The Study of Economic and Environmental Benefits of Distributed Photovoltaic Power Generation Projects in Southern Zhejiang Province on Take the 8 Projects of Pingyang Aipu photovoltaic Power Generation Co., Ltd

Qinghe Xu, Noppadol Amdee*,
Adisak Sangsongfa and Yuth Kaiwan
Muban Chom Bueng Rajabhat University, Thailand
Corresponding Author, E-mail: noppadolamd@mcru.ac.th

****

Abstract

The objectives of this research were 1) to evaluate the economic benefits of distributed photovoltaic (PV) power generation projects, 2) to assess environmental benefits, and 3) to analyze factors influencing power generation capacity and initial investment. The sample consisted of eight distributed PV power plants operated by Pingyang Aipu Photovoltaic Power Generation Co., Ltd. in Pingyang County, Zhejiang Province, selected based on varying capacities and installation methods. Data collection tools included operational data from 2019, such as electricity generation, grid power, self-use electricity, investment amounts, and revenue details. Data analysis methods included descriptive statistics and calculations of payback periods, internal rates of return, and emission reduction effects.

The research results were as follows: 1) The PV systems' average full-load power generation time in the first year was 954 hours, with an internal rate of return of 12.07% and a payback period of 7.73 years, indicating good economic benefits; 2) The energy payback period was 6.1 years, and the projects could save 19,767,413.75 kg of standard coal over 20 years, demonstrating significant environmental benefits; 3) Provincial subsidies accounted for 15.08% of total revenue, grid electricity tariffs for 12.56%, and enterprise self-use electricity for 72.36%. It is recommended to monitor national policy adjustments and their impact on the economic efficiency of photovoltaic projects, study the development of the photovoltaic industry under different international policies, and investigate the investment value of photovoltaic power stations in regions with varying solar radiation conditions.

Keywords: Distributed photovoltaic power generation; Generation capacity; Revenue; Economic benefits; Environmental benefits.

Introduction

Distributed photovoltaic power generation, as a clean and renewable energy generation method, has become essential to China's sustainable development and energy strategy due to its outstanding environmental benefits, wide distribution, and ease of installation. The system is mainly installed on buildings' roofs or their infrastructure's external walls. It advocates the principle of generating electricity close to the building, connecting it to the grid, and using it close to the building. With the continuous improvement of the technical level of distributed photovoltaic power generation and the decline in costs, its installed capacity has made leaps and bounds. According to statistics, in 2023, the new grid-connected capacity of PV was 216.30

* Received: July 20 2024; Revised: August 10 2024; Accepted: August 13 2024

million kilowatts, and the cumulative grid-connected capacity of PV was 608.918 million kilowatts by the end of 2023 (NEA,2024).

However, due to the wide distribution of building rooftops, scattered resources, small individual scale, and large development and construction coordination workload, a certain degree of restriction has been imposed on the development of rooftop distributed PV on a larger scale (NEA,2021). To better promote the development of distributed photovoltaic power generation, on 20 June 2021, the National Energy Administration issued a notice on the submission of pilot schemes for whole-county (city and district) rooftop distributed photovoltaic development, pushing distributed photovoltaic power generation projects to a new high point. Its market has received unprecedented attention, with numerous provinces (Shanxi, Zhejiang, Guangdong, Hubei, Shanghai, Shaanxi, etc.) issuing whole-county promotion pilot policies one after another. Various power generation groups and energy companies (National Energy Group, State Power Investment, State Grid, Datang, Three Gorges, etc.) are jumping at the chance to have a go at the vast distributed photovoltaic power generation market.

Many factors affect the power generation of distributed PV systems, such as our standard solar radiation, ash accumulation losses (Ning et al., 2020), inverter losses, line losses, module attenuation losses, high temperatures, snow and rainfall, haze (Liu et al., 2018; Liu et al., 2017), planned power outages, management levels, etc. In addition, the power generation of a distributed PV system installed on the roof of an enterprise may also be affected by other factors on the enterprise side.

Research Objectives

The objectives of the main theme were: 1) to evaluate the economic benefits of distributed photovoltaic (PV) power generation projects; 2) to assess environmental benefits; 3) to analyze factors influencing power generation capacity and initial investment; and 4) to provide a data model for policy formulation, implementation, and analysis of economic benefits of distributed PV projects.

Literature Review

Currently, the vast majority of analyses of domestic PV power projects are based on theoretical formulas or simulation software to analyze the operational model and economic and environmental benefits of PV power projects. Qiao Yongli et al., applied PVsyst, a PV system simulation and design software, to calculate the average annual power generation of a 6KW distributed PV power generation system (Qiao et al., 2019). Lu Zheng et al. used a fitting function to establish a cost-benefit model on the customer side to derive the main factors affecting the economic benefits of PV power projects (Lu et al., 2021). Ran Bin et al., used the principles of technology economics to study the investment benefits of distributed PV power generation in commercial buildings (Ran et al., 2021). Mei Shufan et al. constructed an equilibrium model for the economic efficiency of wind and thermal power sources based on power market transactions by dividing them into resource zones and optimizing the economic efficiency intervals of power generation enterprises in Xinjiang (Mei et al., 2021). Tong Guangyi et al. used hierarchical analysis and fuzzy comprehensive evaluation methods to study the PV power generation poverty alleviation model and efficiency enhancement mechanism (Tong et al., 2019).

Research Methodology

1. Methodology for calculating economic benefits

The eight projects involved in this project are subsidized by Zhejiang Province at RMB 0.1 per kWh generated, with a subsidy period of 20 years. The project adopts the "self-generation, surplus power online" model, and the price of the grid electricity is calculated according to the benchmark price of RMB 0.4153 Yuan/KWh for coal-fired units in Zhejiang Province. The price of the enterprise's electricity is calculated according to the discounted price of RMB 0.6 per kWh (the industry's general electricity price standard for self-consumption). The power station revenue is R; the self-generated electricity is LS; the surplus electricity is LF; the enterprise self-consumption electricity price is OT; the desulphurization electricity price is DT; then the power station revenue.

R=LS (OT+0.1) +LF (DT+0.1 g)

The service life of general panels is usually designed at 25 years. Considering the 20 years of subsidies in Zhejiang Province and the risk of battery efficiency loss and failure after 20 years, this paper is calculated at 20 years without considering inflation. Operation and maintenance costs are charged at 0.05 RMB per watt per year (general industry rate).

2. Value of electricity generation

The power generation capacity of this project's distributed photovoltaic power generation system is taken according to the actual power generation capacity for 2019, as shown in Table 1.

Table 1 First-year electricity generation from the Pingyang Aipu PV project in 2019

No.	Name of the power station	Capacity (kWp)	Power generation (kWh)	Grid power (kWh)	Self-use of electricity (kWh)
1	GaorunI	792	716081.6	35520	680561.6
2	GaorunII	396	350984.2	30380	320604.2
3	Rangpeng	198	217685.6	60045	157640.6
4	Tongan	499	451652.6	97440	354212.6
5	Lingrui	247	239444.4	64189	175255.4
6	Omete	495	459470.4	109760	349710.4
7	Tianfeng I	274.5	275833.6	98608	177225.6
8	Tianfeng II	338.8	346396.6	30764	315632.6

3. Estimation of electricity generation hours

Photovoltaic hours were estimated using the following formula.

$$t_1 = T_1 \times \eta$$
$$t_2 = T_2 \times \eta$$

Where T_1 is the theoretical panel-side first-year generation hours, T_2 is the theoretical panel-side 20-year average generation hours and η is the overall PV system efficiency. Based on the estimates made at the time of the project, η was taken to be 0.8. t1 t_1 is the number of hours of electricity generated in the first year on the metered side and t_2 is the 20-year average number of hours of electricity generated on the metered side.

4. Static payback period

Table 2 shows data relating to investment, provincial subsidies, feed-in tariffs, corporate self-consumption tariffs, total revenue, O&M costs, and annual net revenue for each of the Pingyang Aipu power stations.

Table 2 Summary of Investment and Revenue of Pingyang Aipu PV Plant

No.	Name of the power station	Investment amount (CNY)	Provincial subsidy (CNY)	Internet access electricity bill (CNY)	Electricity costs for businesses (CNY)	Total income (CNY)	Operating costs (CNY)	Annual net income (CNY)
1	GaorunI	3687930.99	71608.16	14751.46	408336.96	494696.58	39600.00	455096.58
2	GaorunII	1469208.67	35098.42	12616.81	192362.52	240077.75	19800.00	220277.75
3	Rangpeng	943543.20	21768.56	24936.69	94584.36	141289.61	9900.00	131389.61
4	Tongan	2147689.26	45165.26	40466.83	212527.56	298159.65	24950.00	273209.65
5	Lingrui	1037223.61	23944.44	26657.69	105153.24	155755.37	12350.00	143405.37
6	Omete	2040564.30	45947.04	45583.33	209826.24	301356.61	24750.00	276606.61
7	Tianfeng I	1191676.34	27583.36	40951.90	106335.36	174870.62	13725.00	161145.62
8	Tianfeng II	1470819.48	34639.66	12776.29	189379.56	236795.51	16940.00	219855.51

The modules used this time are all Class A modules. According to the data provided by the module manufacturers, the module efficiency will not be lower than 80% of the original module efficiency in 20 years. Taking the system efficiency at the end of the 20th year as 80%, so that the system efficiency decreases by s each year, it is obtained that.

$$(1-s)^{20}=0.8$$

Got s = 0.0115.

Assuming an initial investment of IA and an annual net return of ANI, the formula for calculating the static payback period is

$$\mathrm{IA}=\mathrm{ANI}\times\frac{1\text{-}(1\text{-}s)^{n}}{s}$$

n is the static payback period.

5. Internal rate of return

Calculation of Internal rate of return IRR.

$$\mathrm{IA}=\frac{\mathrm{ANI}}{\mathrm{IRR}}\times(1-\frac{1}{(1+\mathrm{IRR})^{20}})$$

5. Methodology for environmental benefit analysis

5.1 Energy recovery period

PV power systems consume energy from manufacturing, transportation, installation, operation, and dismantling. This paper evaluates PV power systems' energy consumption and output using the energy payback period. The energy payback period is the energy consumed during a PV system's whole life cycle divided by the system's average annual energy output in years. The energy payback period is counted as NT, the total energy consumption over the whole life cycle as TCC, and the annual energy output of the PV system as APS.

$$NT = TCC/APS$$

This paper draws on the research results of Yu et al. (Yuzq et al., 2018). The total energy demand over the whole life cycle of a 1 MW polycrystalline silicon PV system is 1.84*107 MJ, and after unit conversion, it is 5,152 KWh/KW.

5.2 Analysis of emission reduction effects

Coal-fired power generation accounts for over 70% of China's total power generation, and burning coal generates many harmful gases and dust. Distributed photovoltaic power generation, on the other hand, has no pollutant emissions and low energy consumption during the entire operation process. Referring to the average energy consumption data of power plants in China, for every unit of electricity saved, 0.36 kg of standard coal can be saved, and 0.272 kg of carbon dust, 0.997 kg of CO_2, 0.03 kg of SO_2 and 0.015 kg of NOX can be reduced (Wen et al., 2018).

6. Research Scope

6.1 Solar resource situation

This paper uses Pingyang County, Wenzhou City, and Zhejiang Province as the research subjects. The total annual solar radiation in Wenzhou City is 4,000-4,400 MJ/m^2, with the most in Dongtou, an island, and the least in Taishun, a mountainous area. In terms of months, the total radiation is highest in July-August and lowest in January-February (Zhang et al., 2006). The annual average solar radiation in Pingyang County is about 4,300 MJ/m^2, with about 1,190 total load hours in the first year and about 1,055 total load hours in the 20-year average, which is in the middle to upper level within Wenzhou City.

6.2 Implementation of Rooftop Photovoltaic Power Generation Projects

Pingyang Aipu Photovoltaic Power Generation Co., Ltd (hereinafter referred to as Pingyang Aipu) built 8 distributed photovoltaic power generation projects in Pingyang County. The project adopts the contract energy management model, in which the enterprise provides the roof for installing the PV system. Pingyang Aipu is the project builder who will invest in the distributed PV power plant. The rooftop owners have agreed on a preferential tariff for the use of the energy generated by the PV power station since the date of commissioning, with the shortfall being provided by the grid company and the unused portion being sold online to the grid company, each independently settled. In the selection process of this project, the following three principles are followed: 1. clear property rights of the enterprise, the roof load to meet the PV installation conditions, when it comes to colour steel tiles also need to consider the years of colour steel tiles have been used, in principle, colour steel tiles used more than 6 years, do not give priority to the installation; 2. investigation of the previous year's electricity consumption of the enterprise, in principle, the previous year's electricity consumption must be at least more than the proposed installation of the photovoltaic capacity of a year of power generation; 3. The installation capacity is limited by the roof area and related to the transformer capacity, so both cannot exceed the transformer capacity. It was finally determined that eight projects, including Gao Run Phase I, met the construction conditions, and the construction capacity of each enterprise's distributed photovoltaic power plant and other circumstances are shown in Table 3. This batch of projects started in June 2018 and was completed and grid-connected by 31 December 2018.

Table 3 Basic information of each distributed PV plant in Pingyang Aipu

No.	Name of the power station	Roof condition	Transformer capacity (KW)	Roof area (m2)	Previous year's electricity charges for business use (yuan)	Capacity (kWp)	Start time
1	GaorunI	Colour steel tiles	1400	12000	3000000	792	2018.06
2	Gaorun II	Colour steel tiles	400	4500	1000000	396	2018.12
3	Rangpeng	Cement roof	250	3200	300000	198	2018.09
4	Tongan	Colour steel tiles/ Cement roof	500	6500	1000000	499	2018.09
5	Lingrui	Colour steel tiles	250	3500	300000	247	2018.09
6	Omete	Colour steel tiles	630	8000	1000000	495	2018.08
7	Tianfeng I	Colour steel tiles	315	5000	300000	274.5	2018.10
8	Tianfeng II	Colour steel tiles	400	10000	800000	338.8	2018.10

6.3 Data sources

The data for this project comes from the State Grid Pingyang County Electricity Company and Pingyang Aipu and includes 2019 full-year electricity generation, feed-in tariff, enterprise self-consumption, and feed-in tariff, mainly involving 8 PV power projects of Pingyang Aipu with a total installed capacity of 3,240.8 KW.

Research Conceptual Framework

1. Economic Benefits Assessment

Payback Period: Calculating the payback period can help evaluate the economic feasibility of photovoltaic (PV) power generation projects.

Internal Rate of Return (IRR): Use the internal rate of return to assess the long-term economic benefits of the projects.

2. Environmental Benefits Assessment

Energy Payback Period: Evaluate the energy payback situation of the PV system over its entire lifecycle.

Energy Savings and Emission Reductions: Calculate the amount of standard coal saved and the reductions in carbon emissions, sulfur dioxide, and nitrogen oxides during the project's operational period.

3. Analysis of Influencing Factors

Power Generation Capacity: Analyze factors influencing the power generation capacity of PV plants, such as solar radiation conditions, installation angles, and system efficiency.

Initial Investment: Examine the reasons for differences in initial investments among different PV plants, including equipment costs, installation costs, and subsidy policies.

4. Policy Formulation and Implementation

Data Model: Develop a data model based on research findings to formulate and implement economic benefit policies for distributed PV projects.

Policy Impact: Evaluate the impact of national and local policies on the economic and environmental benefits of PV projects.

5. Empirical Analysis

Sample Selection: Select eight distributed PV power plants operated by Pingyang Aipu Photovoltaic Power Generation Co., Ltd. as the research sample to analyze actual operational data.

Data Collection and Analysis: Collect operational data from 2019 and perform descriptive statistics and regression analysis to verify the theoretical model's practical application.

This conceptual framework aims to comprehensively evaluate the economic and environmental benefits of distributed PV power generation projects and provide empirical data support for policy formulation.

Research Results

1. Power generation analysis

According to the first year of power generation of the 2019 Pingyang Aipu PV power project (as shown in Table 2) and Equation 4 to obtain the 20-year power generation of the project's eight distributed power stations. The specific data is shown in Table 4.

Table 4 20 years of power generation from 8 distributed power stations in Pingyang Aipu

Name of the power station	**Gaorun I**	**Gaorun II**	**Rangpeng**	**Tongan**	**Lingrui**	**Omete**	**Tianfeng I**	**Tianfeng II**
Year \ Power generation	Power generation (kWh)	Power generation (kWh)	Power generation (kWh)	Power generation (kWh)	Power generation (kWh)	Power generation (kWh)	Power generation (kWh)	Power generation (kWh)
Year 1	716081.6	350984.2	217685.6	451652.6	239444.4	459470.4	275833.6	346396.6
Year 2	707846.7	346947.9	215182.2	446458.6	236690.8	454186.5	272661.5	342413.0
Year 3	699706.4	342958.0	212707.6	441324.3	233968.8	448963.3	269525.9	338475.3
Year 4	691659.8	339014.0	210261.5	436249.1	231278.2	443800.3	266426.4	334582.8
Year 5	683705.7	335115.3	207843.5	431232.2	228618.5	438696.6	263362.5	330735.1
Year 6	675843.1	331261.5	205453.3	426273.1	225989.4	433651.6	260333.8	326931.7
Year 7	668070.9	327452.0	203090.6	421370.9	223390.5	428664.6	257339.9	323172.0
Year 8	660388.1	323686.3	200755.0	416525.2	220821.5	423734.9	254380.5	319455.5
Year 9	652793.6	319963.9	198446.3	411735.1	218282.1	418862.0	251455.2	315781.7
Year 10	645286.5	316284.3	196164.2	407000.2	215771.8	414045.1	248563.4	312150.2

Year 11	637865.7	312647.0	193908.3	402319.7	213290.5	409283.5	245704.9	308560.5
Year 12	630530.2	309051.6	191678.4	397693.0	210837.6	404576.8	242879.3	305012.1
Year 13	623279.1	305497.5	189474.1	393119.5	208413.0	399924.1	240086.2	301504.4
Year 14	616111.4	301984.3	187295.1	388598.6	206016.2	395325.0	237325.2	298037.1
Year 15	609026.2	298511.5	185141.2	384129.8	203647.0	390778.8	234596.0	294609.7
Year 16	602022.4	295078.6	183012.1	379712.3	201305.1	386284.8	231898.1	291221.7
Year 17	595099.1	291685.2	180907.5	375345.6	198990.1	381842.5	229231.3	287872.6
Year 18	588255.5	288330.8	178827.0	371029.1	196701.7	377451.4	226595.2	284562.1
Year 19	581490.5	285015.0	176770.5	366762.3	194439.6	373110.7	223989.3	281289.6
Year 20	574803.4	281737.3	174737.7	362544.5	192203.6	368819.9	221413.4	278054.8
Average	642993.3	315160.3	195467.1	405553.8	215005.0	412573.6	247680.1	311040.9
Total	12859865.9	6303205.9	3909341.7	8111075.4	4300100.5	8251472.7	4953601.8	6220818.7

From Table 4, we can calculate that the first year of the 8 PV plants with a total installed capacity of 3,240.8 KW will generate 3,057,549 KWh, and the average annual power generation for 20 years will be 2,745,474 KWh. We can calculate that the actual rooftop PV plants in Pingyang County will generate 954 hours at full load in the first year, and the average total load generation hours for 20 years will be 856.7 hours.

From equations 2 and 3, we can obtain the first year's power generation hours t1 = 1190*0.8 = 952 hours and the 20-year average power generation hours t2 = 1055*0.8 = 844 hours. The actual number of hours of power generation is slightly higher than the theoretically calculated value.

Table 4 shows the power generation hours of each PV plant distributed in Pingyang Aipu, as shown in Figure 1 - Annual power generation hours of Pingyang Aipu distributed PV plant. Fig. 1 shows that Rangpeng has the highest average power generation hours in the first year and 20 years, with 1,099.4 hours and 987.2 hours, respectively. This is mainly because the roof of the Rangpeng plant is concrete, and the module layout is designed according to the optimum tilt angle.

Among all colour steel tile roofs, Tianfeng I and Tianfeng II (collectively referred to as Tianfeng Power Station) have higher power generation hours in the first year or 20-year average power generation hours than Gaorun I and Gaorun II (collectively referred to as Gaorun Power Station), mainly because: Gaorun Power Station is installed on the roof of an enterprise producing woven bags, the roof pollution is more serious, and its pollution source with sticky will adhere to the surface of the components, rainwater is difficult to flush, which affects the efficiency of photovoltaic power generation. This affects the efficiency of photovoltaic power generation. The Tianfeng power station is installed on the roof of a company that produces machinery and equipment. The roof is cleaner and on the beach, so its efficiency is better. There is another reason why the Gao Run power station transformers are shut down for some time during the Chinese New Year, during which time the PV power station can only be suspended. Although the Lingrui power station and the Tongan power station are in the same area, there is also a specific difference in their power generation hours (Lingrui power station generates more hours than the Tongan power station), mainly because there is no shade around the roof of Lingrui power station. In contrast, the shorter roof installed in the same shore power station is surrounded by tall buildings, which will create shade and affect its power generation.

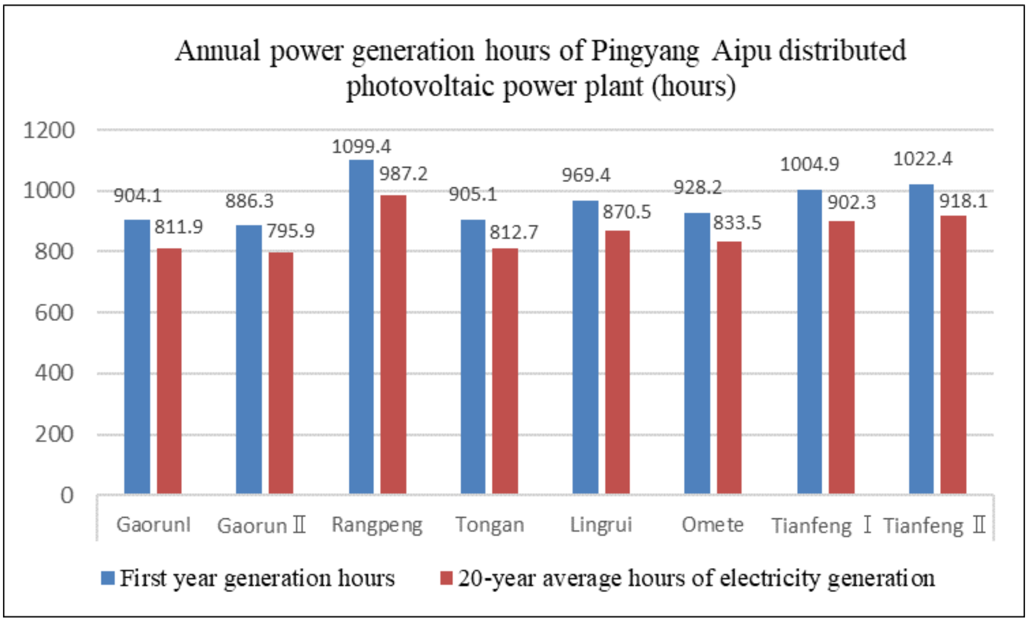

Figure 1 Annual power generation hours of Pingyang Aipu distributed photovoltaic power plant (Source: Constructed by the researcher)

2. Analysis of economic benefits

2.1 Analysis of Revenue Sources

The revenue from the PV power generation project mainly comes from the enterprise's electricity tariff, the electricity tariff for online settlement, and the electricity subsidy for PV power generation in Zhejiang Province. According to Table 3, the revenue source share of Pingyang Aipu power station and the revenue source share of each power station can be obtained. See Figure 2 and Figure 3 for details.

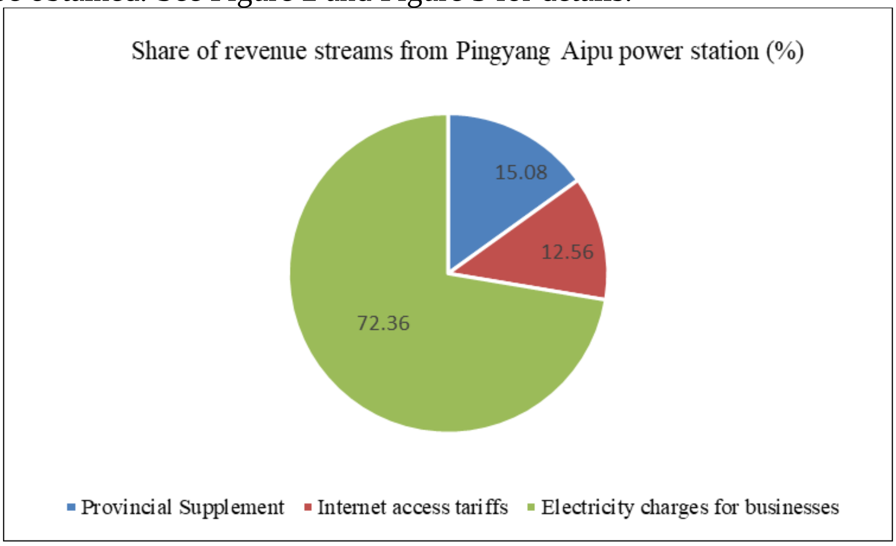

Figure 2 Share of revenue streams from Pingyang Aipu power station
(Source: Constructed by the researcher)

Figure 2 shows that the overall revenue of Pingyang Aipu power station is 15.08% of the provincial subsidy, 12.56% of the electricity bill for online settlement, and 72.35% for the enterprise's use. Figure 3 shows that the proportion of provincial subsidies in each power station varies little, between 14.48% and 15.77%. The difference in the proportion of on-grid tariffs is large, with the proportion of on-grid tariffs for the first phase of Gaorun accounting for only 2.98%, indicating that the vast majority of the electricity generated by PV is consumed directly by the company. In contrast, the proportion of grid electricity costs for Tianfeng Machinery and Electricity accounted for 23.42%, indicating that the enterprise itself does not use much electricity or that the time of normal electricity consumption of the enterprise is poorly matched to the time of PV power generation. Generally speaking, in the case of a certain amount of electricity generation, the greater the proportion of electricity used by the enterprise, the higher the revenue.

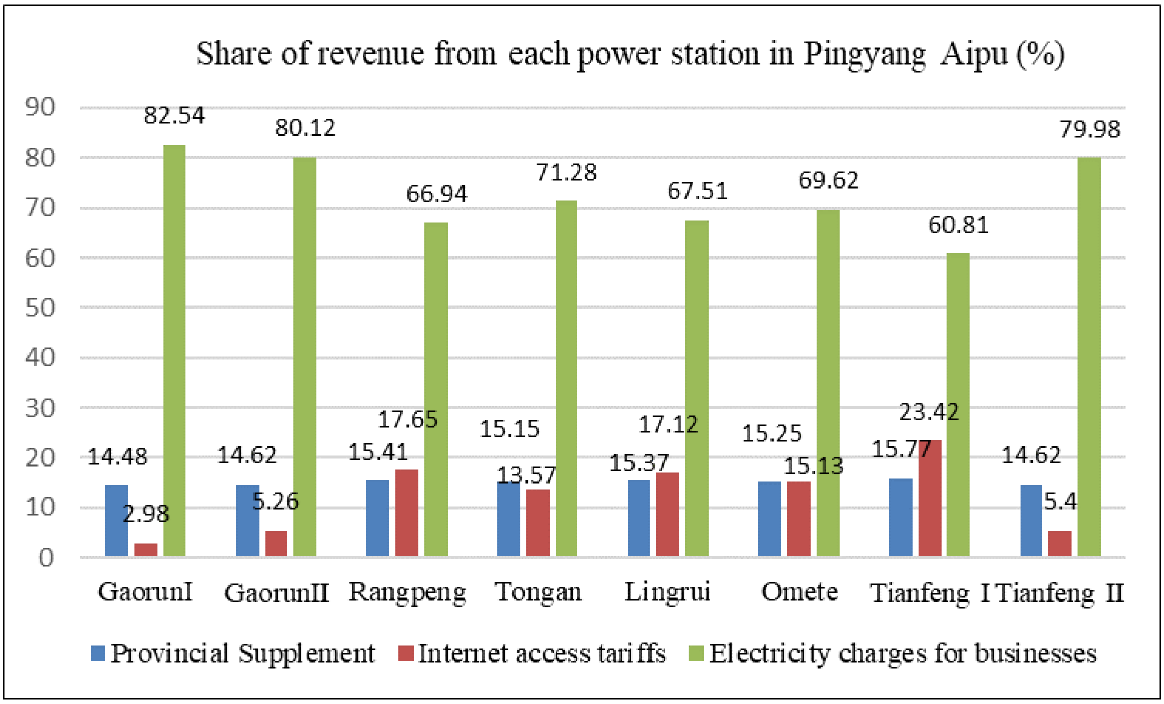

Figure 3 Share of revenue from each power station in Pingyang Aipu
(Source: Constructed by the researcher)

2.2 Payback period and project internal rate of return

The payback period and internal rate of return data for each power station were obtained from Table 3, Equation 4, Equation 5, and Equation 6, as shown in Table 5.

Table 5 Payback period and internal rate of return for the Pingyang Aipu PV Power Project

No.	Name of the power station	Investment amount (CNY)	Annual net income (CNY)	Static payback period	Internal rate of return (IRR)
1	GaorunI	3687930.99	455096.58	8.46	10.74
2	GaorunII	1469208.67	220277.75	6.90	13.88
3	Rangpeng	943543.20	131389.61	7.45	12.64
4	Tongan	2147689.26	273209.65	8.19	11.20
5	Lingrui	1037223.61	143405.37	7.51	12.52
6	Omete	2040564.30	276606.61	7.66	12.20
7	Tianfeng I	1191676.34	161145.62	7.68	12.17
8	Tianfeng II	1470819.48	219855.51	6.92	13.83
Total	Pingyang Aipu	13988655.87	1880986.70	7.73	12.07

As can be seen from Table 5, the overall static payback period for the projects invested by Pingyang Aipu in Pingyang County takes 7.73 years, with an internal rate of return of 12.07%, and the static payback period for each distributed PV power plant ranges from 6.9 to 8.46 years, with an internal rate of return of 10.74% to 13.88%, with Gao Run Phase I was having the most extended static payback period, taking 8.46 years, mainly The reason is that Gaorun Phase I equipment was purchased in May 2018, when the state subsidy of RMB 0.32/watt had not yet been canceled. The power plant cost was relatively high, close to RMB 4.66/watt. In contrast, the sudden 531 policy that year directly canceled the RMB 0.32 subsidy (NEA, 2018), extending the payback period of this power plant, and its IRR also dropped significantly. Gaorun II was the last of this batch of power stations to start construction and was only connected to the grid for power generation at the end of December 2018. After more than half a year of shocks and adjustments in the photovoltaic industry, the overall cost of the power station has dropped significantly, with a cost of RMB 3.71/watt. Therefore, its static payback period is shorter at 6.9 years, with an internal rate of return of 13.88%.

3. Analysis of environmental benefits

According to Equation 7 and the data provided in section 2.5.2, the energy payback period and emission reduction data for each Pingyang Aipu PV power station can be obtained. The specific data is shown in Table 6.

Table 6 Energy payback period and emission reduction results for each distributed power plant in Pingyang Aipu

Name of the power station	Gaorun I	Gaorun II	Rangpeng	Tongan	Lingrui	Omete	Tianfeng I	Tianfeng II
Power station capacity (kW)	792	396	198	499	247	495	274.5	338.8
Total generation capacity (KWh)	12859865.9	6303205.9	3909341.7	8111075.4	4300100.5	8251472.7	4953601.8	6220818.7
Average electricity production (KWh)	642993.3	315160.3	195467.1	405553.8	215005	412573.6	247680.1	311040.9
Energy recovery period (years)	6.3	6.5	5.2	6.3	5.9	6.2	5.7	5.6
Standard coal savings (kg)	4629551.7	2269154.1	1407363	2919987.2	1548036.2	2970530.2	1783296.7	2239494.7
Reduction of carbon dust (kg)	3497883.5	1714472	1063340.9	2206212.5	1169627.3	2244400.6	1347379.7	1692062.7

Reduction of CO_2 (kg)	12821286.3	6284296.3	3897613.6	8086742.2	4287200.2	8226718.2	4938741	6202156.3
Reduction of SO_2 (kg)	385796	189096.2	117280.2	243332.3	129003	247544.2	148608.1	186624.6
Reduction of NO_X (kg)	192898	94548.1	58640.1	121666.1	64501.5	123772.1	74304	93312.3

3.1 Energy payback period

From Equation 7 and Table 6, the total energy payback period of the Pingyang Aipu project is 6.1 years, and the energy payback period of each power station is between 5.2 and 6.5 years, much lower than the conservative life span of 20 years for PV systems. This indicates that the power generated by the power stations in 6.1 years at the latest can offset the energy consumed in the manufacturing, transportation and installation, operation and dismantling, etc. The electricity generated after 6.1 years is pure output.

3.2 Analysis of emission reduction effects

Table 6 shows the energy saving and emission reduction of the Pingyang Aipu PV power plant project. The average power output of Ping Yang Aipu 3,240.8 KW PV power station is 2,745,474.1 KWh in 20 years. The total power output is 54,909,482.64 KWh during its 20 years of operation, which can save 19,767,413.75 kg of standard coal, reduce carbon dust emission by 14,935,379.28 kg, reduce CO_2 emission by 54,744,754.19 Kg, reduce SO_2 emission by 1,647,284.479 kg and reduce NO_2 emission by 823,642.2396 Kg, with the apparent effect of emission reduction. With the official implementation of the carbon emission trading management measures (for trial implementation) (MEE, 2021), carbon emission targets can be traded through the carbon emission trading Centre, further enhancing the economic benefits of PV power generation.

Discussion

This study evaluates the economic and environmental benefits of distributed photovoltaic (PV) power generation projects in Pingyang County, Zhejiang Province, using data from eight PV power plants operated by Pingyang Aipu Photovoltaic Power Generation Co., Ltd. The average payback period was 7.73 years, and the internal rate of return (IRR) was 12.07%, indicating good economic viability. These findings align with Qiao et al. (2019), who reported payback periods of 6 to 10 years and IRRs between 10% and 15% for small-scale PV systems. Our study used actual operational data, which supports the theoretical models used in Qiao's study. Additionally, we found that provincial subsidies comprised 15.08% of total revenue, grid electricity tariffs 12.56%, and enterprise self-use electricity 72.36%. Lu et al. (2021) found that subsidies could account for up to 20% of revenue, which is slightly higher than our results, possibly due to regional policy differences.

Our study found the energy payback period to be 6.1 years for environmental benefits. This is consistent with Yu et al. (2018), who reported that polycrystalline silicon PV systems take 5 to 6 years to be developed. Our results also showed that over 20 years, the PV projects could save approximately 19,767,413.75 Kg of standard coal and significantly reduce carbon emissions and other pollutants. Wen and Qiu (2018) estimated that a 5 KW household PV system could save about 200,000 Kg of standard coal and reduce CO_2 emissions by 500,000 Kg over 20 years. Scaling this to our study's larger capacity shows similar substantial environmental benefits, reinforcing the positive impact of PV systems on reducing fossil fuel dependence and mitigating climate change.

Our findings generally align with existing literature, confirming distributed PV power generation's economic and environmental advantages. Consistency with Qiao et al. (2019) and Lu et al. (2021) on economic metrics, and with Yu et al. (2018) and Wen and Qiu (2018) on environmental benefits supports broader adoption of PV technologies. Some differences, like Lu et al.'s higher subsidy dependence, reflect regional policy variations. This study provides strong evidence for distributed PV projects' economic and environmental viability, emphasizing the need for future research on the long-term impacts of policy changes and technological advancements.

Conclusions

This paper takes the eight distributed photovoltaic power plants invested by Pingyang Aipu Photovoltaic Power Generation Co., Ltd. in Pingyang County as the research object, briefly introduces the principles that the company should follow in selecting the projects, and based on the original data such as its investment amount, first-year power generation and first-year electricity consumption, the total power generation and average power generation of the projects for 20 years are estimated, and the situation of the project revenue sources, static investment payback period, internal rate of return The project's revenue sources, static investment payback period, internal rate of return, energy payback period, energy saving and emission reduction effects are discussed and analyzed. The total installed capacity of the distributed power plant is 3,240.8 KW, the total power generation during the 20-year operation period is 54,909,482.64 KWh, and the average annual power generation for 20 years is 2,745,474 KWh. The energy payback period is only 6.1 years and can save 19,767,413.75 Kg of standard coal, reduce carbon dust emission by 14,935,379.28 Kg, reduce CO_2 emission by 54,744,754.19 Kg, reduce SO_2 emission by 1,647,284.479 Kg, and reduce NO_X emission by 823,642.2396 Kg. The study provides a reference model for formulating and implementing policies to promote distributed photovoltaic power generation projects throughout the county and analyzing economic and environmental benefits. It is an essential reference value for the excellent development of distributed photovoltaic power generation projects.

Suggestions

1. Usage Suggestions

It is suggested that national and local policy adjustments be continuously monitored, as well as their impact on the economic efficiency of PV projects, enabling timely strategy adjustments to maximize economic benefits. Enterprises should consistently adopt and apply the latest PV technologies to enhance system efficiency and extend equipment lifespan, thereby further optimizing the energy payback period and economic benefits. Additionally, promoting distributed PV power generation projects in more regions, especially those with abundant solar resources and high electricity demand, is encouraged to utilize local resources and improve energy utilization efficiency fully.

2. Further Research Suggestions

Future research should focus on the long-term impacts of policy changes and technological advancements on PV system performance, using longitudinal studies to capture the specific effects of these changes on economic and environmental benefits. Comparative studies of PV projects in different regions are suggested to analyze the impact of regional differences on the economic and environmental benefits of PV systems, providing more targeted references for policy formulation. Future research can further analyze the comprehensive impact of PV projects on social, economic, and environmental aspects, assessing their contribution to sustainable development and providing more holistic decision-making support. Additionally, exploring new business models, such as integrating the energy internet and distributed energy systems, can enhance the economic benefits and market competitiveness of PV projects.

3. Practical Implementation and Socio-Environmental Suggestions

During the planning and implementation of PV projects, involving local communities, policymakers, and businesses is essential to ensure broader support and successful integration into the local energy grid. It is crucial to develop training programs for technical staff and educational initiatives for the public to raise awareness about the benefits of PV systems and encourage their adoption. Governments and financial institutions should offer attractive financing options and incentives to reduce the initial investment burden on businesses and homeowners, making PV systems more accessible. Moreover, conducting thorough environmental impact assessments before installing PV systems is essential to minimize disruption to local ecosystems and biodiversity. Ensuring that the benefits of PV projects are equitably distributed, particularly in underserved and low-income communities, promotes social equity and inclusive development. Developing and implementing sustainability metrics to regularly monitor and report on the environmental and social impacts of PV projects ensures that they contribute positively to the community and environment.

References

Liu, W., Liu, C., Lin, Y., Li, J., et al. (2018). Super short-term photovoltaic power forecasting considering influence factor of smog. *Proceedings of the CSEE*, 38 (14), 4086-4096.

Liu, Z., Sun, J., & Geng, L. (2017). Study of extinction characteristics of PV power generation based on haze component analysis method. *Acta Energiae Solaris Sinica*, 38 (12), 3276-3281.

Lu, Z., Sun, W., & Chen, Y. (2021). Cost-benefit evaluation of photovoltaic system based on customer-side. *Acta Energiae Solaris Sinica*, 42 (4), 209-214.

Mei, S., Tan, Q., Li, Y., Ding, Y., & Xu, J. (2021). Economic benefit interval optimization of Xinjiang's power generation enterprise considering supply and demand relationship. *Electric Power Automation Equipment*, 41 (2), 166-171.

Ministry of Ecology and Environment. (2021). Measures for the Administration of Carbon Emission Trading (Trial). *Online*. Retrieved January 5, 2021, from http://www.mee.gov.cn/xxgk2018/xxgk/xxgk02/202101/t20210105_816131.html

National Development and Reform Commission, Ministry of Finance, & National Energy Administration. (2018). Notice on matters related to photovoltaic power generation in 2018. *Online*.Retrieved June 1, 2018, from:https://www.ndrc.gov.cn/ xxgk/zcfb/tz /201806/t20180601_962736.html

National Energy Administration. (2021). Questions on the whole-county promotion policy for distributed photovoltaic power plants. *Online.* Retrieved July 9, 2021, from http://www.nea.gov.cn/2021-07/09/c_1310051436.htm

National Energy Administration. (2024). Last year, the total output value of the photovoltaic industry exceeded 1.75 trillion yuan, and the year-on-year growth of the output of major manufacturing segments exceeded 64 per cent. *Online.* Retrieved March 22, 2024, from http://www.nea.gov.cn/2024-03/22/c_1310768588.htm

Ning, H., Cheng, R., Wang, W., & Yan, Z. (2020). Experimental study on influence of dust accumulation on photovoltaic power generation and dust removal effect. *Acta Energiae Solaris Sinica*, 41 (11), 120-125.

Qiao, Y.-L., Xu, H.-W., & Sun, J. (2019). Simulation and analysis of home grid connected photovoltaic power generation system. *Chinese Journal of Power Sources*, 43 (1), 133-135.

Ran, B., Yang, T.-h., & Wang, C. (2021). Study on the investment benefits of distributed photovoltaic power generation in commercial buildings. *Energy Conservation*, (02), 15-19.

Tong, G., Ni, Q., Pan, Y., Du, S., Su, J., Yang, M., & Yang, G. (2019). Photovoltaic poverty alleviation model and benefit promotion mechanism under background of agricultural informatization. *Transactions of the Chinese Society of Agricultural Engineering*, 35 (10), 131-139.

Wen, Z., & Qiu, G. (2018). Economic and environmental analysis of household photovoltaic system: Taking 5 kW photovoltaic system in Jiangxi Province as an example. *Acta Scientiarum Naturalium Universitatis Pekinensis*, 54 (2), 443-450.

Xu, Q., Amdee, N., & Sangsongfa, A. (2024). Design study of high-power PV grid-connected inverter system based on the particle swarm algorithm. *Primera Scientific Engineering*, 2024, 5 (3),16-38.

Yu, Z., Ma, W., Wei, K., et al. (2018). Analysis of energy payback period and carbon footprint of metallurgical polysilicon photovoltaic system. *Acta Energiae Sinica*, 39 (2), 520-528.