [23] investigated the information asymmetry in e-commerce supply chain channels. They established a more realistic principal–agent model and incorporated fairness preferences into it. The study found that after introducing the fairness preference model, the profits of both manufacturers and retailers achieved Pareto improvement. Zhang et al. [24] invented a game model considering cost learning in which retailers (leaders) set retail profit margins, manufacturers (followers) decide wholesale prices, and the two parties jointly invest in energy efficiency levels. The results indicate that the energy efficiency level is usually controlled by the manufacturer rather than the retailer unless the retailer has great bargaining power. In addition, retailers' preference for decision-making power is weakened by greater cost-learning ability or energy efficiency, but is improved by greater investment costs.

2.2. Cost Sharing

In terms of cost-sharing research, Liu et al. [25], based on the theory of conflict analysis, constructed a theoretical framework of the Chinese GPTs super-conflict equilibrium. Under this framework, an incentive mechanism for GPTs' R&D is designed from the perspective of cost sharing, and the results show that the incentive effect is stable and sustainable. Zhao and Xie [26] built a cost-sharing analysis model for China's industrial and rooftop PV. They found that under the existing subsidy prices and costs of China's small-scale rooftop PV, the investment payback period is short, the risk is low, and the economic performance is good. In addition to the influence of the power generation capacity, loan interest rate, construction cost, and other factors, the capital value and time value of inflation cannot be ignored. Shuai et al. [27] developed an investment cost-sharing model to investigate how to share the costs and benefits of PV power projects between the government and users. The results show that a one-time compensation equivalent to 30% of the initial investment from the local government can encourage the public to install PV facilities, which are subject to the central government's subsidy. Huang and Li [28] analyzed the optimal decision-making behaviors of manufacturing supply chains under three carbon quota allocation mechanisms. They found that cost-sharing contracts can enhance the manufacturer's emission reduction level and the total profit of the supply chain. Zeng et al. [29] studied the incentive mechanism of the supplier and distributor in the construction supply chain composed of an owner and a supplier, and proposed a principal–agent model targeting the optimization of the owner's profit. The results show that the cost-sharing mechanism effectively improves the quality of suppliers. Zhang et al. [30] used the principal–agent framework to construct a contract model considering the risk attitudes of different suppliers, and explored the impact of the inventory cost-sharing ratio on operators' profits and contract parameters. They found that a larger cost-sharing ratio will affect the contract choices of suppliers with different risk attitudes. Zhao and Zhang [31] examined a two-level PV supply chain comprising customers, assemblers, and module manufacturers. A cost-sharing model was established to analyze the impact of government subsidies. They found that a cost-sharing contract could effectively control the delivery time of module manufacturers. Brown and Sappington [32] considered the design of cost-sharing policies to incentivize electric power distribution utilities to prudently manage the expenses associated with distributed energy resource initiatives. The research revealed that optimal cost-sharing strategies are profoundly influenced by an array of environmental variables, with these variables dictating their ultimate impact. Broadly speaking, the cost savings may vary with the prevailing context in subtle and sometimes unexpected ways.

2.3. Differential Game Model

Presently, the use of Stackelberg differential games to study SCC has become a new research hot spot, with a primary focus on the investigation of cost control and collaboration between firms within the supply chain. For example, Zarei et al. [33] proposed cooperative and non-cooperative game models to explore pricing scenarios according to competition among members of the multi-level natural gas supply chain, and determined the price and demand for its products. Lu et al. [34] used Stackelberg differential games to determine the optimal equilibrium solution between the buyer and suppliers in different scenarios of carbon emissions reduction. They also discussed potential competitive and cooperative issues regarding the sustainable product-inventory model of investment in cooperative technology to reduce carbon emissions under carbon emission quotas, as well as trading and carbon compensation policies. Carbon emissions generated by company activities can be effectively lowered through special capital investments in green technology. Zu et al. [35] used low-carbon production as an example and built a Stackelberg differential game model comprising a single-echelon supply chain based on three forms of progressive environmental regulation. Under the SCC mechanism, the manufacturer and supplier have the highest degree of effort and the largest emissions reduction. Employing a Stackelberg differential game model, Peng et al. [36] investigated rivalry and collaboration in pricing and green marketing within dual-channel supply chains. Their application of this model demonstrated that optimal prices are neither always directly proportional to marketing efforts, nor do retailers with greater market shares invariably achieve superior profitability. Yang and Xiao [37] compared three game models of green supply chains with government intervention and concluded that the level of greenness increases with government intervention, but not always in favor of the green supply chain and manufacturers. In recent years, some scholars have utilized game models to address cost-sharing issues in different scenarios. Take the study of Wei and Wang [38] for example: they adopted the differential game method to study the interactive relationship between government intervention and technological innovation under decentralized decision-making without cost-sharing, decentralized decision-making with cost-sharing, and centralized decision-making, aiming to reduce carbon emissions. They found that the optimal level of technological innovation for reducing carbon emissions under decentralized decision-making was the same as that under centralized decision-making without cost-sharing. In order to enhance the optimal levels of government intervention and technological innovation in reducing carbon emissions, it is necessary to establish a virtuous interactive mechanism between government intervention and firms' technological innovation for reducing carbon emissions. Hou et al. [39] constructed a model of an investment game under cost-sharing coordination between a manufacturer and a retailer, and they found that the cost-sharing contract has a moderating effect on firms' abatement investments and profits. Wu et al. [40] explored the cost-sharing strategies of retailers and manufacturers in the Nash game. Considering four types of government subsidies, they found that the cost-sharing effects of sales efforts and carbon reduction efforts were beneficial. Li and Tan [41] designed two differential game models based on cost-sharing methods and penalty systems to explore which method best incentivizes waste incineration plants to invest in pollution control, and the results showed that the cost-sharing mechanism is more effective in controlling pollution.

2.4. Quantitative Reliability Frameworks

In the research on the reliability and performance optimization of PV systems, quantitative reliability frameworks have become a core technical support for analyzing the operational characteristics of multi-component PV systems and improving their power generation efficiency. Huang et al. [42] proposed a performance-based quantitative frame-

work for reliability prediction, which effectively fills the research gap in the reliability assessment of PV systems equipped with dynamic adjustment mechanisms such as bypass diode isolation and recovery. Van Gompel et al. [43] developed a low-cost GNN-based fault diagnosis framework, which innovatively represents PV system clusters as graph structures to integrate inter-system geographical and configurational variations. This approach successfully addresses the critical technical gap in reliability monitoring for small- and medium-scale PV installations. Maihulla and Yusuf [44] constructed a comprehensive analysis framework covering reliability, availability, maintainability, and dependability. By analyzing the changes in system reliability under different fault rates, it provides a quantitative basis for formulating targeted maintenance strategies and optimizing maintenance costs. Kumar et al. [45] proposed an integrated quantitative reliability assessment framework that combines irradiance forecasting, uncertainty modeling, and multi-state analysis, achieving the quantitative evaluation of operational reliability and the optimization of generation planning for PV-integrated systems.

2.5. Research Gap

Existing research has achieved some remarkable results, but there are still some research gaps. A cost-sharing contract is a cooperation model used by supply chain firms in project practice. For PV supply chain firms, the R&D strategies of technical equipment suppliers are usually unique, and uncertainty factors affecting suppliers' effort levels, such as demand, cost and revenue, and product performance, are usually interrelated and cannot be dealt with in isolation. However, existing research lacks consideration of cooperative behavior within PV supply chain firms from R&D to O&M and lacks a targeted analysis of the role of cost-sharing pacts in intelligent upgrading.

In this study, the suppliers and operators belong to upstream and downstream firms in the supply chain of the intelligent upgrading of PV projects. Given the long-term and dynamic changes in intelligent upgrading, Stackelberg differential games focus more on dynamic changes in the game process and the continuity of game time. As such, this study used Stackelberg differential games to analyze the cost-sharing problem in the PV supply chain from a dynamic perspective. By doing so, the study aimed to reveal the importance of cooperation between upstream and downstream companies in the supply chain in order to upgrade the entire industrial chain in the process of intelligent upgrading of PV projects.

3. Model Formulation

3.1. Problem Description

In this study, the supply chain model composed of technical equipment suppliers and PV project operators was selected as the research object to explore whether operators should share R&D costs with suppliers and what sharing model can lead to a win–win scenario. In the non-sharing mode, all R&D costs are borne by suppliers. In the R&D cost-sharing mode, to alleviate R&D pressure on suppliers and improve their enthusiasm toward R&D, operators provide financial support to suppliers for the R&D of intelligent PV products. This study selected a Stackelberg differential game model involving operators as the leaders and suppliers as the followers, and constructed the game model under the two modes of R&D cost sharing and non-sharing. Table 1 displays the variables of the present study.

Table 1. Descriptions of parameters.

Parameters	Description
$E_S(t)$	The supplier's effort level toward R&D for intelligent upgrading at time t, ($E_S(t) > 0$).
$E_X(t)$	The operator's effort level toward O&M for intelligent power stations at time t, ($E_X(t) > 0$).
$G(t)$	The increased power generation per unit product at time t (kWh).
r	The proportion of R&D investment cost borne by the operator ($0 < r < 1$).
R_S	The marginal revenue of the supplier (yuan).
R_X	The marginal revenue of the operator (yuan).
k_S	The cost coefficient of the supplier's R&D efforts ($k_S > 0$).
c	The production cost of the supplier's intelligent PV product (yuan).
w	The wholesale price of the intelligent PV product (yuan).
p	The retail price of the operator's intelligent PV product (yuan).
a	The influence coefficient of the supplier's intelligent R&D efforts on power generation ($a > 0$).
b	The influence coefficient of the operator's efforts toward maintenance on power generation ($b > 0$).
δ	The influence coefficient of power generation loss ($\delta > 0$).
α	The potential market demand for intelligent products (unit).
β	The influence coefficient of the supplier's effort level toward R&D on market demand ($\beta > 0$).
θ	The influence coefficient exerted by intelligent products' enhanced power generation on market demand ($\theta > 0$).
ρ	The discounted rate of the operators and suppliers ($\rho > 0$).

3.2. Model Assumptions

(1) The R&D input cost is $C_S = \frac{1}{2}k_S{E_S}^2(t)$. $k_S > 0$ because the R&D input cost C_S of suppliers is positively related to their R&D efforts $E_S(t)$. When $E_S(t)$ rises, the R&D input cost C_S also increases (i.e., ${C_S}'(E_S(t)) > 0$), and the expanding range shows an upward trend (i.e., ${C_S}''(E_S(t)) > 0$). Considering the convexity of the supplier's R&D effort cost, the above quadratic function represents the coefficient of the supplier's R&D effort cost.

(2) Likewise, the operator's cost of investing in maintenance is $C_X = \frac{1}{2}k_X E_X^2(t)$. $k_X > 0$ because operator C_X is positively related to maintenance efforts. When the degree of effort toward maintenance $E_x(t)$ increases, the cost of maintenance input, C_X, also rises (i.e., ${C_X}'(E_X(t)) > 0$), and the expanding range shows an upward trend (i.e., ${C_X}''(E_X(t)) > 0$). Given the convexity of the operator's cost of maintenance input, the above quadratic function represents the coefficient of the operator's R&D effort cost.

(3) The marginal revenue R_S and the production cost c of the supplier are related to the product price sold to the operator w (i.e., $R_S = w - c$). The operator's marginal income R_X is related to the price of the products purchased from the supplier w and the price sold to the user p (i.e., $R_X = p - w$).

(4) To relieve the supplier's capital pressure and encourage the supplier to conduct R&D, the operator considers sharing the R&D costs; the sharing ratio is r ($0 < r < 1$).

(5) The increase in power generation by intelligent upgrading $G(t)$ is related to the supplier's effort toward R&D and the operator's effort toward O&M; this dynamic process changes with time. The differential game equation indicating the process of change at the intelligence level is as follows:

$$\begin{cases} dG(t) = [aE_S(t) + bE_X(t) - \delta G(t)]dt \\ G(0) = G_0 \end{cases} \quad (1)$$

where a represents the influence of the supplier's effort level toward intelligent R&D on power generation, b indicates the influence of the operator's level of effort toward maintenance on power generation, δ denotes the attenuation coefficient of power generation loss, and $\delta > 0$.

(6) The purchasing behavior of the user (i.e., the project owner) in the market is assumed to be affected by the product's intelligence level. The higher the intelligence level, the greater the demand for the product. The market demand function is expressed as follows:

$$Q(t) = \alpha + \beta E_S(t) + \theta G(t) \tag{2}$$

where α indicates the potential market demand for intelligent products and $\alpha > 0$. In addition, β represents the influence coefficient of the supplier's level of effort toward R&D on market demand, and $\beta > 0$. Moreover, θ refers to the influence coefficient of the increased power generation of intelligent products on market demand, and $\theta > 0$. We restrict attention to parameter ranges and equilibrium trajectories such that market demand remains meaningful and nonnegative, i.e., $Q(t) > 0$ for all t over the planning horizon.

(7) Both the supplier and the operator aim to maximize their own profits over an infinite time horizon, and in this process, they make rational decisions based on complete information and share the same discount rate ϱ ($\varrho > 0$).

4. Stackelberg Model Analysis

4.1. The Stackelberg Model of Non-Sharing R&D Costs

First, the Stackelberg decision-making model without cost-sharing was analyzed. In the case of non-sharing costs, suppliers decide their own effort levels toward R&D and operators choose their own effort levels toward O&M. It is assumed that both parties are rational decision-makers and make choices to maximize their own benefits.

Assumption (7) states that the profits of the operator and supplier have the same discount rate in an infinite time interval. Thus, in this mode, the decision-making problems of the supplier and the operator are as follows:

$$J_S(t) = \int_0^{+\infty} e^{-\rho t}[R_S Q - C_S(E_S(t))]dt \tag{3}$$

$$J_X(t) = \int_0^{+\infty} e^{-\rho t}[R_X Q - C_X(E_X(t))]dt \tag{4}$$

At any time, the supplier's profit is determined by two aspects: the sales income of the supplier sold to the operator, and the R&D and production costs. At any time, the operator's profit is determined by two aspects: the sales revenue and the maintenance cost of intelligent PV products sold to users.

To obtain the feedback equalization strategy, the Hamilton–Jacobi–Bellman (HJB) equation was used to solve the problem. The proof of Proposition 1 is shown in Appendix A.

Proposition 1. *The equilibrium results of the differential game for PV supply chain firms are as follows.*

In the non-sharing model, the suppliers' and operators' strategies for the differential game equilibrium are as follows:

$$E_S^0 = \frac{(\rho\beta + \delta\beta + a\theta)R_S}{k_S(\rho + \delta)},\ E_X^0 = \frac{b\theta R_X}{k_X(\rho + \delta)}$$

The suppliers' and operators' optimal profit functions are as follows:

$$J_S^0(t) = e^{-\rho t}\left(M_1^0 + M_2^0 G(t)\right) \tag{5}$$

$$J_X^0(t) = e^{-\rho t}\left(N_1^0 + N_2^0 G(t)\right) \tag{6}$$

$$\begin{cases} M_1^0 = \frac{\alpha R_S}{\rho} + \frac{R_S^2(\rho\beta+\delta\beta+a\theta)^2}{2k_S\rho(\rho+\delta)^2} + \frac{b^2\theta^2 R_S R_X}{k_X\rho(\rho+\delta)^2} \\ M_2^0 = \frac{\theta R_S}{\rho+\delta} \\ N_1^0 = \frac{\alpha R_X}{\rho} + \frac{\beta^2 R_X R_S}{\rho k_S} + \frac{\alpha\beta a\theta R_X R_S}{\rho(\rho+\delta)k_S} + \frac{\alpha\theta^2 R_X R_S}{\rho(\rho+\delta)^2 k_S} + \frac{b^2\theta^2 R_X^2}{\alpha\rho(\rho+\delta)^2 k_X} \\ N_2^0 = \frac{\theta R_X}{\rho+\delta} \end{cases}$$

4.2. The Stackelberg Model of R&D Cost-Sharing

Because intelligent maintenance will reduce the operator's O&M cost and increase power generation, which will produce a profit for the operator, the operator will actively promote the R&D of intelligent products and be willing to bear part of the R&D cost for the supplier on the premise of gaining a profit. This study further analyzed the impact of the cost-sharing contract on the equilibrium solution of the model and the profits of both parties and explored whether the cost-sharing contract could improve the operator's performance.

Operators and suppliers make their own decisions to maximize their respective profits. In the first stage, operators determine their own O&M efforts $E_X(t)$, and the proportion r of R&D costs borne by them. In the second stage, according to the given $E_X(t)$ and r, suppliers decide their own R&D efforts $E_S(t)$.

In an infinite time interval, the operator's and supplier's profits have the same discount rate ρ, so the operator's decision can be obtained as follows:

$$J_S^* = \int_0^{+\infty} e^{-\rho t}[R_S Q - (1-r)C_S(E_S(t))]dt \tag{7}$$

$$J_X^* = \int_0^{+\infty} e^{-\rho t}[R_X Q - C_X(E_X(t)) - rC_S(E_S(t))]dt \tag{8}$$

The HJB equation was used to solve this problem, and a feedback equalization strategy was obtained. The proof of Proposition 2 is shown in Appendix A.

Proposition 2. *The equilibrium results of the differential game for the PV supply chain are as follows.*

Operators' and suppliers' strategies for the differential game equilibrium are as follows:

$$E_S^* = \frac{(\rho\beta+\delta\beta+a\theta)R_S}{k_S(\rho+\delta)(1-r)},\ r = \frac{2R_X - R_S}{2R_X + R_S},\ E_X^* = \frac{b\theta R_X}{k_X(\rho+\delta)}$$

The optimal profit functions of both parties are:

$$J_S^*(t) = e^{-\rho t}(M_1^* + M_2^* G(t)) \tag{9}$$

$$J_X^*(t) = e^{-\rho t}(N_1^* + N_2^* G(t)) \tag{10}$$

$$\begin{cases} M_1^* = \frac{1}{\rho}\Big[R_S\alpha + R_S\beta S_2 M_2^* + R_S\beta S_3 - (1-r)\frac{1}{2}k_S(S_2M_2^* + S_3)^2 + \\ \qquad aM_2^*(S_2M_2^* + S_3) + bS_1N_2^*M_2^*\Big] \\ M_2^* = \frac{\theta R_S}{\rho+\delta} \\ N_1^* = \frac{1}{\rho}\Big[R_X a + \beta R_X S_2 M_2^* + R_X\beta S_3 - \frac{1}{2}k_X S_1^2 N_2^{*2} \\ \qquad -\frac{1}{2}rk_S(S_2M_2^* + S_3)^2 + N_2^* a S_2 M_2^* + N_2^* a S_3 + N_2^{*2} b S_1\Big] \\ N_2^* = \frac{\theta R_X}{\rho+\delta} \end{cases}$$

where $S_1 = \frac{b}{k_x}$, $S_2 = \frac{a}{k_S(1-r)}$, $S_3 = \frac{R_S\beta}{k_S(1-r)}$.

Proposition 3: *Inferences can be obtained from Proposition 1 and Proposition 2.*

Inference 1. $E_X^0 = E_X^* = \frac{b\theta R_X}{k_X(\rho+\delta)}$.

According to the above formula, for the operator:

- There was no change in the operator's effort level toward O&M in the sharing and non-sharing conditions.
- The operator's effort level toward O&M is directly proportional to the operator's marginal revenue (R_X).
- The operator's effort level toward O&M is inversely proportional to the operator's cost coefficient of investment in maintenance (k_X).
- The operator's effort level toward O&M is directly proportional to the impact coefficient of power generation (b).
- The operator's effort level toward O&M is directly proportional to the impact coefficient of increasing power generation on market demand (θ).

Inference 2. $E_S^0 = \frac{(\rho\beta+\delta\beta+a\theta)R_S}{k_S(\rho+\delta)}$, $E_S^* = \frac{(\rho\beta+\delta\beta+a\theta)R_S}{k_S(\rho+\delta)(1-r)}$, *since* $\frac{E_S^0}{E_S^*} = \frac{(1-r)}{1}$, *therefore* $E_S^0 < E_S^*$.

According to the above formula, for suppliers:

a. In the cost-sharing mode, the supplier's effort level toward R&D is higher than that in the non-sharing mode.
b. The supplier's effort level toward R&D is directly proportional to the supplier's marginal revenue (R_S).
c. The supplier's effort level toward R&D is inversely proportional to the supplier's cost coefficient of R&D input (k_S).

Inference 3. *Due to the proportion of the cost sharing* $r = \frac{2R_X-R_S}{2R_X+R_S}$ *, it can be deduced that:* $r = 1 - \frac{1}{\frac{R_X}{R_S}+\frac{1}{2}}$.

Thus, the value of the sharing ratio r is directly proportional to $\frac{R_X}{R_S}$, that is, r is directly proportional to the operator's marginal revenue, and is inversely proportional to the supplier's marginal revenue.

Inference 4. *The difference in profit between the operator and the supplier:*

(1) The difference in profit between the operator and supplier in the non-sharing mode. This is because the operators' and suppliers' profits comprise a variable related to time; hence, there is no equal value of profit under a time change. However, when $R_X - R_S$, $M_2 = N_2$ can be obtained, and we derive Equations (5) and (6), respectively. $Jx - Js = M_1 - N_1 = X$, where X is a time-independent constant. Namely:
When $R_X = R_S$, $J_X = J_S + X$;
When $R_X > R_S$, $J_X > J_S + X$;
When $R_X < R_S$, $J_X < J_S + X$.

(2) The difference in profit between operators and suppliers in the cost-sharing mode. Likewise, because the operator's and supplier's profits comprise a variable related to time, there is no equal value for profit under a time change. However, when $Rx = Rs$, $M_2^* = N_2^*$ can be obtained, thereby realizing Equations (9) and (10):
$J_X^* - J_S^* = M_1^* - N_1^* = Y$, where Y is a time-independent constant. Namely:
When $R_X = R_S$, $J_X^* = J_S^* + Y$;
When $R_X > R_S$, $J_X^* > J_S^* + Y$;
When $R_X < R_S$, $J_X^* < J_S^* + Y$.

(3) When $R_X = R_S$, $\frac{R_X}{R_S} = 1$, and then the optimal share ratio $r = 1 - \frac{1}{\frac{R_X}{R_S}+\frac{1}{2}} = \frac{1}{3}$.

Inference 5. *The relationship between wholesale price w and the difference in profit:*

The value of wholesale price w has the largest difference in profit between the sharing and non-sharing modes.

Due to $V_S^*(G) - V_S^0(G) = \frac{\beta^2}{4k_S\rho}(w-c)[2(p-w)-(w-c)]$, the partial derivative of w can be obtained: $\frac{\partial}{\partial w}\left(V_S^*(G) - V_S^0(G)\right) = \frac{\beta^2}{2ks\rho}[p-3w+2c]$.

If the partial derivative is equal to zero, then when the supplier's profit difference is the largest, wholesale price w is the following: $w = \frac{p+2c}{3}$.

We can realize $R_X = 2R_S$. As such, the optimal sharing ratio $r = \frac{3}{5}$.

The difference between the profits shared and not shared by the operator is inversely proportional to the wholesale price w.

Because of $V_X^*(G) - V_X^0(G) = \frac{\beta^2}{8k_S\rho}(2P-3w+c)^2$, the operator's profit difference is inversely proportional to the wholesale price w.

5. Simulations and Sensitive Analysis

The actual data of PV firms were used to analyze the cost-sharing effect of intelligent upgrading R&D between suppliers and operators.

5.1. Data Collection

The data employed for model validation are sourced from actual PV industry cases and expert predictions, among which the potential market demand (α) is 200,000. Each component uses a new component-level fault detector, and the production cost of the fault-detector product (c) is 35 yuan. The final price imposed by the operator on the customer (p) is 60 yuan, and the wholesale price of the product (w) is 48 yuan. According to the proportion of cost sharing between the operator and supplier, the wholesale price can fluctuate. The remaining nine items of data are based on experts' experience and predictions. Table 2 lists the data used in this numerical example. The software MATLAB 2020a was employed to analyze specific results.

Table 2. Case parameter assignment.

Operator		Supplier		Market Demand		Other	
k_X	12	k_S	16	$G(0)$	0	ρ	0.9
p	60	c	35	α	200,000		
a	2	w	48	β	1		
δ	0.6	b	1.5	θ	1		

5.2. Results of Numerical Analysis

By substituting the relevant parameters into the analytical expressions given by Proposition 1, Proposition 2, and the inferences, the following calculations and graphs were obtained using MATLAB, including the impact of the cost-sharing ratio r on the profits of both parties, the relationship comparing profits between suppliers and operators before and after cost-sharing, and the impact of the product's wholesale price w on the Pareto improvement effect of the cost-sharing contract. The unit of profit in both the calculation results and the figures is 10,000 yuan.

5.2.1. The Profits of Suppliers and Operators in the Sharing and Non-Sharing Modes

In the sharing mode, profits were determined according to the optimal sharing ratio, $r = 0.297$. Figure 1 presents the profit change curves for both parties.

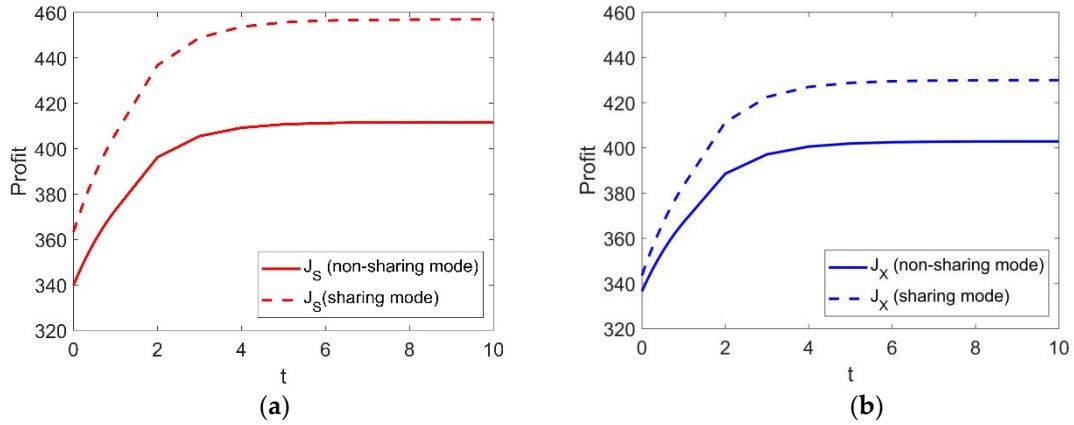


Figure 1. (**a**) Profit comparison of suppliers under different modes; (**b**) Profit comparison of operators under different modes.

In the cost-sharing mode, the profits of both parties increase, and the supplier's profit growth in the cost-sharing mode is significantly higher than that of the operator. In the initial stage, the profits of both parties rise rapidly under the two modes, and the profit growth rate in the cost-sharing mode is greater. Subsequently, the profits of both parties tend to remain flat. When $t = 0$, the supplier's profit in the cost-sharing mode is 234,320 yuan more than that in the non-sharing mode. When $t = 10$, the supplier's profit in the sharing mode is 452,090 yuan more than that in the non-sharing mode. When $t = 0$, the operator's profit in the cost-sharing mode is 70,200 yuan more than that in the non-sharing mode. When $t = 10$, the profit in the cost-sharing mode is 271,050 yuan more than that in the non-sharing mode.

5.2.2. The Supplier's and Operator's Profits Based on Different Share Ratios, r

The results for J_S and J_X under different sharing ratios were calculated according to the formula proposed in this study. The optimal share ratio of the operator is $r = 0.297$; the plotted curve is displayed in Figure 2.

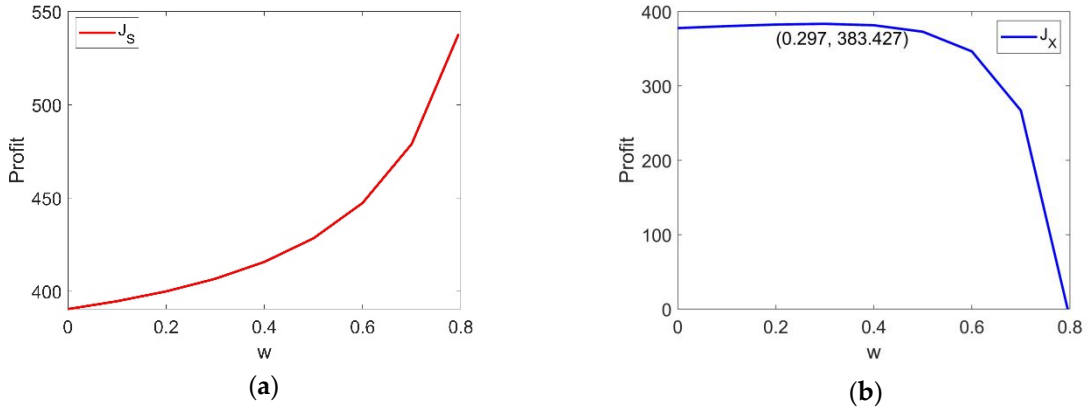


Figure 2. (**a**) The impact of the share ratio on supplier profit; (**b**) The impact of the share ratio on operator profit.

When $r = 0.297$ and $J_X = 3.834$ million yuan, which is larger than that under the other ratios, the operator's profit reaches its maximum. In addition, with an increase in the

share ratio, the supplier's profit monotonously increases, and the rising speed becomes increasingly faster. When $r < 0.297$, the operator's profit monotonically increases. When $r > 0.297$, the operator's profit monotonically declines, and the decreasing speed becomes increasingly faster.

5.2.3. The Relationship Between Wholesale Price w and Optimal Share Ratio r

According to the formula $r = \frac{2R_X - R_S}{2R_X + R_S}$, the cost-sharing ratio is determined by the marginal income of both parties. Based on reality, the supplier's production cost c and the operator's retail price p will not change in a period of time and can be regarded as a fixed value. Hence, wholesale price w directly determines the change in the cost-sharing ratio r. As such, it is necessary to discuss the change in w. When $t = 1$, w increases from 36 to 51.67. Figure 3 depicts the influence curve of the change in the wholesale price of a product w on the optimal sharing ratio r.

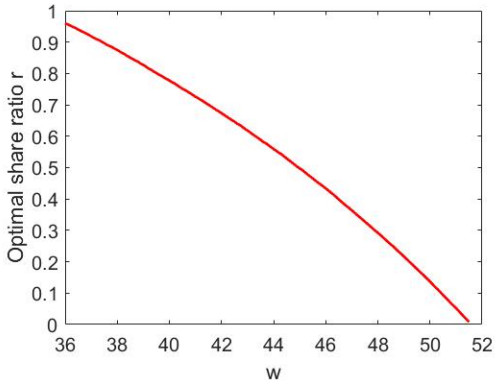


Figure 3. The influence of the product's wholesale price w on the optimal distribution ratio r.

The wholesale price w of a product is inversely proportional to the optimal share ratio r. When $w = 51.67$, $r = 0$—which means that if the wholesale price of the product set by the supplier is higher than 51.67, the cost to the operator is too high—and the R&D cost-sharing subsidy will not be provided to the supplier.

5.2.4. The Profits of Suppliers and Operators at Different Wholesale Prices

When $t = 1$, w increases from 36 to 51.67. Figure 4 portrays the profit trends of the suppliers and operators under the non-sharing and optimal cost-sharing ratios.

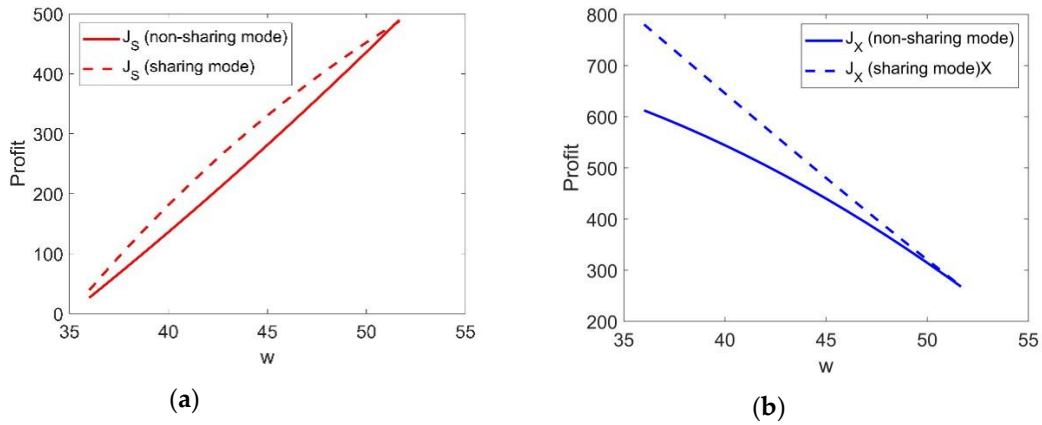


Figure 4. (**a**) The impact of wholesale price w on suppliers under different modes; (**b**) The impact of wholesale price w on operators under different modes.

In any mode, the supplier's profit is directly proportional to the product's wholesale price w, and the operator's profit is inversely proportional to the product's wholesale price w. The profits of both parties in the cost-sharing mode are higher than those in the non-sharing mode. In addition, Figure 4a indicates that the supplier's profit in the sharing and non-sharing modes is relatively close when the wholesale price is low. With an increase in the wholesale price, the profit difference between the operator and supplier exhibits a two-stage change, first rising and then falling. When the wholesale price increases to 51.67, the profits of both are the same. As seen in Figure 4b, when the wholesale price is low, the operator's profit in the cost-sharing mode is significantly higher than that in the non-sharing mode. With an increase in the wholesale price, the difference between the operator and supplier gradually decreases, and when the wholesale price rises to 51.67, their profits remain the same.

5.2.5. The Profit Difference Between Suppliers and Operators over Time

When $R_X = R_S$, $w = 47.5$. In the sharing mode, the profit is calculated according to the optimal sharing ratio $r = 0.333$. Figure 5 presents the profit difference between the operator and supplier in different modes.

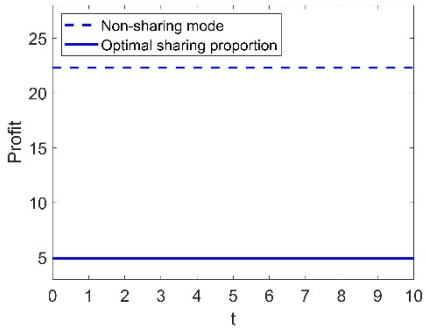


Figure 5. The profit difference between the operator and supplier in different modes.

When time t increases from 0 to 10, the profit difference between the operator and supplier in the non-sharing mode is 223,040 yuan, and the profit difference between them in the sharing mode is 49,260 yuan. Regardless of the sharing and non-sharing modes, the profit difference between the operator and supplier does not change with time and is a constant that is independent of time.

5.2.6. The Profit Difference Between the Supplier and Operator Under Different Wholesale Prices of Products

When $t = 1$, w increases from 36 to 51.67 according to the formula proposed in this paper. Figure 6 displays the change curve of the profit difference between suppliers and operators in the sharing and non-sharing modes.

The profit difference between suppliers and operators in the sharing and non-sharing modes first rises and then falls, reaching an extreme point. When $w = 43$, the profit difference reaches a maximum value of 500,000 yuan, increasing to the left and decreasing to the right. In addition, the profit difference in operators monotonically declines, and the profit difference between the sharing and non-sharing modes falls significantly, with an increase in the wholesale price. When $w = 36$, the operator can obtain the maximum revenue in the sharing mode. The minimum revenue is obtained when $w = 51.67$.

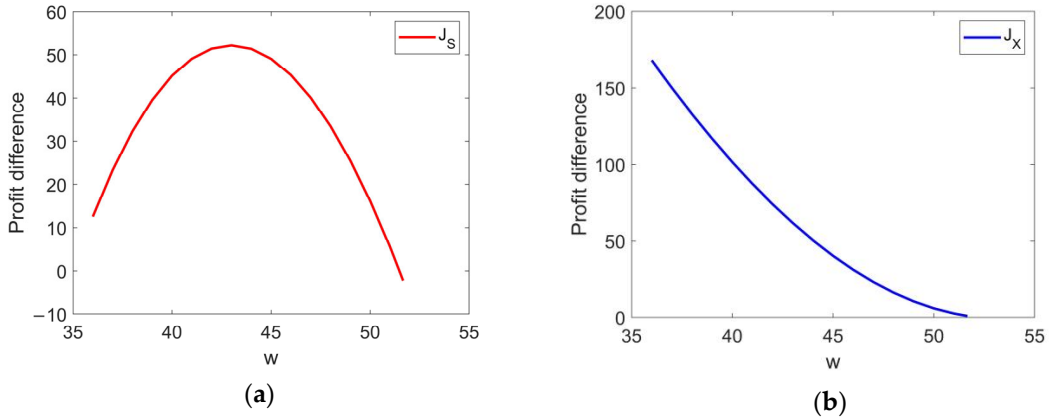


Figure 6. (**a**) Change in suppliers' profit difference with w under different modes; (**b**) Change in operators' profit difference with w under different modes.

5.2.7. The Profits of Suppliers and Operators with a Change in Parameter β

When t = 1, β ranges from 0 to 10 according to the formula proposed in this study. Figure 7 depicts the profit change trend of suppliers and operators based on the non-sharing and optimal sharing ratios.

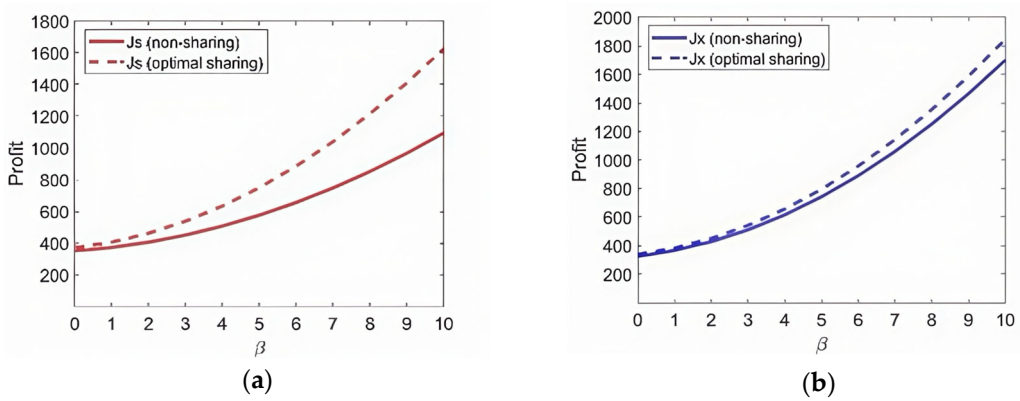


Figure 7. (**a**) The impact of β on supplier profit in the sharing and non-sharing modes; (**b**) The impact of β on operator profit in the sharing and non-sharing modes.

No matter which mode, the profits of both parties are proportional to parameter β, and the profits of both parties in the cost-sharing mode are higher than those in the sharing mode. Figure 7a indicates that the supplier's profits in the sharing and non-sharing modes are close when the value of parameter β is small. As the value of parameter β increases, the profit difference between them gradually widens. As seen in Figure 7b, operators' profits in the sharing and non-sharing modes are close when parameter β is small, and the difference between them gradually widens with the increase in parameter value. In addition, these two Figures suggest that no matter which mode, as the value of parameter β increases, the profits of suppliers and operators increase faster and faster with parameter β.

5.2.8. The Profit Difference Between Suppliers and Operators in the Sharing and Non-Sharing Modes When β Changes

When t = 1, β increases from 0 to 10. According to the formula proposed in this study, the change curve of the profit difference between suppliers and operators in the sharing and non-sharing modes is shown in Figure 8.

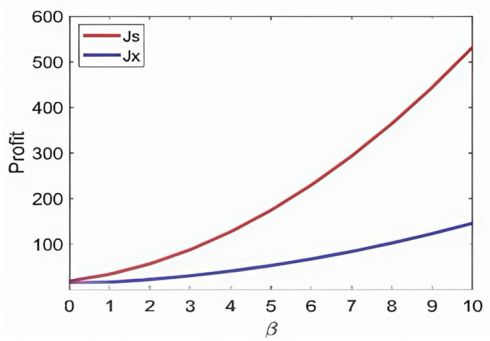


Figure 8. The profit difference between suppliers and operators in the sharing and non-sharing modes with a change in β.

The profit difference in the sharing and non-sharing modes is proportional to parameter β. The operator's profit difference in the sharing and non-sharing modes is also proportional to parameter β. The two differences are close when the value of parameter β is small. With the increase in the value of parameter β, the rising speed of the supplier's profit difference is significantly higher than that of the operator's profit difference. When $\beta = 0$, the supplier's profit differences are 186,360 yuan and 1.86 million yuan, and the operator's profit difference is 1.54 million yuan. The difference between the operator and supplier is only 320,900 yuan; When $\beta = 10$, the supplier's profit difference is 5.31 million yuan and the operator's profit difference is 1.45 million yuan (a difference of 3.86 million yuan).

6. Discussion

6.1. Incentives for the Effort Level of Operators and Suppliers

There is no change in the operator's degree of effort toward maintenance in the cost-sharing mode; that is, the operator's effort level is not affected by cost sharing. Under the incentive of the cost-sharing mechanism, the supplier's effort level improves, and thus, the cost-sharing mechanism encourages suppliers to work harder to develop new products. Because the operator's level of effort toward maintenance is directly proportional to the operator's own impact factor of power generation b, the operator's level of effort toward maintenance can be improved only if the supplier develops intelligent products that can enhance power generation and increase the value of impact factor b. Since the operator's level of effort toward maintenance is proportional to the influence coefficient θ, the greater the impact of the electricity generation increased by intelligent products on market demand, the more the operator's level of effort toward maintenance can be improved.

6.2. Improved Profits for Operators and Suppliers

Figure 1 directly compares the changes in the profits of both parties over time under the two modes. In the cost-sharing mode, the profits of operators and suppliers are both greater than those in the non-sharing mode, which indicates that the cost-sharing mechanism achieves Pareto improvement in the profits of operators and suppliers, promotes their active participation, and makes operators take the initiative to bear part of the R&D costs of suppliers. If we consider maximizing the operator's interests, the optimal sharing ratio $r = \frac{2R_X - R_S}{2R_X + R_S}$ should be chosen, and the operator will gain the most from the sharing ratio.

6.3. The Difference in Profits Between Operators and Suppliers

When the optimal sharing ratio is $r = \frac{1}{3}$, the profit difference between the supplier and operator is equal to a constant independent of time, regardless of the cost-sharing or non-sharing modes, for example:

When $0 < r < \frac{1}{3}$, $J_X < J_S + X$;

When $r = \frac{1}{3}$, $J_X = J_S + X$;
When $r > \frac{1}{3}$, $J_X > J_S + X$.

where X is a constant independent of time.

Because the supplier's profit is directly proportional to the wholesale price w and the operator's profit is inversely proportional to the wholesale price w, it is necessary to choose the value of w appropriately. If considering the interests of both parties, both sides achieve satisfaction on the basis of the operators, and the optimal allocation proportion is mediated because the cost and retail price are relatively fixed; by adjusting the wholesale price, the profit gap narrows between operators and suppliers. At this point, the value is chosen in the wholesale price, the cost price, and the retail price, $w = \frac{p+c}{2}$. The optimal proportion of allocation is $r = \frac{1}{3}$, and the operators' and suppliers' profits achieve a balance.

6.4. The Profit Difference Between Sharing and Non-Sharing for Operators and Suppliers

For suppliers, there is an extreme point in the profit difference between the sharing and non-sharing modes. When $w = \frac{p+2c}{3}$ (i.e., when the optimal sharing ratio is $r = \frac{3}{5}$), the profit difference between the sharing and non-sharing modes reaches a maximum. For the operator, the profit difference is inversely proportional to wholesale price w.

6.5. The Impact of Parameter β on the Profits of Suppliers and Operators

The change in parameter β has a great influence on the profits between suppliers and operators, as well as the profit difference between the sharing and non-sharing modes. The larger the parameter β is, the greater the market demand for intelligent products will be, and the greater the profits of suppliers and operators will be as well. Under the cost-sharing mechanism, the improvement effect also increases with the rise in the influence coefficient β. In addition, the improvement effect of suppliers is greater than that of operators. Thus, the greater the sensitivity β of intelligent products to market demand, the more active suppliers will be in researching and developing intelligent products, and the more active operators will be in selling intelligent products. Further, suppliers will be more inclined to engage in cost-sharing than operators.

7. Managerial Insights

Through theoretical research and model analysis, the following management implications were obtained:

(1) When determining whether and to what extent they should share R&D costs with suppliers. Market demand for intelligent products is a prerequisite for operators to share costs with suppliers. When the market demand is great, operators should choose a higher proportion of cost sharing. Operators should act as suppliers in the product development process based on the actual level of effort expended to design a cost-sharing scheme, and the supplier's actual effort level can be measured through intelligent products to improve the output. When the cost of electricity increases, operators should increase and improve their capacity to further promote market demand for intelligent products. This implication follows from Inference 3 and is supported by the numerical evidence in Figure 2.

(2) To consummate an agreement, operators and suppliers should contemplate the following two scenarios while determining the apportionment ratio: When operators' funds occupy a dominant position, the operators prioritize their own interests and try to maximize them by lowering wholesale prices while selecting the optimal share ratio. When a supplier's technology occupies a dominant position, in terms of cost sharing, the operators need to simultaneously consider the interests of suppliers and choose a satisfactory cost-sharing ratio for both parties so that they can reach a profit-

balance contract. This recommendation is supported by Inference 4 and Inference 5, which analyze the profit differences under different power structures, as confirmed by Figure 4.

(3) Suppliers should design a dynamic adjustment mechanism for the wholesale price of intelligent products, based on changes in the amount of power generation improved by their R&D efforts. As power generation increases, the wholesale price should be raised appropriately to increase revenue for suppliers while ensuring profitability for both parties, and the wholesale price is neither too high nor too low, as this could result in an unequal distribution of benefits. This is consistent with Inference 5 and the inverse relationship between wholesale price w and the optimal sharing ratio illustrated in Figure 3.

8. Conclusions

In the context of intelligent upgrading of PV power stations, downstream operators can achieve better market performance by cooperating with the intelligent upgrading of upstream suppliers through hard maintenance, which is a typical form of cooperation in supply chain management practices. This study assumed that consumer demand would be affected by the intelligence level of the PV product and the quality of maintenance. Since projects are affected by efforts toward intelligent upgrading and have dynamic characteristics of change in multi-period continuous production, two differential game models of operators and suppliers were constructed.

The following conclusions were obtained by solving the model and analyzing the calculation examples. First, there is no change in operators' maintenance efforts in the sharing and non-sharing modes, and suppliers' efforts will be improved under the incentive of the cost-sharing mechanism, which will encourage suppliers to work harder to develop new products. Second, in the cost-sharing mode, the profits of both operators and suppliers are greater than those in the non-sharing mode. In our baseline setting and tested parameter ranges, the cost-sharing mechanism yields higher profits for both the operator and the supplier, achieving a Pareto improvement. When the optimal sharing ratio is reached, operators gain the most from the sharing mechanism. In addition, when the wholesale price is the median of the cost price and the retail price, and the profit difference between suppliers and operators is equal to a constant that has nothing to do with time (whether in the cost-sharing mode or not), and the profits of operators and suppliers are balanced. Finally, under the cost-sharing mechanism, the greater the market demand for intelligent products, the greater the profit improvement effect of suppliers and operators, and the improvement effect of suppliers is greater than that of operators.

This study analyzed how cost-sharing contracts improve the profits of suppliers and operators. However, the study identifies several limitations. To simplify the analysis, this study employs a linear demand function. While the qualitative incentive effect of cost sharing is expected to persist under more realistic demand specifications, such as nonlinear or truncated linear forms, the closed-form expressions and equilibrium outcomes may differ. Second, the model assumes information symmetry. In practice, if the supplier's R&D efforts are non-observable or the operator receives only noisy performance signals, pure cost sharing alone may be insufficient. Additionally, the model does not incorporate policy factors such as government subsidies or carbon trading mechanisms. These external interventions could influence the optimal sharing ratio and pricing incentives by altering marginal revenues or effective costs, representing a valuable dimension for subsequent research. Finally, the current model is limited to a single manufacturer and two retailers. Future work could explore the intelligent upgrading of the PV industry in scenarios

involving multiple firms, within the framework of multi-level supply chains or complex competitive networks.

Author Contributions: Conceptualization, Y.H.; methodology, Y.H. and Y.C.; software, Y.H.; validation, Y.H. and Y.C.; formal analysis, Y.H. and Y.C.; investigation, Y.H. and L.H.; resources, L.H.; data curation, Y.H.; writing—original draft preparation, Y.C. and Y.H.; writing—review and editing, Y.H. and L.H.; visualization, Y.C.; supervision, L.H.; project administration, Y.H. and L.H.; funding acquisition, Y.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Major project of National Social Science Foundation of China (Grant No. 22&ZD068 and 23VRC040), and the Fundamental Research Funds for the Central Universities of China (Grant No. DUT25RW305), Research Launch Fund of Ningbo University of Technology (grant No. 2023KQ095) and Philosophy and Social Science Research Base of Ningbo (Grant No. JD6-026).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the School of Economics and Management, Ningbo University of Technology (NBUT2025061701) on 17 June 2025.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: We declare that we have no financial and personal relationships with other people or organizations that could inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, "R&D cost sharing of intelligent upgrading of photovoltaic power stations".

Appendix A

Proof of Proposition 1. The model first solves the operator's optimal control problem. According to Equation (4), the operator's optimal profit function J_X at time t is:

$$J_X^0(t) = e^{-\rho t} V_X(t) \tag{A1}$$

where $V_X^0(t) = \max\limits_{E_X^0} \int_t^\infty e^{-\rho(s-t)} \left\{ R_X Q(t) - C_X^0\left(E_X^0(t)\right) \right\} ds$.

The operator's optimal control problem satisfies the following HJB equation:

$$\begin{aligned} \rho V_X^0(t) = \max_{E_X^0} \Big\{ & R_X\left[\alpha + \beta E_S^0(t) + \theta G(t)\right] - \tfrac{1}{2} k_X \left(E_X^0\right)^2(t) + \\ & V'_X(G)\left(a E_S^0(t) + b E_X^0(t) - \delta G(t)\right) \Big\} \end{aligned} \tag{A2}$$

Equation (A2) is a concave function of E_X^0, and $J_X^{0\prime}$ represents the first derivative of J_X^0. The derivative solution of the above formula is:

$$E_X^0 = \frac{b V'_X(G)}{k_X^0} \tag{A3}$$

Equation (A3) shows that the operator's maintenance effort E_X^0 is proportional to the influence of the effort level toward maintenance on power generation b and is inversely proportional to the cost coefficient of the coefficient for the maintenance effort k_X.

Just as in the above proof process, Equation (3) indicates that the supplier's optimal profit function at time t is:

$$J_S^0(t) = e^{-\rho t} V_S^0(t) \tag{A4}$$

where $V_S^0(t) = \max_{E_S^0} \int_t^\infty e^{-\rho(s-t)} \{R_S Q(t) - C_S^0(E_S^0(t))\} ds$.

The supplier's optimal control satisfies the following HJB equation:

$$\begin{aligned} \rho V_S^0(t) = \max_{E_S^0} \Big\{ & R_S[\alpha + \beta E_S^0(t) + \theta G(t)] - \tfrac{1}{2} k_S (E_S^0)^2(t) + \\ & V'_S(G)(aE_S^0(t) + bE_X^0(t) - \delta G(t)) \Big\} \end{aligned} \tag{A5}$$

Equation (A5) is a concave function of E_S^0, and $J_S^{0'}$ denotes the first derivative of J_S^0. The derivative solution of the above formula is:

$$E_S^0 = \frac{R_S \beta + a V'_S(G)}{k_S^0} \tag{A6}$$

Equation (A6) shows that the supplier's R&D effort E_S^0 is proportional to the marginal income R_S, the influence of R&D effort on power generation a, and the influence of R&D effort on market demand β; it is inversely proportional to the R&D cost coefficient k_S^0.

Take E_X^0 and E_S^0 into Equations (A2) and (A5), then get:

$$\begin{aligned} \rho V_X^0(t) = R_X & \left[\alpha + \beta \left(\frac{R_S \beta + a V_S'^0(G)}{k_S} \right) + \theta G(t) \right] - \tfrac{1}{2} k_X \left[\frac{b V_X'^0(G)}{k_X} \right]^2 + \\ & V'_x(G) \left[\left(a \frac{R_S \beta + a V_S'^0(G)}{k_S} \right) + b \frac{b V_X'^0(G)}{k_X^0} - \delta G(t) \right] \end{aligned} \tag{A7}$$

$$\begin{aligned} \rho V_S^0(t) = R_S & \left[\alpha + \beta \frac{R_S \beta + a V_S'^0(G)}{R_S} + \theta G(t) \right] - \tfrac{1}{2} k_S \left[\frac{R_S \beta + a V_S'^0(G)}{k_S} \right]^2 + \\ & V'_S(G) \left(a \frac{R_S \beta + a V_S'^0(G)}{R_S} + b \frac{b V_X'^0(G)}{R_X} - \delta G(t) \right) \end{aligned} \tag{A8}$$

Based on the characteristics of the differential equations in Equations (A7) and (A8), the linear optimal value function of G is the solution to the HJB equation.

Thus, let the functional expressions of $V_X^0(t)$ and $V_S^0(t)$ be:

$$V_X^0(t) = N_1^0 + N_2^0 G(t),\ V_S^0(t) = M_1^0 + M_2^0 G(t) \tag{A9}$$

where N_1^0, N_2^0, M_1^0, and M_2^0 are the undetermined coefficients. Substitute Equation (A9) into Equations (A7) and (A8), respectively, sort and compare the coefficients of similar terms, and obtain the constraint equations N_1^0, N_2^0, M_1^0, and M_2^0. We solved the equations to obtain N_1^0, N_2^0, M_1^0, and M_2^0, and substituted them into Equation (A9). The expressions for the functions $V_X^0(t)$ and $V_S^0(t)$ can be obtained as follows:

$$V_X^0(t) = N_1^{0\wedge} + N_2^{0\wedge} G(t),\ V_S^0(t) = M_1^{0\wedge} + M_2^{0\wedge} G(t) \tag{A10}$$

By substituting Equation (A10) into Equations (A1) and (A3), the operators' and suppliers' optimal profit value functions are given by Equations (5) and (6), respectively. By substituting the derivative of the profit function into Equations (A3) and (A6), the supplier's optimal R&D effort and the operator's optimal maintenance effort can be derived. The proof is complete. □

Proof of Proposition 2. A reverse induction method is used to solve this problem. First, the supplier's decisions are resolved. The same process is followed as that in the proof of Proposition 1. Per Equation (8), the supplier's optimal profit function at time t is:

$$J_S^* = e^{-\rho t} V_S(G) \tag{A11}$$

where $V_S^*(t) = \max_{E_S^*} \int_t^\infty e^{-\rho(s-t)} \{R_S Q(t) - (1-r) C_S^*(E_S^*(t))\} ds$.

The supplier's optimal control satisfies the HJB equation:

$$\begin{aligned} \rho V_S^*(G) = \max_{E_S^*} \Big\{ & R_S[\alpha + \beta E_S(t) + \theta G(t)] - (1-r)\tfrac{1}{2} k_S E_S^{*2}(t) + \\ & V_S'^*(G)\left[a E_S^*(t) + b E_X^*(t) - \delta G(t)\right] \Big\} \end{aligned} \tag{A12}$$

Equation (A12) is a concave function of E_S^*, $J_S^{*\prime}$ represents the first derivative of J_S^*, and the maximization problem is solved. The derivative solution of the above formula is:

$$E_S^* = \frac{a V_S'^*(G) + R_S \beta}{k_S (1-r)} \tag{A13}$$

The response function shows that the supplier's degree of effort toward R&D E_S^* rises with the increase in the R&D cost ratio r undertaken by the operator, the supplier's own marginal profit R_S, the impact-related degree a of the effort toward R&D on the increase in power generation, and the impact coefficient β of the supplier's effort toward R&D on market demand; it declines with the increase in the R&D cost coefficient k_S.

Just as in the proof process of Proposition 1, the operator's optimal profit function J_X^* at time t is:

$$J_X^* = e^{-\rho t} V_X^*(G) \tag{A14}$$

where $V_X^*(t) = \max_{E_X^*} \int_t^\infty e^{-\rho(s-t)} \left\{ R_X Q^{(t)} - C_X^*(E_X^*(t)) - r C_S^*(E_S^*(t)) \right\} ds$.

Then, the operator's optimal control satisfies the following HJB equation:

$$\begin{aligned} \rho V_X^*(G) = \max_{E_X^*} \Big\{ & R_X(\alpha + \beta E_S^* + \theta G) \tfrac{1}{2} k_X E_X^{*2} - \\ & \tfrac{1}{2} r k_S E_S^{*2} + V_X'^*(G)\left(a E_S^* + b E_X^* - \delta G\right) \Big\} \end{aligned} \tag{A15}$$

According to the Hessian matrix, Equation (A15) shows that E_X and r are concave functions, and we can obtain the following according to the first-order conditions:

$$E_X^* = \frac{b V_X'^*(G)}{k_X},\ r = \frac{2R_X - R_S}{2R_X + R_S} \tag{A16}$$

To facilitate the derivation, we obtained the following from Equations (A16) and (A13):

$$E_X^* = \frac{b V_X'^*(G)}{k_X} = S_1 V_X'^*(G)$$

$$E_S^* = \frac{a}{k_S(1-r)} V_S'^*(G) + \frac{R_S \beta}{k_S(1-r)} = S_2 V_S'^*(G) + S_3$$

where $S_1 = \frac{b}{k_X}$, $S_2 = \frac{a}{k_S(1-r)}$, $S_3 = \frac{R_S \beta}{k_S(1-r)}$.

By substituting E_X^* and E_S^* into Equations (A15) and (A12), we obtained:

$$\begin{aligned} \rho V_X^*(G) = {} & R_X\left(a + \beta\left(S_2 V_S'^*(G) + S_3\right) + \theta G\right) - \tfrac{1}{2} k_X S_1^2 V_X'^*(G)^2 - \\ & \tfrac{1}{2} r k_S \left(S_2 V_S'^*(G) + S_3\right)^2 + N_2^* \left[a\left(S_2 V_S'^*(G) + S_3\right) + b S_1 V_X'^*(G) - \delta G\right] \end{aligned} \tag{A17}$$

$$\rho V_S^*(G) = R_S\left[\alpha + \beta\left(S_2 V_S'^*(G) + S_3\right) + \theta G(t)\right] - (1-r)\tfrac{1}{2}k_S\left(S_2 V_S'^*(G) + S_3\right) + V_S'^*(G)\left[a\left(S_2 V_S'^*(G) + S_3\right) + bS_1 V_X'^*(G) - \delta G(t)\right] \quad \text{(A18)}$$

According to the characteristics of the differential equations in Equations (A17) and (A18), the linear optimal value function of G is the solution to the HJB equation.

Let the expressions of functions $V_X^*(G)$ and $V_S^*(G)$ be:

$$V_X^*(G) = N_1^* + N_2^* G(t),\ V_S^*(G) = M_1^* + M_2^* G(t) \quad \text{(A19)}$$

where N_1^*, N_2^*, M_1^*, and M_2^* are the undetermined coefficients. Substitute Equation (A19) into Equations (A17) and (A18), respectively, then sort and compare the coefficients of similar terms and obtain the constraint equations N_1^*, N_2^*, M_1^*, and M_2^*. We solved the equations to obtain $N_1^{*\wedge}$, $N_2^{*\wedge}$, $M_1^{*\wedge}$, and $M_2^{*\wedge}$, and substituted them into Equation (A19). The expressions for the functions $V_X^*(t)$ and $V_S^*(t)$ can be obtained as follows:

$$V_X^*(G) = N_1^{*\wedge} + N_2^{*\wedge} G(t),\ V_S^*(G) = M_1^{*\wedge} + M_2^{*\wedge} G(t) \quad \text{(A20)}$$

By substituting Equation (A20) into Equations (A11) and (A14), respectively, we obtained the suppliers' and operators' optimal profit value functions as in Equations (9) and (10), respectively. The proof is complete. □

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