Peer-to-peer trade and the economy of distributed PV in China

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Published in Journal of Cleaner Production, 2021, 280, 124500.
DOI: 10.1016/j.jclepro.2020.124500

Abstract: With the deepening of power market reform, distributed power generation is gaining momentum. This paper tests the distributed photovoltaic (DPV) economy under different business models by taking three provinces to stand for typical resource zones. The Internal return rate (IRR) is used to measure the economy, while the improved levelized cost of electricity (LCOE) is used to model the generation cost. Three business modes, namely pure producer (all generation sold to the grid), prosumer (self-use and the rest sold to the grid), and peer-to-peer trade (P2P, all generation traded via the grid) are studied. Results show that peer-to-peer trade is more profitable and is a win-win solution to both DPV owner and electricity consumers. However, peer-to-peer trade is possible only when power grid's role is properly defined in China's power sector reform. Electricity trading mechanism should be improved to facilitate peer-to-peer trade.

Keywords: Distributed photovoltaic, Business model, Prosumer, Peer-to-peer trade

1. Introduction

Solar power is considered as one of the most promising low-carbon alternatives to fossil fuels for future electricity systems (Liu and Lv, 2019). Photovoltaic (PV) power is regarded as one of China's most promising low-carbon energy generation approaches (Binz and Anadon, 2018). To solve the problem of increased fossil fuel consumption and environmental pollution, China has been taken active measurements to promote solar energy generation nationwide. Distributed photovoltaic (DPV) is far ahead in the development momentum with its flexible application form. China, North America, Europe, and Asia-Pacific are the major markets for DPV worldwide. They currently account for about 95% of the global total. The International Energy Agency (IEA) predicted in its "Renewable 2019" report (IEA, 2019) that the global DPV installed capacity would exceed 600 GW by 2024, in which China will account for nearly half of the growth. By then, China will have the largest DPV installed capacity in the world.

Under the strong policy support and vigorous technological development, China's installed capacity of DPV has been increasing year by year (Yuan et al., 2014). In terms of new installations, the proportion of DPV to the total PV increased from 6.19% to 45.02% between 2013 and 2019. In 2019 China's total installed capacity of DPV has reached 64.16 GW. By the end of 2018, China's total installed PV capacity accounted for 36.2% of the global total. PV power generation takes only 2.5% of China's total. DPV power generation is even less than 1/3 of that in PV. The economic potential of DPV has not been released yet.

DPV power generation usually refers to the power generation system that uses solar energy resources and has the following features: It is located near the users; the installed capacity is small; and it is connected to the grid with a voltage level of 35 kV or less. DPV can replace the power generated by fossil fuel with clean electricity. It can also improve energy utilization efficiency (Pang et al., 2019). The development of DPV is crucial to China's sustainable development. China has issued and implemented a series of policies (See Appendix Table A1 for details) to support the development of DPV energy. China's DPV industry has been improved greatly based on preferential policies (Lin and Luan, 2020). The electricity bills saved by the DPV can reduce the burden of business expenses without subsidies (Wu et al., 2019). However, with the rising popularity of DPV, various problems come to light. DPV power generation is largely restricted to meteorological factors such as actual solar radiation, which projects

Nomenclature

NPV	Net Present Value
LCOE	the annual costs per unit energy generated
E_n	the annual energy generation
$Cost_n$	Total life cycle cost
$Revenues_n$	En multiplied by the present values of the LCOEn
$CAPEX_n$	the annual value of the initial investment cost
$OPEX_n$	the annual operating expenses
TAX_n	the annual tax
$CAPEX$	the initial capital cost of the project
$OPEX$	the operation and maintenance cost rate
I_n	the rate of insurance costs
C_n	interest on the loan
R_n	the DPV roof rent
P_n	the labor wage
r	the discount rate
N	the operating life of the power plant
C	the installed capacity
H	the annual utilization hours
O_u	the own usage rate
η	the system efficiency rate
d	the equipment attenuation rate
a	the construction period

resource's intermittency. Moreover, the excessive installation in some areas has also led to overcapacity (Ueckerdt et al., 2015). In China, to analyze the business model of DPV power generation would be crucial to the future development of DPV.

China has developed three main DPV business models taking into account the current national context. They are "pure producer" (all generation sold to the grid), "prosumer" (self-use and the rest sold to the grid), and "peer-to-peer trade" (all generation traded via the grid). According to the Classification of China's solar resource areas (NDRC, 2017), this paper selects three typical provinces from the three major solar resource areas as the research objects. As to the selection of research object, Tibet is located in the Class-I resource area and has abundant solar energy resources at a very unique geographical location. It is not representative. Other provinces in Class-I resource area, such as Qinghai and Xinjiang, have more similarities to Inner Mongolia than Tibet. Considering the development of the DPV market, Inner Mongolia is selected as the representative province for the Class-I resource area (the data are mainly taken from West Inner Mongolia area). Henan is selected as the representative province for the Class-II resource area. Zhejiang is selected as the representative province for the Class-III resource area.

This paper focuses on the economy of DPV in the subsidy-free situation. This paper's three main contributions are as follows: Firstly, employing improved LCOE model and IRR to evaluate the economics of DPV makes the indicators more consistent with the actual. Secondly, comparing the differences of economic returns for DPV under the situation of canceling the feed-in tariffs. Finally, identifying the factors that restrict the development of DPV and providing some policy implications to promote the development of DPV. The overall structure of the paper is designed as follows. Section 2 is literature review. Section 3 presents the model and some business models. Section 4 sets the parameters and reports the results. Section 5 conducts sensitivity analysis and provides further discussion. Section 6 summarizes the paper with conclusions.

2. Literature review

Solar PV is becoming one of the most widely applied renewable technology in the world. According to the latest 5-year forecast (from 2019 to 2024) from IEA, solar PV will be leading in the renewable power capacity addition. It will account for almost 60% of the expected renewable power capacity growth (in total 1200 GW). The most popular Solar PV applications are centralized PV and distributed PV. Centralized PV is generally built-in large areas in deserts, Gobi and other areas, making full use of the abandoned land resources. DPV is generally built on the roofs of buildings, plant roofs and vegetable sheds to make full use of space. DPV power generation could be applied in urban and rural construction, industry, agriculture etc. The research on applying solar technologies for greenhouse strawberry production can greatly change energy and environmental damage (Hosseini-Fashami et al., 2019). This paper appraises the economics of rooftop PV. Rooftop generally refer to industrial factory roof, commercial building roof and residential roof etc. Solar rooftop generation could reduce CO_2 emissions, avoiding losses in electricity transmission and distribution systems (Cardenas et al., 2017).

The economic analysis of DPV is conducted under the framework of China's electricity system. Researchers usually use the LCOE model to study the economics of DPV. LCOE is an economic indicator widely used by scholars (Liu et al., 2016) to evaluate the comprehensive competitiveness of DPV power generation technology. Chen et al. (2015) showed that the LCOE model could predict the LCOE development trend of PV power generation projects in China. Researchers usually use the IRR model to compare the economic benefits between different projects. Lou et al. (2019) used the IRR model to analyze the economics of DPV projects in different regions under parity conditions. Indicators such as IRR and investment payback period can be used to compare the economics of DPV power generation in different regions.

Li et al. (2020) summarized China's DPV power development's current status and looked into the supporting policies and implementation paths for China's DPV power in different stages. Sun and Chen (2018) discussed the existing DPV grid-connected technology, indicated the necessity of grid-connected technology research to promote DPV development. Ma et al. (2018) analyzed the three business models' revenue sources regarding DPV power generation projects. They compared the market trading model of DPV in China with the distributed trading mechanism and its development status in abroad. Wang et al. (2020) proposed a novel distributed P2P energy transaction method based on the double auction market to promote economic benefit and energy self-sufficiency. Gong et al. (2020) proposed an effective distributed energy management framework for modeling and optimizing clean smart islands.

Almost no research has been conducted on which DPV business model is more advantageous in the subsidy-free situation. Using improved LCOE model and IRR, this paper evaluates the economics of DPV and compares three business models' economic returns. The results show that the "peer-to-peer trade" model would be more prominent under the subsidy-free situation.

3. Economic evaluation methodology

3.1. LCOE model

There are various economic evaluation methods for power generation projects. The LCOE model is most commonly used to compare power generation technologies or consider grid parity for emerging technologies (Branker et al., 2011). In this paper, the LCOE model is employed to assess the economics of DPV. During the power generation project's entire life cycle, LCOE is the ratio of the sum of the present values of costs to the sum of the present values of energy production when the net present value is zero (Zhang et al., 2020). At the cost of unit power generation, the DPV power generation project can only reach the lowest expected return rate. It does not have excess economic profits (Chen et al., 2015).

The discount rate r is one of the most important exogenous parameters in costing calculation. The discount rate r is used to calculate the present value of future expenses and sales revenue. During the lifetime N years of projects, it is assumed that the total discounted value of the revenues equals to the total discounted present value of the costs. At this time, the net present value (NPV) of the project is zero. The formula is as follows:

$$\sum_{n=0}^{N}\frac{Revenues_n}{(1+r)^n}=\sum_{n=0}^{N}\frac{Cost_n}{(1+r)^n} \tag{1}$$

$$NPV=\sum_{n=0}^{N}PV=\sum_{n=0}^{N}(Revenues_n-Cost_n)=0 \tag{2}$$

In equation (1), revenues could be expressed as the sum of the annual energy generation E_n multiplied by the present values of the $LCOE_n$. LCOE is the annual costs per unit energy generated. Equation (1) can be evolved into equation (3).

$$\sum_{n=0}^{N}\frac{LCOE_n\times E_n}{(1+r)^n}=\sum_{n=0}^{N}\frac{Cost_n}{(1+r)^n} \tag{3}$$

When the LCOE is a constant annual value, equation (3) can be written as equation (4).

$$LCOE=\frac{\sum_{n=0}^{N}\frac{Cost_n}{(1+r)^n}}{\sum_{n=0}^{N}\frac{E_n}{(1+r)^n}} \tag{4}$$

In equation (4), the LCOE is the total discounted costs during the lifetime, including the project's initial investment divided by the sum of the discounted energy produced. When calculating the cost of DPV projects, we mainly consider the project investment costs, capital costs, operation and maintenance costs, taxes etc. Equation (4) can be evolved into equation (5).

$$LCOE=\frac{\sum_{n=0}^{N}\frac{CAPEX_n+OPEX_n+TAX_n}{(1+r)^n}}{\sum_{n=0}^{N}\frac{C\times H\times(1-O_u)_n}{(1+r)^n}} \tag{5}$$

It is noted that the sum calculation starts from n = 0, including the initial investment cost of the project in the first year. The initial capital cost of the project does not need to be discounted. In other words, the initial cost can be annualized throughout the life of the project. This paper improves the LCOE model by increasing house rents and labor wages in operation and maintenance costs and introducing system efficiency and equipment attenuation rates. Equation (5) is the most common LCOE that is not extended. Equation (6) is an improved LCOE that is more applicable for DPV.

$$LCOE=\frac{CAPEX+\sum_{n=1}^{N}\frac{CAPEX\times(I_n+OPEX)+TAX_n+C_n+R_n+P_n}{(1+r)^n}}{C\times H\times(1-O_u)\times\eta\times\frac{365-a}{365}+\sum_{n=1}^{N}\frac{C\times H\times(1-O_u)_n\times\eta\times(1-d)^n}{(1+r)^n}} \tag{6}$$

In the formula, $CAPEX_n$ is the annual value of the initial investment cost; $OPEX_n$ is the annual operating expenses; TEX_n is the annual tax; $CAPEX$ is the initial capital cost of the project; $OPEX$ is the operation and maintenance cost rate; C is the installed capacity; H is the annual utilization hours; O_u is the own usage rate; N is the operating life of the power plant; I_n is the rate of insurance costs; P_n is the labor wage; C_n is interest on the loan; R_n is the DPV roof rent; r is the discount rate; η is the system efficiency rate; d is the equipment attenuation rate; a is the construction period (less than 1 year).

Fig. 1 is the inferential flowchart of the LCOE model. The previous studies did not consider the initial first-year generation separately, which is improved in this paper by including DPV's equipment attenuation rate, system efficiency rate, and first-year generation. In this paper, house rents and labor wages are added into the operation and maintenance cost, the system efficiency and equipment attenuation rate are also included regarding the LCOE model. The improved LCOE model is more in line with current practical DPV application scenarios.

3.2. IRR model

The Internal Rate of Return (IRR) refers to the discount rate when the total present value of capital inflow is equal to the total present value of capital flows and the net present value is equal to zero. The IRR is generally regarded as the index of profitability of project investment. It reflects the efficiency of investment. IRR is also often applied in the economic evaluation of power projects. In addition to calculating the project's IRR, the IRR model can also calculate the project's payback period and net present value. This paper uses IRR and payback period to evaluate the economy of the projects. The project is feasible when the IRR is greater than or equal to the benchmark rate of return.

In this paper, the cash inflows mainly include major business income; cash outflows mainly include fixed assets investment, operation cost, insurance premium, loan and interest repayment, value added tax and income tax. The calculation formula is as follows:

$$FNPV(FIRR)=\sum_{t=0}^{n}(CI-CO)_t(1+i)^{-t}=0 \tag{7}$$

In the formula, $FNPV$ is financial net present value; i is IRR; $(CI-CO)_t$ is net cash flow in year t; n is the operating life of the power plant.

4. Economic analysis

Net metering is a type of electricity price settlement policy. It is a process to let grid companies pay for the development of DPV. The net metering model is widely applied in developed countries. Its essence is to allow all users to share the costs of DPV. It is usually applied at the initial stage of DPV development. It is more cost-effective for countries with high public electricity rates in developing countries. The net metering system would be causing the following problems in China. (I) heavy cost burden for power grid companies; (II) serious unfair problems; and (III) lack of efficiency

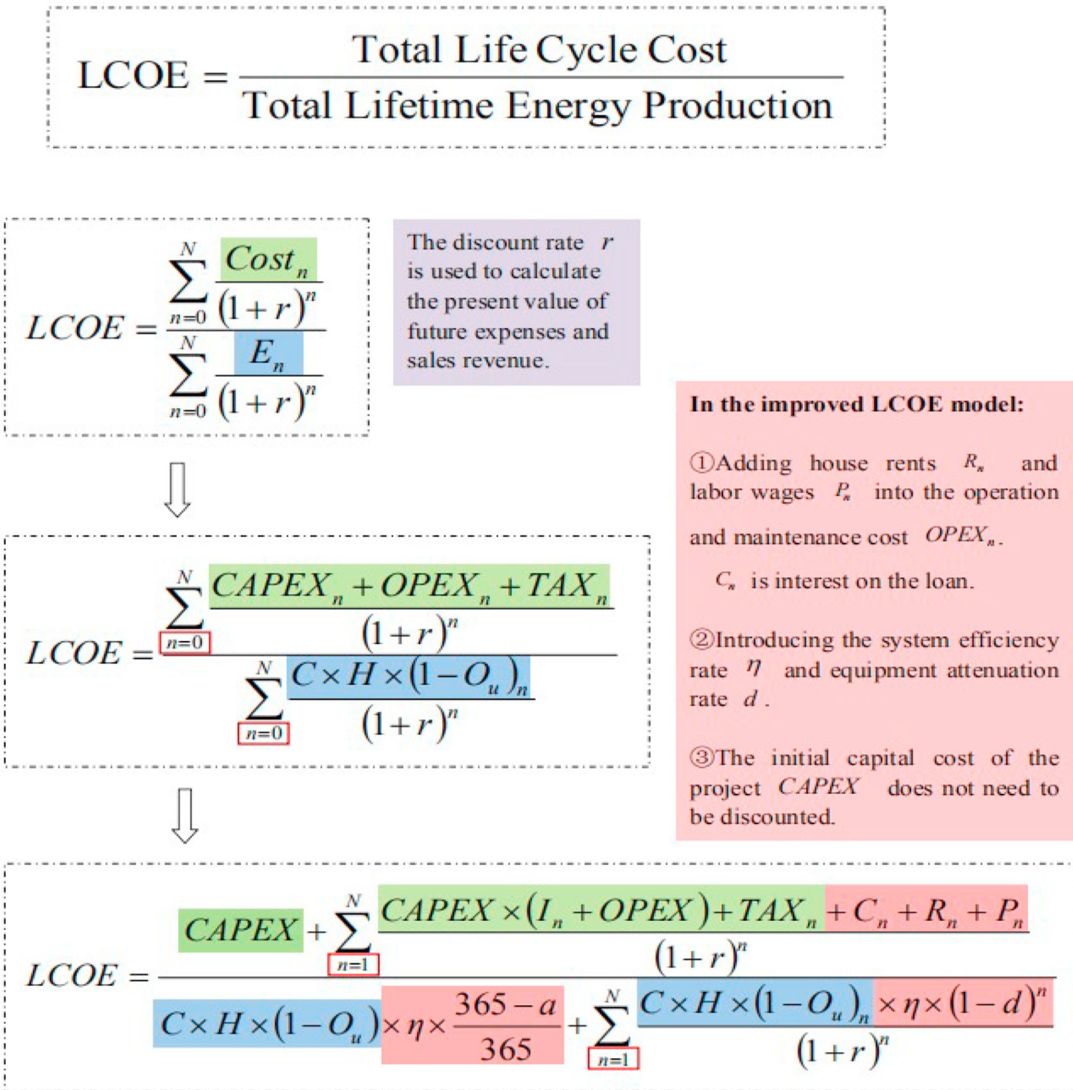

Fig. 1. The connection between steps of the LCOE method.

of location price signal guidance.

In August 2013, the National Development and Reform Commission (NDRC) issued the "Notice on the role of price leverage to promote the healthy development of the PV industry" (NDRC, 2013). Two DPV business models were proposed, namely, "pure producer" and "prosumer". In October 2017, the NDRC together with the National Energy Administration (NEA) issued the "Notice on launching pilot projects of DPV peer-to-peer Trade" (NEA, 2017), the third and the latest business model, "peer-to-peer trade" is proposed. These three business models are most widely applied in China. In this paper, we will focus on these three business models mentioned above.

The "Pure producer" business model refers to unified sales and purchase, restricting the producer from using the electricity and selling total electricity generated to the power grid. In this model, the distributed power supply is used as a centralized power supply; the grid purchase all electricity generation at a benchmark feed-in tariff.

"Prosumer" business model is where the producer only uses part of its electricity and sell the remaining part to the local power grid. DPV power stations are only allowed to trade with the grid, and the trading electricity will be purchased according to the local desulfurized coal benchmark feed-in tariff.

"peer-to-peer" trade is also defined as the "neighborhood trading". All the power generated should be traded via the grid, under which the distribution network serves as a trading platform. Distributed power generation projects directly conduct power trading with power users and directly pay the wheeling costs to local grid companies. Table 1 explains the basic definitions of electricity tariffs in China's power industry. Fig. 2 explains the transaction forms of the three business models.

Among the three DPV business models, the "peer-to-peer trade" model was initiated and developed in China. China's "prosumer" model is similar to Germany's "self-consumption" model. "Pure producer" is a special model of the "prosumer" when the power generation for self-use is set to be zero. "Peer-to-peer trade" and "prosumer" are all trading via the grid. Their users are different. The user of "prosumer" can only be the power grid. The user of "peer-to-peer trade" has options to choose. They can be resident users or neighboring companies, etc.

This paper chose the rooftop DPV power generation system to assess the DPV power generation's economy. The DPV projects'

Table 1
The basic definitions of electricity tariff in China's power industry.

Name	Concept
Feed-in tariff	The settlement price of electricity provided by the power generation company to the grid.
Transmission-distribution price	A general term for the price at which grid operators provide access systems, interconnection, power transmission, and sales services. A unified policy and hierarchical management by the government.
General industrial and commercial electricity price	General industrial electricity prices, non-industrial electricity prices and commercial electricity prices are collectively referred to as general industrial and commercial electricity prices.
Large industrial electricity price	Applicable to industrial methods for material production and direct production services. The electricity price of a transformer with a certain capacity and above.
Benchmark feed-in tariff for PV power stations	The selling price charged by a PV power station when selling electricity to the grid company.
Coal-fired benchmark feed-in tariff	The price of electricity sold by coal-fired power companies to the grid.
Weighted price	Electricity prices for non-resident users fluctuate from time to time, for which a weighted electricity price would be more reasonable.
Wheeling cost	The fee charged by the power grid to recover the investment and operation and maintenance costs of the power grid and obtain a reasonable return on assets.
Trading price (of electricity)	The actual electricity price sold to users when conducting DPV "peer-to-peer trade".
Transaction fee	The commission fee incurred when conducting "peer-to-peer trade".

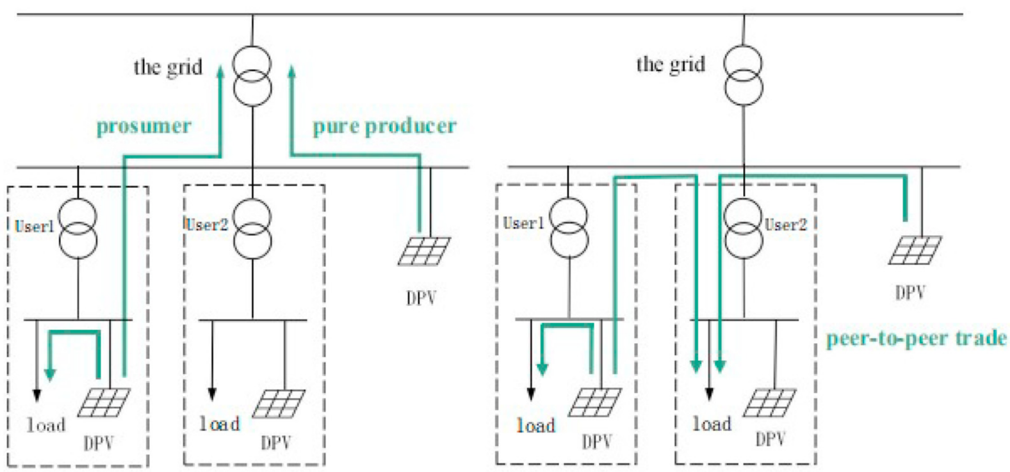

Fig. 2. Transaction Diagram of three business models.

capacity are set at 1 MW, the typical project scale in China. The cost analysis of 1 MW DPV is shown in Table 2. The paper uses Excel to calculate the LCOE of DPV power generation projects in each province. The cash flow statement for all investments is calculated using an excel table, through which the key economic and technical indicators for evaluating DPV power generation are derived, namely, the project investment recovery period and IRR. This paper selected three typical provinces for analysing the DPV business models, including Inner Mongolia, Henan and Zhejiang.

4.1. Parameters and assumptions

With the PV curtailment rate declines, China's PV power generation's grid parity will be implemented gradually. China will soon enter into the time of subsidy-free time regarding DPV power generation. This paper assumes that DPV power generation is at a state of subsidy-free parity grid.

Financial parameters are essential for the calculation. They are generally consisting of loan interest rate and duration, benchmark rate of return, discount rate, useful life, loan life, salvage rate, depreciation life and self-owned capital ratio. Since October 2015, the central bank has adjusted the long-term loan interest rate to 4.9%. Almost all small distributed power generation projects are owned by small and medium-sized companies or private investors. They have a certain high risk. It is generally difficult for this high-risk category investors to obtain sufficient loans from commercial banks. This paper sets the DPV long-term loan interest rate at 6%.

The service life of a PV power plant is closely related to its important components. The service life of PV units are mostly about 25–30 years. This paper sets the units' service life to 25 years. The loan term of DPV power generation projects is generally 15–20 years. Considering the short life cycle of DPV power generation projects, we set the loan period to 15 years, the depreciation time to 20 years, the residual value rate to 5%, the standard financing arrangement to 70% loans and 30% self-funded. The benchmark of return rate is 8%. Operation and maintenance costs include roof rental, operation and maintenance costs, insurance costs, system efficiency and attenuation rates. According to the industry practice, the 1 MW DPV power generation project required an area of about 10,000 square meters. This paper sets 1 MW DPV of roof installation. The annual rent of the roof is 4 CNY/m^2. This paper assumes none of the rent increases. The rent is paid once a year.

The cleaning and maintenance services provided under the management of the energy contract require 0.5 employees. The labor salary is 60,000 CNY per year per person. The research shows that the inverter efficiency is 95%, the transformer efficiency is 95%, other efficiency is 89% (Zahedi, 2009). Considering the technical progress and installation conditions, this paper sets the system efficiency to 85%. According to the survey of similar projects, the attenuation rate of PV power generation systems is generally between 0.5% and 0.8%. Considering the industry regulations, the cumulative attenuation rate of PV grid-connected power

Table 2
The cost analysis table of 1 MW DPV.

Name	Type	Unit price (CNY/W)	Proportion
PV module	Mono crystalline/Poly crystalline	1.9	44.7%
Grid-connected inverter	Centralized/Stringed/Distributed/Micro-inverse	0.29	6.8%
PV support bracket	Aluminum alloy/hot-dip galvanized/stainless steel	0.32	7.5%
Combining manifolds	AC/DC	0.167	3.9%
DC/AC cable	2.5 mm^2,4.0 mm^2,6.0 mm^2	0.177	4.2%
Fixture/cement foundation	/	0.182	4.3%
Monitoring system	Monitoring, data collector, irradiator, etc	0.2	4.7%
Cost of design	Design of PV power station and grid-connection design	0.064	1.5%
Engineering insurance	Construction and installation engineering all insurance	0.02	0.5%
System debugging	/	0.02	0.5%
Construction fee	Installation labor costs	0.455	10.7%
Other construction costs	Pre-project costs, production preparation costs, construction management costs, unforeseen costs, etc	0.455	10.7%
Total		**4.25**	100%
EPC Total (EPC Profit margin: 8%)		**4.59**	

generation projects should not exceed 20% in 25 years. We adjusted the system attenuation rate to 0.6%.

Taxation of DPV power generation projects generally includes income tax, value-added tax, urban construction and maintenance tax and education surcharge. DPV power generation implements the policy of “three exemptions and three halves”. The income tax rate payable by the enterprise is 0% for the first three years, 12.5% for the fourth to six years and 25% thereafter. DPV taxpayers sell self-produced power products using solar energy and implement the policy of “charging and refunding 50% immediately”. We set the VAT rate to 13%, the urban maintenance and construction tax rate to 5%, the education surcharge rate to 3%. The discount rate reflects the time value of funds and the degree of risk of cash flows. The discount rate for this project is 8%. The own usage rate is 70%. The key variables and basic parameters of the 1 MW DPV project are shown in Table 3.

4.2. Analysis of calculation results

4.2.1. Analysis of LCOE results

This paper take 1 MW DPV power generation project as an example. Under the baseline scenario, the own usage rate is 70%. The trading electricity used for DPV “peer-to-peer trade” accounts for 30% of the total power generation. The LCOE of DPV in each province is shown in Table 4.

By comparing LCOE in three provinces, the average value of DPV LCOE in the benchmark scenario is 0.4968 CNY/kWh. The economic efficiency of DPV in China is affected by the utilization hours. It occurs a large economic deviation of PV. The maximum deviation can reach 0.143 CNY/kWh.

Fig. 3 shows full investment IRR and payback period of general industrial and commercial users and full investment IRR and large industrial users’ investment payback period. The IRR of Henan and Zhejiang are higher than the benchmark rate of return. The static payback period of Henan and Zhejiang projects’ full investment remains between 6 and 8 years. They are much shorter than the full 25-year life cycle of PV power generation projects. The revenue outlook in Henan and Zhejiang is more optimistic.

The IRR of Inner Mongolia is lower than the benchmark rate of return. Inner Mongolia adopted a low coal benchmark feed-in tariff. The general industrial and commercial and large industrial tariffs are too low. The trading price is subject to these market restrictions when participating in “peer-to-peer trade”. The relatively low IRR indicates that, the profitability of DPV power generation “peer-to-peer trade” is closely related to the local power market.

Table 3
Summary table of key variables and basic parameters of the 1 MW DPV project.

Variable	Parameter Setting	Basic value Setting
Initial outlay cost	Total investment in power generation (CNY)	4590000
	Unit investment cost (CNY/kW)	4590
	Unit roof area (m^2/MW)	10000
Financial costs	Own capital ratio (%)	20
	Loan period (yr)	15
	Loan interest rate (%)	6
	Operational life (yr)	25
	Depreciation period (yr)	20
	Residual value rate (%)	5
Operation maintenance	Insurance rate (%)	0.25
	Comprehensive maintenance rate (%)	1.5
	Roof rent (CNY/m^2/yr)	4
Tax policy	Value added tax (%)	13(halve)
	Urban construction tax (%)	5
	Education surcharge (%)	3
	Income tax (%)	25
Generating capacity	Expected annual utilization hours (h)	Inner Mongolia: 1600 Henan: 1400 Zhejiang: 1200
	Installed capacity (MW)	1
	System efficiency (%)	85
	System attenuation rate (%)	0.6
	Expected annual power generation (kWh/yr)	Inner Mongolia: 1290000 Henan: 1130000 Zhejiang: 970000

Table 4
The LCOE of DPV in three provinces.

Province	Resource area	Unit cost (CNY/kW)	Utilization hours (h)	Financing cost (%)	LCOE (CNY/kWh)
Inner Mongolia	I	4590	1600	6%	0.4287
Henan	II	4590	1400	6%	0.4900
Zhejiang	III	4590	1200	6%	0.5717

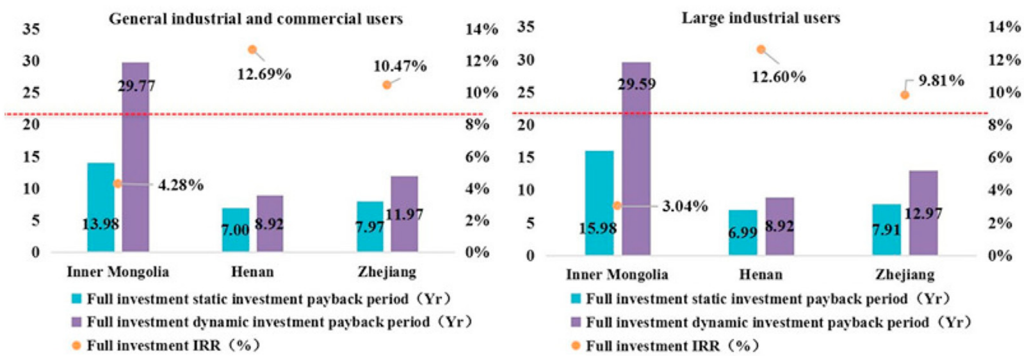

Fig. 3. Full investment IRR and investment payback period.

4.2.2. Analysis of IRR results

The electricity price varies from time to time for non-resident customers in China. Electricity prices are divided into peak-time electricity price, normal-time electricity price, valley-time electricity price. The more reasonable electricity price is the weighted price. According to China's solar resource distribution table (Wang, 2019), this paper assumes that the daily sunshine time is 9:00−16:00. This paper uses the time weighting ratio based on the proportion of electricity prices in different periods. The weighted electricity price is shown in Table 5. The feed-in tariff of different business models are shown in Table 6.

The "pure producer" business model's income is the total electricity generation multiplied by the full feed-in tariff. The "prosumer" business model's income equals the amount of self-use electricity multiplied by weighted price plus trading electricity multiplied by the feed-in tariff. The income of the "peer-to-peer trade" business model equals the amount of self-use electricity multiplied by weighted price plus trading electricity multiplied by the difference between trading price and wheeling cost. The income of DPV power generation projects under three business models are shown in Fig. 3. The IRR of DPV power generation projects under three business models are shown in Fig. 4.

According to Figs. 4 and 5, the IRR of "pure producer" in the three provinces are all far lower than the benchmark rate of return (8%), indicating that the "pure producer" business model does not have the competitive economic advantage of DPV projects. Taking Henan as an example, the full investment IRR of "peer-to-peer trade" is 12.69%. Compared with "pure producer" and "prosumer", the full investment IRR of the "peer-to-peer trade" model is 8.32% and 2.16% higher, respectively. The revenue has a significant increase significantly. Inner Mongolia has a low coal benchmark feed-in tariff. The general industrial and commercial and large industrial tariffs are too low. The trading price is subject to these market restrictions when participating in "peer-to-peer trade". Both the revenue and IRR of "peer-to-peer trade" in Inner Mongolia is still higher than that of "prosumer". The results show that the "peer-to-peer trade" of the DPV power generation significantly impacts the project's economics.

4.2.3. Analysis of wheeling cost results

The wheeling cost refers to the grid company's fee to recover the grid framework's investment cost. It also refers to the required operation and maintenance costs to obtain a reasonable return on investment assets. It is only possible to be sold when the trading price is not higher than the general industrial and commercial electricity price or the large industrial electricity price. The trading price is equal to the general industrial and commercial tariffs or the large industrial tariffs. The trading price minus the LCOE gives the upper limit of wheeling costs. The upper limit of wheeling costs in Inner Mongolia, Henan and Zhejiang are shown in Table 7.

According to the calculations in Table 7, the upper limit of the wheeling cost for Henan's general industrial and commercial is 0.1668 CNY (0.6568−0.49 = 0.1668 CNY). The upper limit of the wheeling cost for large industrial in Henan is 0.1392 CNY (0.6292−0.49 = 0.1392 CNY).

According to the policy (NEA, 2017), the wheeling cost's accounting system is based on the national transmission-distribution price. Users who pay the wheeling cost no longer need to pay the transmission-distribution price. When connecting the DPV project to the grid by 10 kV, the substation's high voltage side is 35 kV. The

Table 5
Peak and flat electricity prices and weighted electricity prices.

Resource area	Province	Electricity price (CNY/kWh)			Weighted price (CNY/kWh)
		peak	Flat	Low	
I	Inner Mongolia	0.3415	0.3415	0.1708	0.3415
II	Henan	0.9648	0.6262	0.3292	0.7713
III	Zhejiang	1.2157	0.9177	0.4057	0.7714

Table 6
The feed-in tariff of different business models.

Province	Coal feed-in tariff (CNY/kWh)	Surplus feed-in tariff (CNY/kWh)	Full feed-in tariff (CNY/kWh)	Weighted price (CNY/kWh)
Inner Mongolia	0.2829	0.2829	0.40	0.3415
Henan	0.3779	0.3779	0.45	0.7713
Zhejiang	0.4153	0.4153	0.55	0.7714

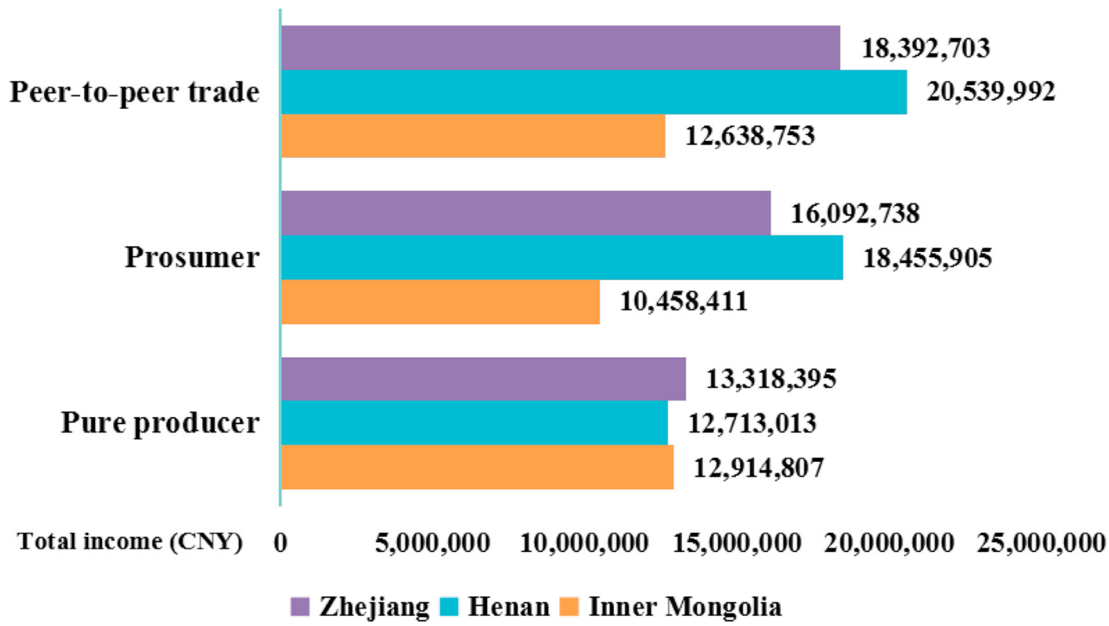

Fig. 4. The income of DPV power generation projects under three business models.

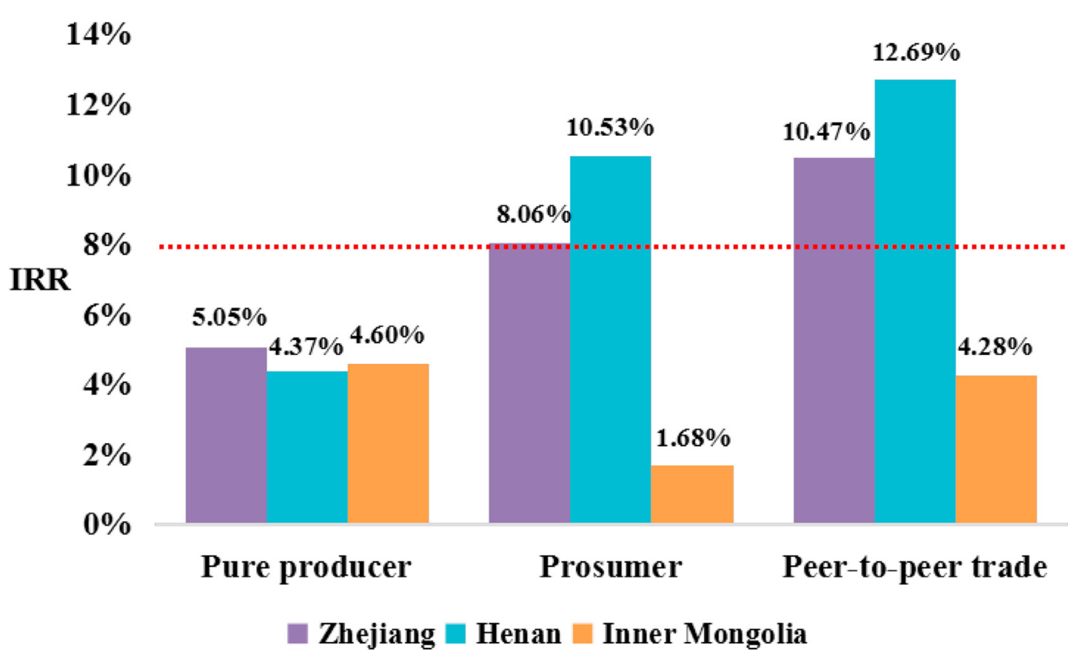

Fig. 5. The IRR of DPV power generation projects under three business models.

10 kV transmission and distribution price minus the 35 kV transmission and distribution price gives the standard wheeling costs. The standard wheeling costs in Inner Mongolia, Henan and Zhejiang are shown in Table 8.

According to the calculations in Table 8, the wheeling cost of general industrial and commercial users in Henan is 0.033 CNY (0.32−0.287 = 0.033 CNY). The wheeling cost of large industrial users in Henan is 0.015 CNY (0.2137−0.1987 = 0.015 CNY).

Table 7
The upper limit of wheeling costs.

Province	LCOE (CNY/kWh)	General industrial and commercial electricity price (CNY/kWh, <1 kV)	Large industrial electricity price (CNY/kWh, 10 kV)	General industrial and commercial wheeling cost (CNY/kWh)	Large industrial wheeling cost (CNY/kWh)
Inner Mongolia	0.4287	0.6042	0.4478	0.1755	0.0191
Henan	0.4900	0.6568	0.6292	0.1668	0.1392
Zhejiang	0.5717	0.7519	0.6644	0.1802	0.0927

Table 8
The standard of wheeling costs.

Province	Transmission-distribution price (General industrial and commercial)			Transmission-distribution price (Large industrial)		
	1–10 kV	35 kV	wheeling cost (CNY/kWh)	1–10 kV	35 kV	wheeling cost (CNY/kWh)
Inner Mongolia	0.3415	0.2453	0.0962	0.1743	0.1246	–
Henan	0.32	0.287	0.033	0.2137	0.1987	0.015
Zhejiang	0.3729	0.3529	0.02	0.2146	0.1946	0.02

According to the calculation above, the wheeling costs for general industrial and commercial users in Inner Mongolia lie between 0.0962 and 0.1755 CNY/kWh. The wheeling cost for Inner Mongolia's large industrial users is lower than 0.0191 CNY/kWh.

The wheeling cost for general industrial and commercial users in Henan ranges from 0.033 to 0.1668 CNY/kWh. The wheeling cost for Henan's large industrial users is between 0.015 and 0.1392 CNY/kWh.

The wheeling cost for general industrial and commercial users in Zhejiang ranges from 0.02 to 0.1802 CNY/kWh. The wheeling cost for Zhejiang's large industrial users ranges from 0.02 to 0.0927 CNY/kWh.

5. Sensitivity analysis and discussions

5.1. Sensitivity analysis

The sensitivity analysis is set in the DPV "peer-to-peer trade". The wheeling cost, trading prices, transaction fees and electricity trading volume have a certain influence on the IRR of the project. This paper analyzed the sensitivity of the four factors.

5.1.1. Impact of wheeling costs

The wheeling cost for general industrial and commercial users is different from that of large industrial users. We set up 6 cases for the scenario when the trading user is general industrial and commercial users. We set the wheeling costs to be 0.11 CNY/kWh, 0.12 CNY/kWh, 0.13 CNY/kWh, 0.14 CNY/kWh, 0.15 CNY/kWh and 0.16 CNY/kWh, respectively. For the scenario when the trading user is large industrial users, we also designed six cases, for which the wheeling costs are 0.03 CNY/kWh, 0.04 CNY/kWh, 0.05 CNY/kWh, 0.06 CNY/kWh, 0.07 CNY/kWh, and 0.08 CNY/kWh, respectively (See Appendix Table A2 for details).

According to the sensitivity analysis results of the wheeling costs in Fig. 6, the trends of the IRR of different wheeling costs in the three provinces are very similar, showing a slight downward trend with the increase of wheeling costs collectively, indicating that the increase in wheeling costs has minimal negative impact on "peer-to-peer trade" benefits.

5.1.2. Impact of trading prices

The trading price shall be independently negotiated between distributed generation projects and nearby power users. This paper assumes six cases. The trading price is 1 cent, 2 cents, 3 cents, 4 cents, 5 cents, and 6 cents lower than the general industrial and commercial or large industrial electricity prices.

The trading prices' sensitivity analysis results in Fig. 7 show similar trends in the IRR of different trading prices in the three provinces, demonstrating a slight downward trend due to the decrease in electricity prices. This result is similar to the one displayed in the wheeling costs. The reduction of trading prices has a certain negative but not obvious impact on "peer-to-peer trade" benefits.

5.1.3. Impact of transaction fees

The transaction organizer charges transaction fees under the assumption that there is "peer-to-peer trade". The organizer's role could either be taken by the power grid or an incremental distribution network operator. This paper sets eight cases. Transaction fees account for the total transaction amount to 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40%.

The results show that transaction fees have a significant impact on the "peer-to-peer trade" of DPV power generation. According to the IRR curves trend for different transaction fees in Fig. 8, Henan and Zhejiang provinces are more similar, demonstrating a significant downward trend as transaction fees increase. Comparing to Henan and Zhejiang, the downward trend in Inner Mongolia is more obvious, indicating that the increase in transaction fees has a great negative impact on the return of "peer-to-peer trade".

5.1.4. Impact of electricity trading volume

Under the "prosumer" and "peer-to-peer trade" models, the transaction users are general industrial and commercial and large industrial users, respectively. This paper sets ten cases. The proportion of electricity trading volume are 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90%.

According to Fig. 9 and Fig. 10, the results show that electricity trading volume significantly impacts the project's IRR. The situation in Zhejiang is very similar to that in Henan. The IRRs of "peer-to-peer trade" under different electricity trading volumes are significantly higher than that of "prosumer". The IRR in Inner Mongolia shows a different trend. The IRR of "peer-to-peer trade" under different electricity trading volume is always higher than the IRR of "prosumer". The gap in between gradually enlarges as the proportion of electricity trading volume increases. In the "peer-to-peer trade" of DPV power generation, the lower the proportion of electricity trading volume, the higher the IRR of the project, the better performs the economy.

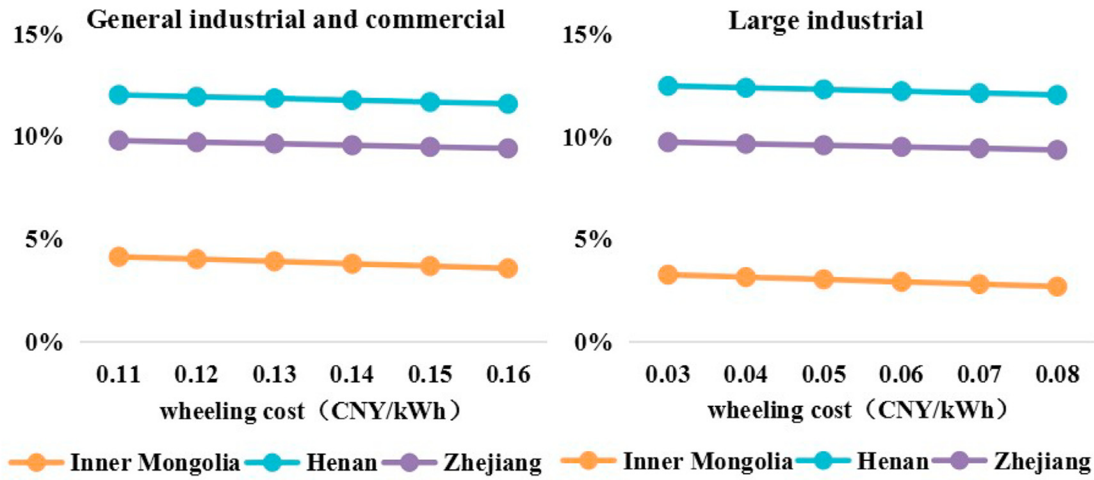

Fig. 6. The full investment IRR curve of different wheeling costs.

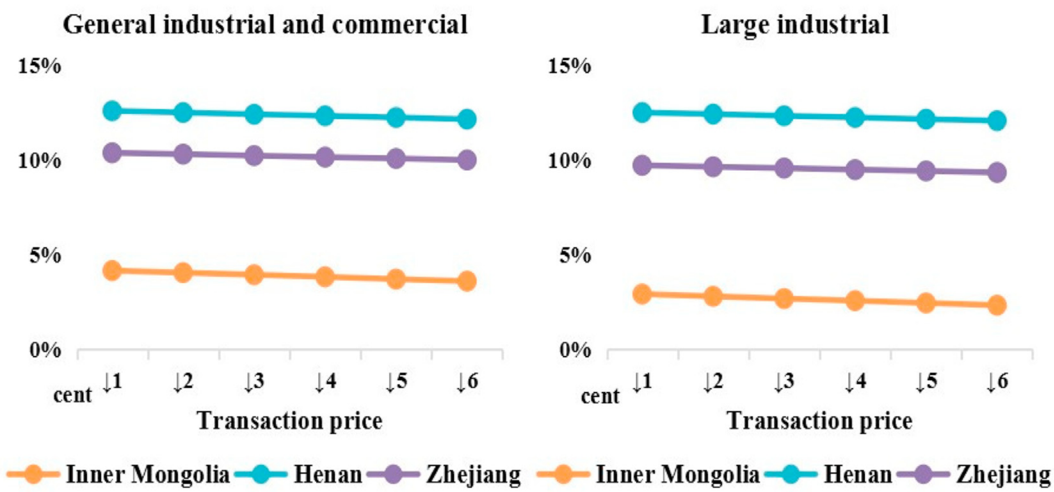

Fig. 7. The full investment IRR curve of different trading prices.

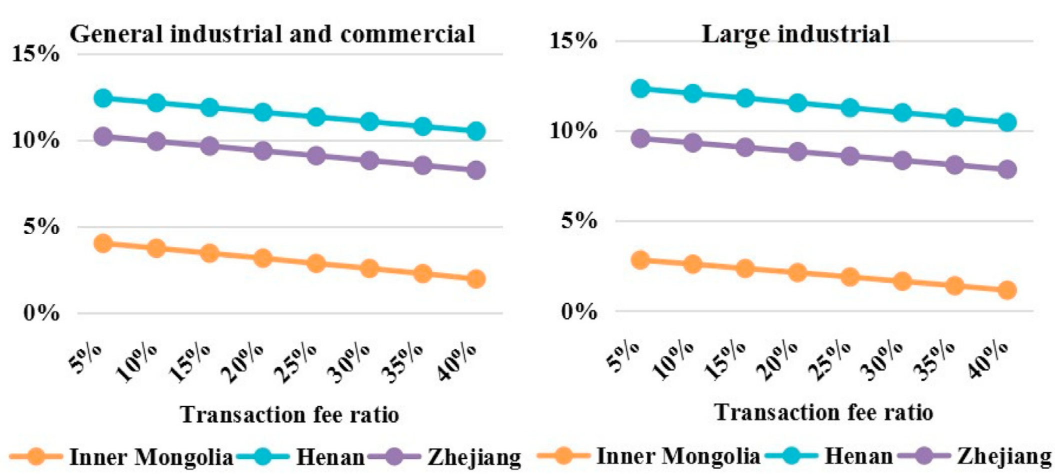

Fig. 8. The full investment IRR curve of different transaction fees.

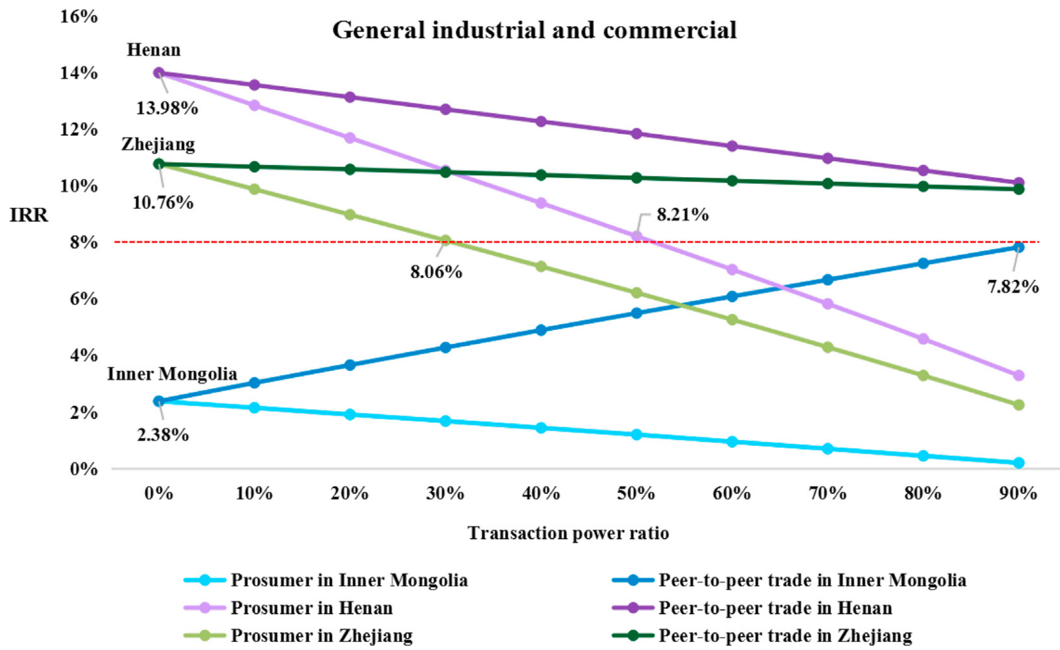

Fig. 9. The full investment IRR curve of different electricity trading volume.

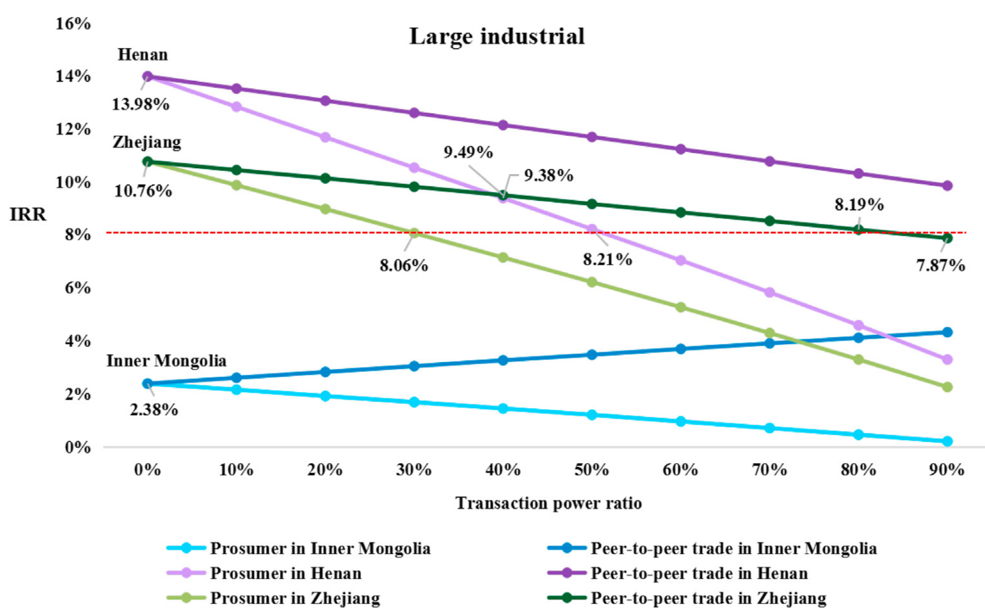

Fig. 10. The full investment IRR curve of different electricity trading volume.

6. Discussions

6.1. Further discussions

According to the results, the DPV "peer-to-peer trade" business model in Henan and Zhejiang is generally profitable in this paper's designed scenarios. The "peer-to-peer trade" model has better economic advantages than "pure producer" and "prosumer" models. "Peer-to-peer trade" can greatly promote the economy of DPV power generation projects. However, the experiments conducted in this paper also brought some problems in light. To further promote the "peer-to-peer trade" business model in China, the following problems need to be handled.

Wheeling costs are too low for grid companies. Shareholders will not accept the standard of unbalanced interest. The lack of profit guarantees would seriously inhibit grid companies' enthusiasm to participate in the "peer-to-peer trade" model. The wheeling cost approval should reasonably quantify the value of grid transmission and distribution and distributed power generation value. Based on the real cost, each voltage class's transmission and distribution price should be accounted for to measure the wheeling cost. DPV could only develop healthily through fairness competition.

Transaction efficiency directly affects the enthusiasm of DPV project investors to participate in "peer-to-peer trade". Transaction fees directly affect the economy of DPV projects. Reduce transaction fees and improve transaction efficiency to attract investors to participate in DPV "peer-to-peer trade". The reasonable approach is to seek a win-win policy for multiple parties to share part of the DPV project investors' transaction fees. Policies must be introduced to ensure the priority consumption of DPV electricity. As much as possible to achieve low-voltage grid-connected, nearby consumption. It is necessary to configure the personnel involved in the grid-connected services to improve PV quality services' quality and efficiency.

6.2. Policy implications

At the national level, this paper suggests establishing and implementing technical standards and market norms to help build a healthy market mechanism for DPV power generation. More adjustments and improvements should be conducted on the "peer-to-peer trade" model to establish a fair and effective market competition mechanism and optimize resource allocation.

At the local government level, this paper suggests strengthening cooperation with local investment and financing institutions, establishing a financing platform, and developing a variety of financing channels. More efforts must be made to reduce financing costs. We suggest that the local government choose an appropriate business model based on local resource conditions and economic development. It is important to provide policy support to encourage local users to participate in DPV "peer-to-peer trade". The joint role of resources, markets, and policies would promote the local DPV power generation industry's market development.

At the grid company level, this paper suggests strengthening the evaluation of grid-connection projects. The current regulations and processes must be revised and improved promptly. Improving the profitability of grid companies is an important way to promote the DPV "peer-to-peer trade" development. The feasible approach is to change the grid company's profit model. The specific approach is to transform the income spreads to revenue regulation. Link its permitted revenue to the transmission and distribution volume and reasonable costs to protect power grid companies' interests.

7. Conclusions

For the future investment of DPV projects, especially after the cancellation of feed-in tariffs, "peer-to-peer trade" could greatly promote the DPV power generation's economy. The "peer-to-peer trade" consumer has a more flexible choice than the "prosumer". Compared to the "pure producer" business model, a higher trading price could be derived through the "peer-to-peer trade". The marketization of DPV would become a new driving force for economic development. A handsome return of DPV power generation under the "peer-to-peer trade" model is to be expected.

The "peer-to-peer trade" model is more profitable and is a win-win solution to both DPV owners and electricity consumers. However, "peer-to-peer trade" is possible only when the power grid's role is properly defined in China's power sector reform. Not every region is suitable for the "peer-to-peer trade" model of DPV power generation. As shown in this paper, the IRR of DPV power generation in Inner Mongolia under the "peer-to-peer trade" model is relatively low, indicating that the PV resource's geographic advantages in the western provinces could not compensate for the low electricity prices. The key areas suitable to promote the "peer-to-peer trade" are those with high terminal electricity prices in Middle East China.

CRediT authorship contribution statement

Peiyun Song: Formal analysis, Data curation, Writing - original draft. **Yiou Zhou:** Writing - review & editing. **Jiahai Yuan:** Conceptualization, Methodology, Supervision, Project administration.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgments

The paper is supported by the funding of the National Natural Science Foundation of China (71673085), the Fundamental Research Funds for the Central Universities (2018ZD14) and 111 Project (B18021). The authors would also like to acknowledge great thanks to anonymous reviewers for their valuable comments, which largely improve this paper's academic quality. The usual caveats apply.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124500.

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