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Research on the Cost of Distributed Photovoltaic Plant of China Based on Whole Life Cycle Perspective

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ABSTRACT Because of the continuous reduction of subsidies for distributed photovoltaic power generation and the future participation in bidding, the cost per kilowatt hour of the electricity will become an important economic indicator for investment decision-making and bidding strategies. In this paper, a cost-benefit model of distributed photovoltaic power plant (DPPP) has been proposed based on its own characteristics. This paper further presents an investment decision analysis method about the cost of electricity per kilowatt hour through analyzing several parameters, such as the whole life cycle of installed costs, the annually effective utilization hours, the loan interest rates, the feed-in tariff, the income tax rate, and the subsidized electricity prices of the DPPP. The fruitful work that related to various economic indicators results in a solution of effective analysis of the DPPP investment decisions. Furthermore, this paper provides the reference for the cost accounting of the future photovoltaic power generation bidding on the grid.

INDEX TERMS Cost per kilowatt hour, distributed photovoltaic, total life cycle.

I. INTRODUCTION

With the rapid development of the distributed photovoltaics, research on investment decision management and electricity cost of distributed photovoltaic power plant (DPPP) has attracted much attention from the academia.

Firstly, in the field of the comprehensive benefits of DPPP research, Ming *et al.* [1] mainly consider the line loss benefits, electricity price benefits and environmental benefits of distributed generation. Zhendong *et al.* [2] analyze the benefits of grid-connected photovoltaic systems from the economic, environmental, and social benefits. Rui *et al.* [3] constructs the revenue evaluation model, cost evaluation model, and further present value model of the distributed power/microgrid project respectively. He takes into account the electricity revenue, subsides, and reduce the loss of power, delay the social benefits of distribution network backup costs. Wang *et al.* [4] provide a provincial quantitative analysis based on photovoltaic power generation and photovoltaic subsidy policies. Adaramola [5] conduct an economic analysis of a rooftop 2.07 kW grid-connected photovoltaic power generation system to determine the its annual and monthly energy cost. Bakhshi and Sadeh [6] presents a comprehensive economic analysis method for selecting PV array structure types and proposes an efficiency model for calculating annual power generation. In grid-connected photovoltaic (GCPV) systems, applying a solar tracker results in a higher energy production level. However, this does not necessarily mean a greater profit due to the excess of generation selling, since the capital and maintenance costs increase as well. Georgitsioti *et al.* [7] consider the change in supporting mechanisms - feed-in tariffs (FIT), and study the cost-effectiveness of residential PV systems in the UK. Furthermore, Huiming *et al.* [8] find that the PV-based targeted poverty alleviation policies focus on project construction and electricity (agricultural products) sales, then the income distribution of photovoltaic power generation. Shi *et al.* [9] present a two-tier model for optimal allocation of distributed power sources in the active distribution networks. The objective of upper-level planning is to minimize the annual comprehensive cost of distribution networks, and the objective of lower level planning is to minimize the active power cut-off of distributed generation

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through active management mode. Zhang *et al.* [10] proposes a multidisciplinary approach to jointly plan PEV charging stations and distributed PV power plants on a coupled transportation and power network. Numerical experiments show that investing in distributed PV power plants with PEV charging stations has multiple benefits, e.g., reducing social costs, promoting renewable power integration, and alleviating power congestion. The benefits become more prominent for utilizing PV generation with reactive power control, which can also help to enhance power supply quality. Su *et al.* [11] propose an optimization model to maximize the economic benefits for rooftop PV-battery distributed generation in a peer-to-peer (P2P) energy trading environment. The goal of the proposed model is to investigate the feasibility of such a renewable source participated in P2P energy trading by examining the economic benefits.

Secondly, in terms of the operation strategy of DPPP, Jinhua *et al.* [12] establish the cost/benefit model of photovoltaic power plant based on the evaluation of the initial investment, operation and maintenance cost, loan interest, residual value, on-grid benefits, subsidy benefits, and energy saving benefits of photovoltaic power plant so as to analyze different investment entities' level of profitability under different operating strategies. Ketterer [13] uses the generalized autoregressive conditional heteroskedasticity model to assess the impact of wind power levels and the volatility of electricity prices; Ouyang and Lin [14] argue that the feed-in tariffs should be improved and dynamically adjusted based on the levelized cost of energy to better support the development of renewable energy; Antonelli and Desideri [15] points out that the pricing policy of implementing fixed feed-in tariffs can guarantee the basic benefits of PV companies and compensate investment costs; furthermore, Slade [16] introduces the diversified operation mode of the PV power generation project and establishes the lifecycle investment cost and benefit model. Yang and Zhao [17] analyze the key points of policies on technical support, management drive, and financial support. Focusing on the efficiency of PV power and the power load of users, including households and enterprises, in Shanghai City over 24 h in 2016, this study analyzes the costs, benefits, internal rates of return, and investment recovery periods of distributed PV and ES systems in the current policy context. Pierro *et al.* [18] analyze and quantify the effects of PV penetration in a target region and to evaluate the energy as well as economic benefits of using day-ahead PV forecast for power transmission scheduling. For this purpose, they compare the resulting operational imbalances from these new models against two reference models currently used by the local grid operators.

Thirdly, some researchers focus on the investment analysis of DPPP. Jian *et al.* [19] and Wei [20] do the analysis of cost/benefit research, considering the initial investment, operation and maintenance costs, loan interest, loss costs, power outage losses, on-grid benefits, subsidy benefits, and energy saving revenue from the life cycle perspective of the PV power plant. But they do not consider the tax cost of the operation period. Wei [21] and Sicheng [22] mainly analyze the installed cost, operation and maintenance cost and loan interest of photovoltaic power generation. Zhijie and Chunlong [23] provide a brief analysis of the economy of residential DPPP generation as well as industrial and commercial DPPP generation. Bibin *et al.* [24] qualitatively analyze the cost of high-permeability DPPP to assess the rural power grids. Rese and Roemer [25] discuss how the current photovoltaic power industry can maximize the benefits through the minimal investment; Kebede [26] presents the grid-connected solar photovoltaics in Ethiopia and studies the potential power generation of a 5 MW photovoltaic grid-connected power plant in Addis Ababa; Reichelstein and Yorston [27] finds that the cost of generating electricity from photovoltaic power generation is comparable to the retail electricity price paid by commercial users in the United States. In some areas, utility-scale PV installations are not yet cost-competitive with fossil fuel power plants; Asumadu-Sarkodie and Owusu [28] uses RETScreen software to assess the potential and economic viability of Ghana's solar PV; Batman *et al.* [29] consider the cost of taxation, the time of use and the feed-in tariffs and assess the economic feasibility of the grid-connected photovoltaic system in Istanbul; Campoccia *et al.* [30] analyze the photovoltaic tax support policies based on computational comparison of different economic indicators, such as payback period, internal rate of return, net present value to implemented by six representative countries in the EU. Edalati *et al.* [31] and Mohammadi *et al.* [32] assess the feasibility of Iranian PV power plant projects from the technical, financial and environmental conditions. Kusakana [36] analyze the impact brought about by the different demand sector profiles on the daily operational cost and optimal scheduling of grid-connected photovoltaic systems with bidirectional power flow for the specific case of Bloemfontein in South Africa. For this purpose, residential, commercial and industrial daily load curves are used to estimate daily load demands. Chenjun *et al.* [37] build an event-driven and co-simulation platform to simulate the abovementioned interaction among distributed photovoltaic systems, active distribution systems, and incentive policy under a long-term time frame. The platform includes an investment model of distributed photovoltaic systems investors and an active distribution systems model with consideration of the growth of the active distribution systems.

In general, the existing research only focus on the aspects of photovoltaic power generation operation strategy, comprehensive benefits, and the economy of DPPP. However, the investment decision-making for DPPP lacks comprehensive and systematic economic decision support, which may lead to blind investment for a new energy investor. Particularly, under the background of the continuous reduction of subsidies for distributed photovoltaic power generation and the future participation in bidding, the cost per kilowatt hour of the electricity will become an important economic indicator for investment decision-making and bidding strategies.

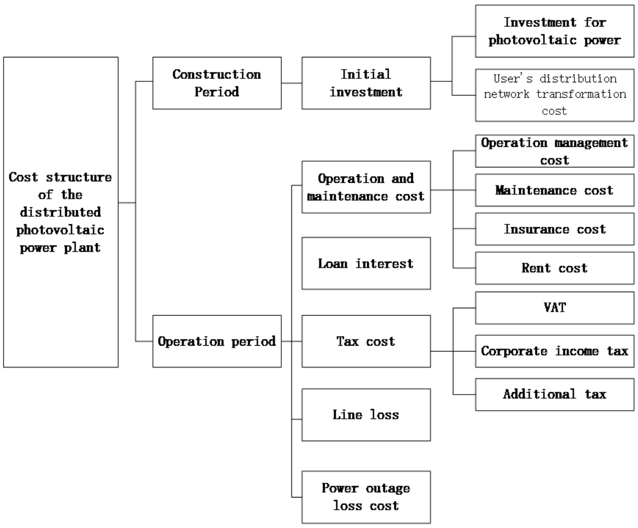

FIGURE 1. Cost structure of the distributed photovoltaic power plant.

This research aims to develop a cost-benefit model through exploring the economic indicators of the whole life cycle of distributed photovoltaic power plant. This paper also summarizes the investment decision-making methods about the photovoltaic power generation cost of DPPP. The findings are to offer theoretical and practical support for the investment decision of DPPP, and to provide the reference for the cost accounting of the future photovoltaic power generation bidding on the grid.

This paper is divided into three sections: Section 1 introduces the cost and benefit structure of distributed photovoltaic power generation based on the whole life cycle. The cost component model and benefit composition model of distributed photovoltaic power generation are established respectively based on the whole life cycle perspective; Section 2 analyzes the sensitivity of the factors affecting the cost and benefit of the power plant; Section 3 is an empirical study about cost-benefit calculation of DPPP. Based on the cost-benefit structure of distributed PV power generation project in the whole life cycle, the cost and benefit can be calculated. Furthermore, this paper also conducts the cost and benefit analysis, and presents the corresponding policies and recommendations.

II. DISTRIBUTED PHOTOVOLTAIC POWER PLANT COST-BENEFIT MODEL

A. DISTRIBUTED PHOTOVOLTAIC POWER PLANT COST MODEL

The investment cost of distributed photovoltaic power plant mainly includes the installed cost during the construction period, the operation and maintenance cost during the operation period, loan interest, taxes, line losses, power outage losses [20], etc., as shown in Figure 1.

TABLE 1. Investment cost per unit capacity breakdown.

No.	Name of products	Unit price (yuan /watt)	The price level in the fourth quarter 2017.
1	Polysilicon component	2.8 ~ 3.0	
2	Grid connected inverter	0.3 ~ 0.4	
3	Lightning protection combiner box	0.05 ~ 0.1	
4	AC distribution boxes	0.05 ~ 0.1	
5	Bracket	0.3 ~ 0.4	
6	Cable	0.4 ~ 0.5	
7	Central monitoring system	0.1 ~ 0.2 (compressible)	
8	Boosting transformer	0.2 ~ 0.3	
9	Civil works (roads and buildings)	0 ~ 0.5	
10	Research, design, installation, commissioning and other expenses	1.6 ~ 1.8 (compressible)	
	Total	5.8 ~ 7.3 (EPC)	
Comment：EPC income is usually controlled at 0.2 yuan / watt.			

1) INITIAL INVESTMENT DURING PROJECT CONSTRUCTION PERIOD

$$\begin{cases} C_{ivs} = WC_w \\ C_w = C_{w1} + C_{w2} \end{cases} \tag{1}$$

In the formula: C_{ivs} is the installed cost; W is the installed capacity; C_w is the unit installed capacity cost (yuan/watt); C_{w1} is the unit installed capacity cost (yuan/watt) for the investment of the photovoltaic power; C_{w2} is the unit installed capacity cost (yuan/watt) for the user's distribution network transformation cost. Table 1 is the detailed reference value of unit capacity investment cost.

2) ANNUAL OPERATION COST OF PHOTOVOLTAIC POWER PLANT

$$\begin{cases} C_{op} = C_{ivs} R_{op} \\ R_{op} = R_{op1} + R_{op2} + R_{op3} \end{cases} \tag{2}$$

In the formula: C_{op} is the annual operation and maintenance cost; R_{op} is the annual total operating and maintenance rate; R_{op1} is the annual operating and maintenance rate; R_{op2} is the annual insurance rate; R_{op2} is the annual rental rate. Table 2 is the operation and maintenance rate reference table.

3) ANNUAL LOAN INTEREST OF PHOTOVOLTAIC POWER PLANT

The repayment method of the photovoltaic power plant is based on the fixed installment method:

TABLE 2. Investment cost per unit capacity breakdown.

No.	Name	Rate
1	Annual operating and maintenance rate	1%
2	Annual insurance rate	0.1%
3	Annual rental rate	7.5 ~ 8.5 yuan/m²

4) FORMULA OF ANNUAL DEPRECIATION EXPENSE OF PHOTOVOLTAIC POWER PLANT

$$C_{dep}^{i} = (C_{ivs} - V_r)(n - i + 1)/[(n + 1)n/2] \tag{3}$$

In the formula: C_{idep} is the cost of depreciation for i-year; V_r is the remnant value of equipment (remnant value rate generally should be 5%); n is equipment lifetime (by 20 years). Depreciation formula uses the sum-of-the-years-digits method.

5) ANNUAL TAX COST OF PHOTOVOLTAIC POWER PLANT

$$\begin{cases} C_{tax} = C_{vat} + C_{cit} + C_{adt} \\ C_{vat} = C_{opt} - C_{ipt} \\ C_{opt} = \left(E_g P_c + E_c P_s\right) \times 17\%/(1 + 17\%) \\ C_{ipt} = (70\% \sim 75\%)\, C_{ivs} \times 17\%/(1 + 17\%) \\ C_{cit}^{i} = \begin{cases} 0 & 1 \le i \le 3 \\ I_b \times 12.5\% & 4 \le i \le 6 \\ I_b \times 25\% & i \ge 7 \end{cases} \\ I_b = I_g + I_{sub} + I_{self} - C_{op} - C_{loan} \\ \qquad -C_{vat} - C_{adt} - C_{dep} - C_{loss} - C_{cut} \\ C_{adt} = C_{vat} \times 11\% \end{cases} \tag{4}$$

In the formula: C_{vat} is value-added tax(17%); C_{cit} is corporate income tax(25%); C_{adt} is additional tax(6∼12%); C_{opt} is output tax; C_{ipt} is input tax; C_{ivs} is total profit; E_g is annual on-grid electricity; P_c is the benchmark feed-in tariff for local coal-fired generating unit; E_c is annual self-generation and self-consumption electricity; Ps is users' weighted electricity price. According to relevant national policies, in VAT formula central financial subsidy income does not need to pay VAT, and the fixed assets of photovoltaic power plant (about 70∼75% of total investment) can be deducted for VAT. In the formula of corporate income tax, it will enjoy the life of "three exemption, three half".

6) ANNUAL LOSS OF PHOTOVOLTAIC POWER PLANT

$$C_{loss} = [(Eg + Ec)\, Pg + EgPc]\, Rl \tag{5}$$

In the formula: C_{loss} is annual loss; E_g is annual on-grid electricity; E_c is annual self-generation and self-consumption electricity; P_g is the electricity price with government subsidy; P_c is the benchmark feed-in tariff for local coal-fired generating unit; R_l is the annual line loss rate (It generally should not be more than 4%).

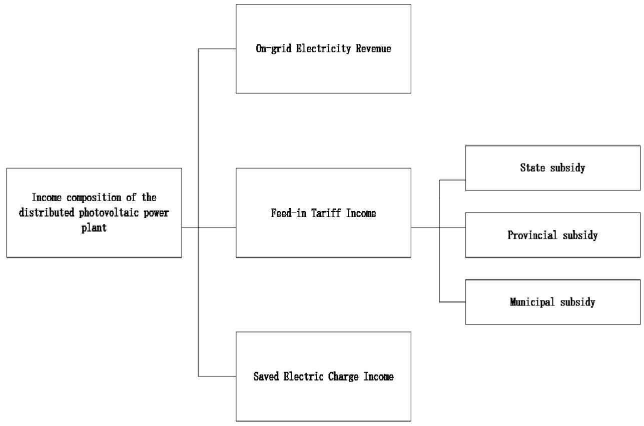

FIGURE 2. Income composition of the distributed photovoltaic power plant.

7) ANNUAL POWER OUTAGE LOSS COST OF PHOTOVOLTAIC POWER PLANT

$$C_{cut} = \left[\left(E_g + E_c\right) P_g + E_g P_c\right] (1 - R_{rel}) \tag{6}$$

In the formula: $C_{cut}$is the annual power outage loss cost; R_{rel} is power supply reliability rate (power supply reliability rate of State Grid can reach 99.8984%).

B. DISTRIBUTED PHOTOVOLTAIC POWER PLANT REVENUE MODEL

The revenue of distributed photovoltaic power plant mainly includes on-grid electricity revenue, feed-in tariff income, and saved electric charge income, as shown in Figure 2.

1) ANNUAL ON-GRID ELECTRICITY REVENUE OF PHOTOVOLTAIC POWER PLANT

$$I_g = E_g P_c \tag{7}$$

In the formula: I*g* is annual on-grid electricity revenue; E*g* is annual on-grid electricity; P*c* is the benchmark on-grid electricity price for the local coal-fired generating unit.

2) ANNUAL SAVED ELECTRIC CHARGE INCOME OF PHOTOVOLTAIC POWER PLANT

$$I_{\text{sub}} = \left(E_g + E_c\right) P_g \tag{8}$$

In the formula: Isub is annual feed-in tariff income; Ec is annual self-consumption electricityPg is the electricity price with government subsidy.

3) ANNUAL POWER OUTAGE LOSS COST OF PHOTOVOLTAIC POWER PLANT

$$\begin{cases} I_{self} = E_c P_s (1 - \eta) \\ P_s = k_f P_f + k_p P_p \end{cases} \tag{9}$$

In the formula: I_{self} is annual saved electric charge income; E*c* is annual self-consumption electricity P*s* is self-consumption electricity price; η is power factor adjustment percentage; Pf is peak tariff kf is the peak period accounts for the proportion of the total period of PV output; Pp is off-peak tariff; kp is off-peak period accounts for the proportion of the total period of PV output.

C. DISTRIBUTED PHOTOVOLTAIC POWER PLANT PRESENT VALUE MODEL

Calculating the present value of the overall income and cost in the total life cycle of a PV power plant shall be converted to the sum of the present value at the beginning of construction at a specified discount rate.

1) PRESENT VALUE OF OVERALL COST FOR A PV POWER STATION IN TOTAL LIFE CYCLE

$$C_p = C_{ivs} - V_r (1 + i_c)^{-n} + \sum_{t=1}^{n} \left(C_{op} + C_{loan} + C_{tax} + C_{loss} + C_{cut}\right) (1 + ic)^{-t} \tag{10}$$

In the formula: Cp is lifetime total cost present value; n is equipment lifetime; ic is discount rate (Social discount rate is 8%)

2) PRESENT VALUE OF OVERALL INCOME FOR A PV POWER STATION IN TOTAL LIFE CYCLE

$$C_p = C_{ivs} - V_r (1 + i_c)^{-n} + \sum_{t=1}^{n} \left(C_{op} + C_{loan} + C_{tax} + C_{los} + C_{cut}\right) (1 + i_c)^{-t} \tag{11}$$

In the formula: Ip is lifetime total income present value; n is equipment lifetime; ic is the discount rate.

D. ECONOMIC EVALUATION MODEL OF DISTRIBUTED PHOTOVOLTAIC POWER

The economic evaluation indicators of distributed photovoltaic power plants mainly include net present value, payback period, internal rate of return and cost per kilowatt hour of the electricity, as shown in Figure 3.

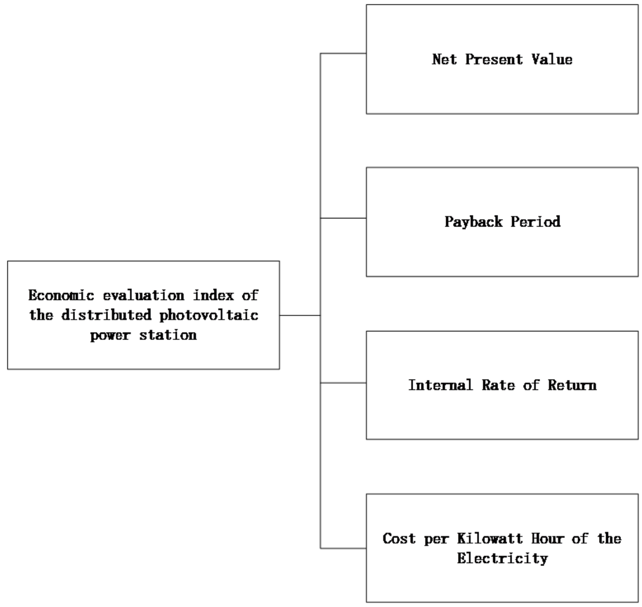

FIGURE 3. Economic evaluation index of the distributed photovoltaic power plant.

1) NET PRESENT VALUE OF PHOTOVOLTAIC POWER PLANT IN TOTAL LIFE CYCLE

$$V_{net} = I_p - C_p \tag{12}$$

In the formula: Vnet is lifetime net present value; Ip is lifetime present value of total income; Cp is lifetime present value of total cost.

2) PAYBACK PERIOD OF PHOTOVOLTAIC POWER PLANT

$$\sum_{t=1}^{T} \left(I_g + I_{sub} + I_{self} - C_{op} - C_{loan} - C_{tax} - C_{loss} - C_{cut}\right) (1 + i_c)^{-t} = C_{ivs} \tag{13}$$

In the formula: T is payback period; the formula can be solved by tabulation method.

3) INTERNAL RATE OF RETURN OF PHOTOVOLTAIC POWER PLANT

$$\sum_{t=1}^{n} \left(I_g + I_{sub} + I_{self} - C_{op} - C_{loan} - C_{tax} - C_{loss} - C_{cut}\right) (1 + i_{irr})^{-t} = C_{ivs} - V_r \left(1 + i_{irr}\right)^{-n} \tag{14}$$

In the formula: iirr is internal rate of return; the formula can be solved by tabulation method.

4) COST PER KILOWATT HOUR OF THE ELECTRICITY OF PHOTOVOLTAIC POWER PLANT

$$LCOE = \frac{Cp}{\sum_{t=1}^{n} (Eg + Ec) (1 + ic)^{-t}} \tag{15}$$

In the formula: $LCOE$ is the cost per kilowatt hour of the electricity.

III. ANALYSIS OF FACTORS AFFECTING COST AND BENEFITS OF DISTRIBUTED PHOTOVOLTAIC POWER PLANTS

A. SENSITIVITY ANALYSIS OF NET PRESENT VALUE OF DISTRIBUTED PHOTOVOLTAIC POWER PLANTS

Uncertain factors affecting the cost-benefit of distributed PV power plants include installed cost, annual effective utilization hours, loan interest rate, tax rate, benchmark feed-in tariff, subsidized electricity price, operation and maintenance cost, self-consumption electricity price, and

TABLE 3. The boundary conditions.

No.	Projects	Units	Original data
1	Installed capacity	KW	2000
2	Unit costs	yuan/W	6
3	Operation and maintenance rate	%	1.1
4	Discount rate	%	8
5	Proportion of loan	%	70
6	Annual interest rate of loan	%	5.635
7	Loan term	year	5
8	Repayment method		fixed installment
9	Residual value rate	%	5
10	Depreciation period	year	20
11	Line loss rate	%	2
12	Power supply reliability rate	%	99.8984
13	Value-added tax	%	17
14	Corporate income tax	%	25
15	Additional tax	%	11
16	Fixed asset ratio	%	70
17	Efficiency of PV systems	%	77
18	Annual slant surface peak sunshine hours	h	1360.7
19	Self-consumption ratio	%	70
20	On-grid ratio	%	30
21	State-subsidized electricity price	yuan/kWh	0.37
22	State-subsidized period	year	20
23	Zhejiang province subsidized electricity price	yuan/kWh	0.1
24	Zhejiang province subsidized period	year	20
25	Taizhou subsidized electricity price	yuan/kWh	0.1
26	Taizhou subsidized period	year	5
27	User weighted eletricity price	yuan/kWh	0.85
28	Zhejiang province coal-fired benchmark electricity price	yuan/kWh	0.4153

self-consumption ratio. levels of sensitivity:

$$SAF = \frac{\Delta A/A}{\Delta F/F} \tag{16}$$

In the formula: SAF is levels of sensitivity;F/F expresses the change rate of uncertain factors F(%);A/A expresses the corresponding change rate of evaluation index A(%) when uncertain factors F changes; The larger SAF is, the more sensitive to uncertain factors F the evaluation index A is; otherwise, it is not sensitive.

Boundary conditions of the sensitivity analysis are shown in Table 3.

According to the analysis of formula (16), net present value sensitivity analysis of photovoltaic power plant is shown in Figure 4.

As it can be seen from Figure 4, the degree of sensitivity of the affecting factors to the net present value is: annual effective utilization hours> unit installation cost>self-consumption electricity price>subsidized electricity price>self-consumption electricity ratio>income tax rate>benchmark feed-in tariff>loan interest> operation and maintenance cost. Investment income is more sensitive to annual effective utilization hours, unit installation cost, self-consumption electricity price, subsidized electricity price and self-consumption electricity ratio, but it is not sensitive enough to benchmark feed-in tariff, loan interest, operation, and maintenance cost and income tax rate. Therefore, to invest in photovoltaic projects, the investor should focus on the sunshine resource of the project site, installation cost, self-consumption electricity price, and self-consumption electricity ratio.

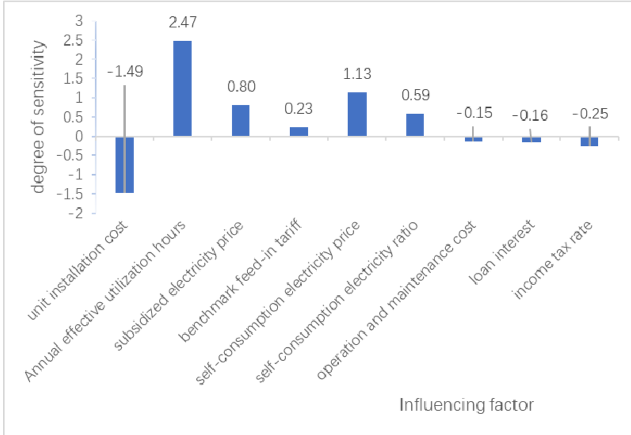

FIGURE 4. Net present value sensitivity analysis.

B. SENSITIVITY ANALYSIS OF ELECTRICITY COST OF DPPP

According to the analysis of the boundary conditions of Table 3 and formula (16), the sensitivity analysis of electricity cost of distributed photovoltaic power plants is shown in Figure 5.

As shown in Figure 5, electricity cost is more sensitive to annual effective utilization hours and unit installation cost, but it is not sensitive enough to operation and maintenance cost, loan interest and income tax rate. The key of reducing electricity cost for the PV plant is to improve solar cell technique because the cost of PV modules in unit installed costs accounts for more than 50%.

C. INFLUENCE OF SUNSHINE RESOURCES AND SUBSIDY POLICIES ON THE COST AND BENEFIT OF DPPP

Due to the difference in the solar resources in different regions, the effective time of PV power generation is diverse. It results in different power generation of PV systems, which will also bring about the different power generation costs of the same PV power generation system in different regions. In terms of manual management and equipment maintenance, the PV power generation has a greater cost advantage than other traditional energy sources. In addition, government tax

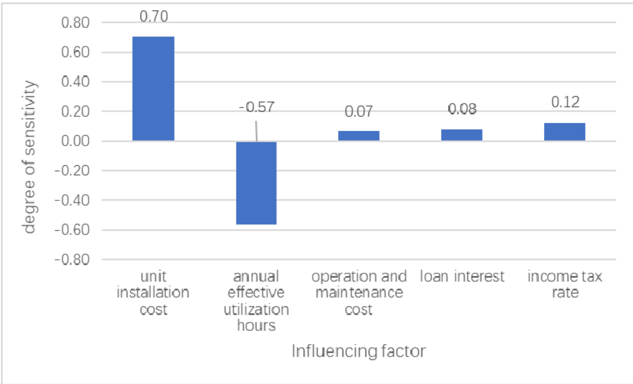

FIGURE 5. Sensitivity analysis of electricity cost.

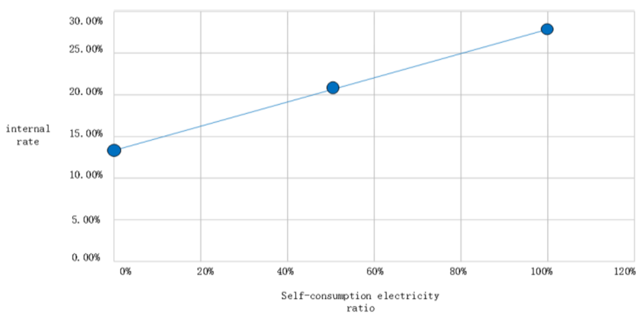

FIGURE 6. Self-consumption electricity ratio and internal rate diagram.

and subsidy policies will also affect the cost of PV power generation. The level of sunshine resources and subsidy policies is proportional to the level of economic benefits of distributed photovoltaic power plants. Under the same conditions, choosing the region with better sunshine resource and higher subsidy can gain higher benefits.

At present, China has got a great improvement in PV power generation, mainly because the state has formulated a series of preferential policies. The local government increases the PV subsidies, which strongly support the development of the solar power industry. Compared with the on-grid tariff of the local coal-fired unit benchmark, the excess part of the PV power plant can get subsidies relying on the renewable energy development fund. And the PV power plant can also formulate full-power subsidy regulations to construct DPPP. Based on these factors, such as the changing power generation costs and the development scale, the state promotes the reduction of benchmark on-grid tariffs and the establishment of electricity price standards of DPPP.

D. INFLUENCE OF SELF-CONSUMPTION ELECTRICITY RATIO ON THE COST AND INCOME OF DPPP

According to boundary conditions in Table 3, industrial and commercial electricity price in peak, valley and flat period is 0.85 yuan/kWh; benchmark feed-in tariff is 0.4153 yuan/kWh; so the relationship between self-consumption electricity ratio and internal rate of return (IRR) is shown in Figure 6. Increasing self-consumption electricity ratio can increase the economic benefits of DPPP, achieve local consumption of photovoltaic power generation, and reduce the impact of photovoltaic power generation on the power grid. The research has indicated that the higher the self-consumption ratio of photovoltaic generation, the higher its IRR is.

TABLE 4. Comparison of operation and maintenance costs of different power generation methods.

Cost	Photovoltaic	Coal-fired	Hydroelectric
Fuel fees	none	high	none
Materials expenses	low	high	high
Water fees	low	high	none
Wages and Welfare	low	high	high
Insurance expenses	low	high	high
Overhaul expenses	none	high	high
Other management fees	low	high	high

E. INFLUENCE OF SELF-CONSUMPTION ELECTRICITY RATIO ON THE COST AND INCOME OF DPPP

The operation and maintenance phase is the longest period of the whole life cycle, ranging from several years to several decades. In this process, the principle of minimum operation and maintenance costs must adhere from beginning to the end. The influencing factors that affect the costs in this stage can be simply divided into three aspects, including the human aspects, the material aspects, and the financial aspects. Operation and maintenance costs mainly refer to the maintenance costs of PV modules. According to the current PV project experience, the operation and maintenance rate is usually no more than 3%. Under the normal circumstances, the larger installed capacity usually means the lower operation and maintenance rate. The main power generation equipment of DPPP is solar panel. During the operation period, it merely needs the regular clean, so its maintenance workload is not heavy. Compared with the traditional power generation mode, the power plant equipment is static with no fuel cost and operation and maintenance personnel required. The operation and maintenance costs are lower than traditional power generation. The costs of operation and maintenance for different power generation methods are shown in Table 4.

Usually, there are many kinds of operation and maintenance plans for the PV project. It is necessary to ensure the feasibility of the technology and the feasibility of the economy when choosing the reasonable operation and maintenance plans. The decision-making design phase of the project has a large impact on operation and maintenance costs. The cost management of the operation and maintenance phase is also very important. In the operation and maintenance of the project, the pre-project phase and the implementation phase exert a huge influence on the operation and maintenance costs

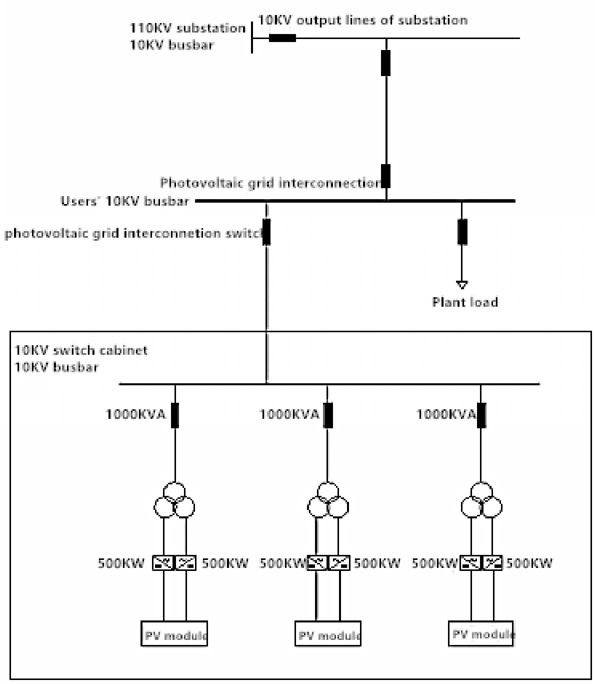

FIGURE 7. **Photovoltaic power plant access system diagram.**

of the project. In general, the construction cost is anticorrelated with the operation and maintenance cost. If the relatively good construction technology is adopted in the construction of PV project, the technology is advanced and the efficiency is high in the later operation and maintenance, which would also lead to the lower costs and expenses in the operation and maintenance phase. On the contrary, if the technological level of the PV project construction is relatively low, although the construction cost reduces, the later operation and maintenance costs would be greatly increased, and would not make the cost of the whole life cycle reach the maximum value.

IV. CASE STUDY

A. PROGRAM INTRODUCTION

The distributed rooftop photovoltaic power plant is located at the industrial park in Taizhou City, Zhejiang Province, with a total capacity of 16.85MW. It consists of seven substations: sub-station1 2MW, sub-station2 850kW, sub-station3 3MW, sub-station4 3MW, sub-station Station5 5MW, sub-station6 1MW, sub-station7 2MW. Each photovoltaic substation is connected to each plant's 10kV power distribution room. Each power distribution room 10kV power supply comes from different 10kV feeders of 110kV substation. The typical access system diagram is shown in Figure 7. The distributed photovoltaic power plant has a voltage level of 10kV, and its on-grid mode is ''self-generation, self-consumption and surplus power is on-grid''. It adopts a contracting energy management operation mode. Because the seven substations are connected to each other independently, this paper takes the photovoltaic substation1 as an example to analyze the operating cost and benefit.

TABLE 5. **Life-cycle cost-benefit calculation.**

year	Total income (10000 yuan)	Operation and maintenance cost (10000 yuan)	Financial cost (10000 yuan)	Depreciation expense (10000 yuan)	Tax cost (10000 yuan)
0					
1	263.47	13.20	197.44	108.57	
2	261.58	13.20	197.44	103.14	
3	259.69	13.20	197.44	97.71	
4	257.80	13.20	197.44	92.29	
5	255.91	13.20	197.44	86.86	
6	234.32	13.20		81.43	20.86
7	232.57	13.20		76.00	52.25
8	230.83	13.20		70.57	53.05
9	229.08	13.20		65.14	53.85
10	227.34	13.20		59.71	54.64
11	225.59	13.20		54.29	55.44
12	223.85	13.20		48.86	56.24
13	222.10	13.20		43.43	57.04
14	220.36	13.20		38.00	57.84
15	218.62	13.20		32.57	58.63
16	216.87	13.20		27.14	59.43
17	215.13	13.20		21.71	60.23
18	213.38	13.20		16.29	61.03
19	211.64	13.20		10.86	61.82
20	209.89	13.20		5.43	62.62
Total	4630.03	264.00	987.18	1140.00	824.97

B. ANALYSIS OF ELECTRICITY COST OF THE DPPP

1) Analyzing boundary conditions of cost per kilowatt hour of the electricity for a photovoltaic substation is shown in Table 3.
2) The result of cost-benefit calculation for photovoltaic substation1 is shown in Table 5.

The distributed rooftop photovoltaic power plant is located at the industrial park in Taizhou City, Zhejiang Province, with a total capacity of 16.85MW. It consists of seven substations: sub-station1 2MW, sub-station2 850kW, sub-station3 3MW, sub-station4 3MW, sub-station Station5 5MW, sub-station6 1MW, sub-station7 2MW. Each photovoltaic substation is connected to each plant's 10kV power distribution room. Each power distribution room 10kV power supply comes

TABLE 5. **Life-cycle cost-benefit calculation (continued).**

year	Generation loss cost (10000 yuan)	Power outage cost (10000 yuan)	Residual value (10000 yuan)	Total cost (10000 yuan)	Net income (10000 yuan)	Present Value Interest Factor
0				360.00	-360.00	1.00
1	2.84	0.14		213.62	49.86	0.93
2	2.82	0.14		213.60	47.99	0.86
3	2.80	0.14		213.58	46.12	0.79
4	2.78	0.14		213.56	44.24	0.74
5	2.76	0.14		213.53	42.37	0.68
6	2.34	0.12		36.52	197.80	0.63
7	2.32	0.12		67.89	164.68	0.58
8	2.31	0.12		68.67	162.16	0.54
9	2.29	0.12		69.45	159.63	0.50
10	2.27	0.12		70.23	157.11	0.46
11	2.26	0.11		71.01	154.58	0.43
12	2.24	0.11		71.79	152.06	0.40
13	2.22	0.11		72.57	149.53	0.37
14	2.20	0.11		73.35	147.01	0.34
15	2.19	0.11		74.13	144.49	0.32
16	2.17	0.11		74.91	141.96	0.29
17	2.15	0.11		75.69	139.44	0.27
18	2.13	0.11		76.47	136.91	0.25
19	2.12	0.11		77.25	134.39	0.23
20	2.10	0.11	60.00	18.03	191.86	0.21
Total	47.29	2.40		2425.85	2204.18	

from different 10kV feeders of 110kV substation. The typical access system diagram is shown in Figure 7. The distributed photovoltaic power plant has a voltage level of 10kV, and its on-grid mode is "self-generation, self-consumption and surplus power is on-grid". It adopts a contracting energy management operation mode. Because the seven substations are connected to each other independently, this paper takes the photovoltaic substation1 as an example to analyze the operating cost and benefit.

3) The analysis of major economic and technical indicators is shown in Table 6.

According to Table 6, the distributed PV substation has an investment payback period of 6.52 years and an internal rate of return of 23.69%, which has significant economic returns. The power cost of the distributed photovoltaic power station is 0.8385 yuan/kWh, which is higher than the cost of traditional energy source. The economic benefits still depend on state subsidies.

TABLE 6. **Summary of major economic indicators.**

No.	Projects	units	indicators
1	Installed capacity	KWP	2000
2	total power generation in 20 years	10 thousand kWh	3807.48
3	Static total investment	10 thousand yuan	1200
4	Proportion of borrowing funds	%	70
5	Income of self-consumption electricity	10 thousand yuan	2265.45
6	Income of on-grid electricity	10 thousand yuan	474.37
7	Income of state subsidy	10 thousand yuan	1890.20
8	Total power generation income in 20 years	10 thousand yuan	4630.03
9	Total net profit of power generation	10 thousand yuan	2204.18
10	IRR	%	23.69
11	Payback period	year	6.52
12	Electricity cost	yuan/kWh	0.8385

V. CONCLUSION

The PV market is still a policy-type market, and the changes in incentive policies have a huge impact on the PV market and DPPP. The operating model adopted by PV power generation in the future will depend on the game among the government, power supply companies, and independent investors. In the process of the cost and benefit research, based on the traditional comprehensive benefits, the operation strategies and the investment analysis, this paper has established a cost-benefit model of DPPP. This paper also has analyzed the sensitivity of different influencing factors, such as the whole life cycle of installed costs, the annually effective utilization hours, the loan interest rates, the feed-in tariff, the income tax rate, and the subsidized electricity prices of DPPP. Moreover, the research has proposed a method of analyzing the cost and benefit of DPPP based on the whole life cycle and used this method to conduct practical case analysis. This research has taken the Taizhou 2MW DPPP project as an example, studied the cost-benefit factors of DPPP projects through collecting and collating the research data, and analyzed the cost-effectiveness of the project according to the various factors and the actual conditions. The conclusion can be made as follows:

1) The main factors affect the economics of DPPP include the hours of effective use per year, unit installed cost, self-use electricity price, subsidized electricity price, and proportion of self-use electricity. The costs of distributed photovoltaic power stations are sensitive to the annual effective utilization hours, unit installation cost,

self-consumption electricity price, subsidized electricity price, and self-consumption electricity ratio, etc. The cost of DPPP is sensitive to the annual effective utilization hours and unit installation costs.

2) This paper provides an economic evaluation method for investment decision-making of distributed photovoltaic power generation, which can provide the reference for investment decision-making.
3) The electricity cost-benefit model in this paper provides a method to calculate the electricity cost of photovoltaic generation, which provides the quotation basis for the future photovoltaic power generation bidding on the grid.

Furthermore, the borrowing ratio and the proportion of Internet access of the distributed PV power generation project are fixed. Through empirical research, we can know that the results of different borrowing ratios and online ratios are different, and the impact is not a simple positive or negative correlation. It is necessary to find the most suitable point to further address that issue. Only at this point is the best benefit which is also the focus of the further study.

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