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Assessing the effectiveness of China's net-metering subsidies for household distributed photovoltaic systems

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A B S T R A C T

Consumer incentives play a vital role in promoting the adoption of renewable energy technology. In China, the government implemented a single, nation-wide net-metering subsidy to cultivate the distributed photovoltaic electricity generation market in 2013 and then had to reduce it twice due to the falling cost of photovoltaic modules and the large resultant financial gap. The aim of this study was to evaluate whether these subsidy adjustments were accurate, and also to identify the factors affecting the subsidy design. We applied a techno-economic evaluation to examine the actual market performance of China's household distributed photovoltaic system in five typical cities with different levels of solar radiation and electricity consumption patterns, and then investigated the subsidy policy's effectiveness through a cost-benefit analysis. The results show that a 3–7 kW photovoltaic capacity in different regions of solar radiation can meet the residential electricity demand. We found that the examination of net-metering effectiveness should consider both regional difference in solar radiation and the different levels of electricity demand. Additionally, the cost-benefit analysis also indicated that a reasonable, regionally differentiated metering subsidy should be in the range of 0.05–0.27 yuan/kWh.

1. Introduction

Solar energy is considered an essential resource in promoting energy transition and alleviating climate change because it is inexhaustible and non-polluting (Kabir et al., 2018; Kayal and Chanda, 2015). Photovoltaic (PV) power generation, as the main application of solar energy, has gradually been replacing coal-fired power generation in recent years (Lund, 2007). With technical improvements and market expansion, two patterns of solar power generation have formed, centralized and distributed PV electricity generation systems (Poullikkas, 2010). In China, the new added installed capacity of centralized PV power generation reached 33.49 GW in 2017. The centralized PV system accounts for a higher percentage of cumulative installed capacity compared to distributed PV power generation because of its earlier development and technology maturity (Zhang et al., 2012). In contrast, the cumulative installed capacity of distributed PV power generation only accounted for 15%–20% of total PV power generation between 2013 and 2016. However, in recent years, some unique advantages of the distributed PV system over remote large-scale PV plants has been gaining attention, including its rooftop installation near demand centers, as well as lower transmission cost and electricity losses (Haghdadi et al., 2017; Zhang et al., 2015). For example, distributed PV new added capacity experienced a remarkable increase from 4.26 GW in 2016 to 19.44 GW in 2017, which indicates the strong growth of this system (Anaya and Pollitt, 2015).

To cultivate China's distributed PV market, the Chinese government implemented a net-metering policy in 2013. According to this policy, the owners of distributed PV systems could receive a subsidy of 0.42 yuan/kWh[1]. Meanwhile, home owners can use household PV production to offset some or all of their electricity consumption and then sell excess energy to the utility grid (Eid et al., 2014). This means that they could benefit not only from policy subsidies of PV power generation but also from electricity sales (Comello and Reichelstein, 2017). Apart from China, the

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[1] "Yuan" is the unit of China's currency "RMB," which was approximately equal to 0.148 US$ during the period of net-metering policy from 2013 to 2017.

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residential and commercial segments in many countries such as Denmark, Italy, Lithuania, and the Netherlands have benefited from the net-metering policy. In China, this policy stimulated further expansion of the distributed PV market, but the problem of an excessive financial gap arose. Specifically, the fixed net-metering subsidy was not consistent with the declining cost of PV power generation. The government has owed huge subsidies to power companies due to the inflexible adjustment of the subsidy amount. The subsidies in arrears imposed a heavy burden on government finance, creating a financial gap (Lin and Jiang, 2011). According to the statistics of the National Energy Administration, China's PV financial gap reached about 49.6 billion yuan by the end of 2017, accounting for nearly half of the total renewable energy financial gap. As a result, heavy financial pressure forced the government to reduce metering subsidies from 0.42 yuan/kWh to 0.37 yuan/kWh in 2017 and the current subsidy is 0.32 yuan/kWh. With the technological innovation and market expansion of the PV industry, the cost of distributed PV power generation is falling accordingly. Thus the adjustment of the net-metering subsidy is also necessary (Zou et al., 2017b). However, the adjustment intensity determines the policy effectiveness and development path of the PV industry. Therefore, it is necessary to investigate thoroughly whether this series of adjustments of the subsidy is appropriate and what factors are related to the subsidy design.

Previous studies on the effectiveness of subsidy policy mainly include two parts: the development of renewable technologies and the socio-economic impact thereof (Menz and Vachon, 2006; Dong, 2012; Ma et al., 2014; Torani et al., 2016; Ramírez et al., 2017; Pacudan, 2018). For renewable technology development, some studies have employed an econometric method to examine the effect of different state-level policies on the adoption of renewable technologies, such as comparing the effect of feed-in tariffs and renewable portfolio standard on promoting wind capacity (Menz and Vachon, 2006; Dong, 2012; Ma et al., 2014). Similarly, Torani et al. (2016) have developed a stochastic dynamic model under two sources of uncertainty to investigate the effectiveness of four policies on accelerating PV adoption: electricity price, technological change, subsidies, and carbon tax. The results show that the policies of subsidies and taxes become increasingly ineffective with the increase of the technological innovation rate. However, the intensity of subsidy policy in the current renewable market, such as the net-metering and feed-in-tariff policy, is still ambiguous for policymakers in the process of rapid cost reduction of PV power generation (Ramírez et al., 2017; Pacudan, 2018). For social and economic impact, many researchers have adopted the input-output method and computable general equilibrium (CGE) models to investigate the impact of canceling renewable energy subsidies in the transportation and other macro-economic sectors (Solaymani and Kari, 2014; Gelan, 2018). The results show that the policy shock can significantly reduce carbon emissions, but will negatively affect social welfare, GDP, and employment. Therefore, previous studies on PV subsidies usually consider the static subsidy intensity and ignore the impact of technological improvement on subsidy design. Focusing on the net-metering policy of PV power generation, this study will evaluate the effectiveness of current subsidies and design a reasonable subsidy intensity, which aims to release the financial burden on the public sector from the social and economic point of view.

A prerequisite for the policy evaluation of renewable energy is the modeling of related technology engineering. One common method is techno-economic evaluation, which can analyze policy effectiveness based on technical feasibility and cost optimization of renewable energy technologies. Technical feasibility means to simulate the operation of a power generation system to meet electricity demand (Purohit and Purohit, 2010; Ma et al., 2015; Christoforidis et al., 2016). Cost-effectiveness is commonly measured by certain economic indicators, such as project investment payback and levelized cost of energy (LCOE) (Yamamoto, 2012; Olatomiwa et al., 2015; Camargo et al., 2016). However, policy evaluation of net-metering subsidy considers not only technical and economic factors, but also regional differences. Especially in China, natural resource availability, energy demand, and economic level vary in different regions (Perpiña Castillo et al., 2016; He et al., 2016). On one hand, different natural resource availability and household electricity demand across regions will exert an influence on the different technology choices for renewable energy (Sen and Bhattacharyya, 2014). On the other hand, local economic development will also affect the generation costs and profits of distributed PV owners by encouraging different electricity prices (Nyholm et al., 2017; La Monaca and Ryan, 2017). Therefore, this study aims to assess the policy's effectiveness thoroughly and develop a regionally differentiated subsidy policy by selecting five typical areas with solar resource differences as a case and taking users' electricity consumption variations into consideration.

In addition, some studies consider the impact of temporal factors on subsidy policy because of the steady decline of investment cost and the continuous progress of technology (Brown and Sappington, 2017; Zhang et al., 2011; Kalish and Lilien, 1983; Xiong and Yang, 2016; Hagerman et al., 2016). Several researchers have used learning curve models to investigate the change patterns of subsidy intensity with the technical diffusion of renewable energy (Zhang et al., 2011; Kalish and Lilien, 1983). Similarly, other scholars have found the best entry and exit occasions for governmental subsidies (Xiong and Yang, 2016; Hagerman et al., 2016). Therefore, it is important to identify the factors that affect the effectiveness of the net-metering policy over time, such as LCOE and reasonable subsidy levels, so as to give some policy recommendations for the long-term development of China's PV power generation.

2. Material and methods

This study analyzed the market performance of China's distributed PV system and the effectiveness of the related net-metering subsidy. Specifically, a techno-economic evaluation is employed to examine the operation of the PV power generation system, and the net-metering policy's effectiveness is investigated through a cost-benefit analysis. The notations used in this study are shown in Table 1.

2.1. Techno-economic evaluation

This study adopted a techno-economic analysis to examine the current application of China's distributed PV power system and used the HOMER (Hybrid Optimization of Multiple Energy Resources) software as the main research tool. HOMER models the renewable power generation systems using hourly simulation and cost optimization, and is widely used in different systems and regions, such as PV systems in the United States, hybrid grid-connected PV-wind power systems in Spain, and the grid-tied hybrid microgrid system in Pakistan (Janko et al., 2016; González et al., 2015; Otsuka et al., 2001). To conduct the techno-economic evaluation, the study used HOMER to investigate the following two key aspects.

2.1.1. Technical feasibility analysis

A technical feasibility study was done for meeting the users' electricity demand of household distributed PV system. To simulate the actual implementation of the system configurations, HOMER combines different component sizes depending on the

Table 1
Notations for key parameters.

Parameter	Definition (unit)
$E_{\mathrm{PV,prod}}$	electricity produced only by distributed PV modules (kWh)
$E_{\mathrm{gird,\ purchase}}$	electricity purchased from the public grid (kWh)
$E_{\mathrm{AC,load}}$	electricity that serves residential load from AC terminals (kWh)
$E_{\mathrm{grid,\ sales}}$	surplus electricity sold to the public grid (kWh)
E_{excess}	excess power that cannot serve the load demand or be stored in batteries (kWh)
E_{loss}	electricity lost through system operation (kWh)
C_{NPC}	total net present cost (yuan)
$C_{\mathrm{ann,tot}}$	sum of all annualized costs of each system component (yuan)
CRF (i, N)	function returning the capital recovery factor
i	annual real interest rate (%)
N	project lifetime (year)
LCOE	levelized cost of energy (yuan)
$R_{\mathrm{ann,tot}}$	annual total revenue of the user who invested in the distributed PV system (yuan/year)
P_{subsidy}	subsidy implemented by the government (yuan/kWh)
P_{coal}	local coal-fired electricity price in China (yuan/kWh)
PR_{unit}	unit profit of users (yuan)

characteristics of load profile and solar radiation profile, and balances the electricity generated from each system component. With the approach of this model simulation, a feasible distributed PV system will be selected. The relationship of electricity balance in the system can be expressed by equation (1):

$$E_{PV,prod} + E_{grid,purchases} = E_{AC,load} + E_{grid,sales} + E_{excess} + E_{loss} \quad (1)$$

where $E_{\mathrm{PV,prod}}$ is the electricity produced only by PV modules (kWh); $E_{\mathrm{gird,\ purchase}}$ is the electricity purchased from the public grid (kWh), not only for peak shaving and valley filling during the daytime, but also to meet users' electricity demand when the PV system cannot maintain power supply at night; $E_{\mathrm{PV,prod}}$ and $E_{\mathrm{gird,\ purchase}}$ represent the energy supply of the distributed PV system; $E_{\mathrm{AC,load}}$ is the electricity which serves residential load from AC (Alternating Current) terminals (kWh); $E_{\mathrm{grid,\ sales}}$ is the surplus electricity sold to the public grid (kWh); E_{excess} is the excess power which cannot serve the load demand nor be stored in batteries (kWh); E_{loss} is the electricity lost through system operation (kWh), such as the power attenuation of components, charging and discharging of batteries, as well as the instability of equipment operation and maintenance.

2.1.2. Cost-effectiveness analysis

After the system operating simulation, the optimal distributed PV systems will be obtained by the total net present cost (expressed by C_{NPC}). C_{NPC} represents the net present cost in the system's lifetime, including investment cost, replacement cost, and operation and maintenance cost. It can be calculated by equation (2):

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, N)} \quad (2)$$

where $C_{\mathrm{ann,tot}}$ is the sum of all annualized costs of each system component, CRF (i, N) is a function returning the capital recovery factor, i and N are the annual real interest rate (%) and the project lifetime (year), respectively. This study assumed no variable operation and maintenance costs.

Then, based on the C_{NPC} and the actual power consumption ($E_{\mathrm{AC,load}} + E_{\mathrm{grid,\ sales}}$), LCOE was calculated. LCOE is a vital indicator of the comparative competitiveness between a distributed PV system and traditional electricity supply; it can be expressed by equation (3):

$$LCOE = \frac{C_{ann,tot}}{E_{AC,load} + E_{grid,sales}} \quad (3)$$

2.2. Cost-benefit analysis

After examining the actual performance of current distributed PV systems and selecting the feasible ones, the effectiveness of the net-metering policy for distributed PV systems was investigated. A cost-benefit analysis is used to compare the cost and profit of household distributed PV systems in different regions. Here, the cost of each PV system results from the optimization of HOMER software and is expressed by the LCOE indicator. The benefit of users who invest in the distributed PV system can be obtained from two sources. The first is government subsidies for electricity generated by the distributed PV system, including electricity consumed by users and sold to the power grid. As mentioned in the Introduction, in 2013, the Chinese government implemented a net-metering subsidy of 0.42 yuan/kWh for distributed PV power. With the declining cost of PV power generation and the rapid expansion of the PV industry, the subsidy decreased to 0.37 yuan/kWh in 2017 and to 0.32 yuan/kWh in 2018.

The users of the distributed PV system can also sell excess electricity to the power grid and make a profit, which is the second source. The Chinese government requests power grid companies to purchase the renewable electricity at the local coal-fired price. The profit of users who invest in the distributed PV system can be expressed by equation (4):

$$R_{ann,tot} = \left(E_{AC,load} + E_{grid,sales}\right) * P_{subsidy} + E_{grid,sales} * P_{coal} \quad (4)$$

where $R_{\mathrm{ann,tot}}$ is the annual total revenue of a user who invests in the distributed PV system (yuan/year); P_{subsidy} is the subsidy implemented by the government (0.42 and 0.37 yuan/kWh); P_{coal} is the local coal-fired price in China (yuan/kWh), as a benchmark for reference before carrying out the evaluation of the distributed PV project.

To investigate the effectiveness of the net-metering policy, the unit profit should also be calculated. In other words, if the net-metering policy is effective, the users of distributed PV system can make a profit over its lifetime. The unit profit of users can be expressed by equation (5):

$$PR_{unit} = \frac{R_{ann,tot} - C_{ann,tot}}{\left(E_{AC,load} + E_{grid,sales}\right)} \quad (5)$$

3. Construction and parameter description of the distributed PV system

To investigate the effectiveness of China's current distributed PV net-metering policy, this study constructed distributed grid-connected systems of PV power generation. Based on the form of PV power generation, different locations with typical characteristics were chosen as a case study to consider regional differences.

3.1. Distributed PV power generation system

Since 2013, China has implemented a net-metering policy to encourage residential customers to adopt the distributed PV power generation system. Against this background, the users of the distributed PV system can not only produce electricity for their own energy use, but also sell electricity to a power grid to make a profit. As shown in Fig. 1, the distributed PV system model is composed of five important parts: PV modules, battery, primary load, inverter, and power grid. Initially, solar energy is directly converted into electric energy through the PV voltage effect of PV modules in the system. Then the electric energy can be stored in the battery or supplied to the direct current (DC) section. The inverter can be used to convert the DC electricity into AC electricity to meet residential electricity demand. In addition, the distributed PV system is connected to the public grid, which means that the public grid can provide supportable electricity to users.

3.2. Characteristics of system components

The PV module is one of the key components in a distributed PV system, which influences system operation and power generation cost. In the past decade, with the increasing scale of PV production, the capital cost of China's PV modules has plunged from 35.00 yuan/W in 2008 to 2.26 yuan/W in 2017. Focusing on China's PV market in 2017, as shown in Fig. 2, the price of PV modules fluctuated between 2.13 and 2.42 yuan/W. The yearly average price of 2.26 yuan/W is used as the capital cost of PV modules in modeling systems.

In addition to PV modules, inverters and batteries are also indispensable parts of distributed PV systems. As shown in Table 2, the economic data and main technical characteristics of these components were collected from other studies (Adefarati and Bansal, 2017; Zou et al., 2017a). In general, the price of inverters

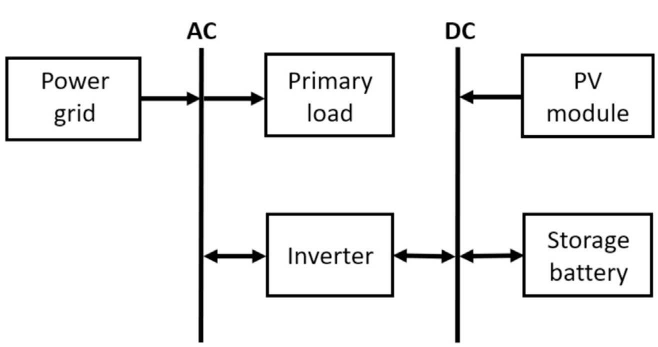

Fig. 1. Schematic diagram of distributed grid-connected PV power systems.

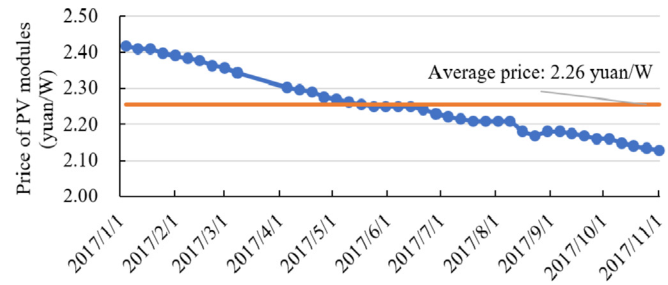

Fig. 2. The price trend of China's PV modules in 2017[2].

Table 2
The economic cost and technical characteristics of each component of the PV system.

Components	Economic and technical parameter	Value chosen (unit)
System	Fixed capital cost	3500 (yuan)
	Fixed operation & maintenance cost	35 (yuan/year)
	Project lifetime	20 (years)
	Nominal discount rate	8%
	Expected inflation rate	2%
PV module	Capital cost	2255 (yuan/kW)
	Replacement cost	2255 (yuan/kW)
	Operation & maintenance cost	22.5 (yuan/kW)
	Lifetime	20 (years)
	Derating factor	80%
Battery	Capital cost	600 (yuan)
	Replacement cost	600 (yuan)
	Lifetime	5 (years)
	Efficiency	80%
Inverter	Capital cost	750 (yuan/kW)
	Replacement cost	750 (yuan/kW)
	Lifetime	15 (years)
	Efficiency	85%

and batteries in China's current market has experienced a slow downward trend in recent years, and their costs are around 500–1000 yuan.

3.3. Regional selection

To analyze the effect of China's net-metering policy on distributed PV systems in different areas, five typical cities were selected from five regions with varying levels of solar radiation as the research objects. They are Chongqing, Guangzhou, Beijing, Yushu, and Lhasa. These cities not only represent different levels of solar radiation, but also have heterogeneous load characteristics. The load characteristics will influence the operation of a distributed PV system and related users' profit.

3.3.1. Solar radiation and PV policy of the five cities

The selected five cities have different levels of solar radiation. The highest radiation in these cities occurs from April to August. As can be seen from Fig. 3, the yearly average radiation of Lhasa is the highest and reaches its maximum of 6.485 kWh/m^2/day in May; by contrast in Chongqing, the yearly average solar radiation is lower than in other cities and its minimum radiation is 0.296 kWh/m^2/day in October. In addition, the five cities also have different coal-fired benchmark prices, which will influence users' revenue from selling PV electricity to the power grid. Since 2015, the Chinese government has implemented a national policy that encourages

[2] Data source: PV insights website (http://pvinsights.com/).

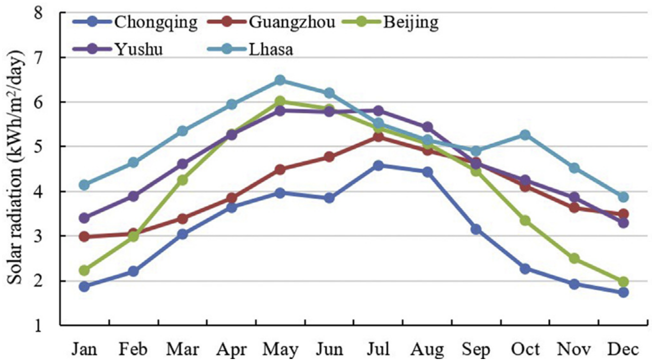

Fig. 3. Solar radiation profile of the five cities.[3]

Table 3
Coal-fired benchmark prices and PV policies in five cities.

City	Coal-fired benchmark price (yuan/kWh)	PV poverty alleviation policy	National net-metering subsidy (yuan/kWh)
Chongqing	0.3964	No	2018: 0.37
Guangzhou	0.3598	No	2017: 0.42
Beijing	0.4530	No	
Yushu	0.3247	Yes	
Lhasa	0.4993	No	

Data source: China Statistical bulletin for national economy and social development.

rural residents to invest in distributed PV systems, with the goals of solving the problem of electricity shortage and guaranteeing PV-investors' economic benefits in rural areas. The residents who installed PV systems can not only obtain financial aid from discounted bank loans and anti-poverty funds, but also sell excess electricity to the power grid and gain economic returns. It is worth noting that Yushu, with higher solar radiation, is located in such a PV poverty alleviation policy area. Thus, the less developed areas in north-western China represented by Yushu have a great potential for the application of the distributed PV system. This is why we chose this city as a case study(See. Table 3).

3.3.2. Load characteristics of the five cities

The household electrical load in each city reflects unique residential power characteristics. To make the load profile more representative in these cities, the primary residential load data given in the HOMER software are adjusted based on the regional difference and actual electricity demand. According to the Chinese total social electricity consumption statistics, the monthly household electricity consumption is divided into three categories based on the different levels of electricity demand (low, medium, and high). As shown in Table 4, household retail electricity prices are different in those three categories. The daily electricity load is calculated according to different levels of monthly household electricity demand. In general, the characteristic of daily electricity load is similar to the practical case, where the load is higher during the day and lower in the night. It is worth noting that the electricity demand and related retail electricity price will influence the operation of the distributed PV system and residents' profit. In addition, the seasonal or daily peak and valley load time in each city is influenced by geographical location and seasonal changes. For example, Beijing's cooling and heating load are significantly higher than other cities owing to its hot summer and cold winter, and meanwhile its early sunrise time makes the peak load time earlier than that in the western regions, such as Lhasa and Yushu. To make the data represent the fluctuations more accurately, two random variability factors, day-to-day and time-step-to-time-step variability, were set at 10% and 20%, respectively (Bhakta et al., 2015; Hittinger et al., 2015).

4. Techno-economic evaluation of distributed PV systems in China

The techno-economic evaluation examined the feasible distributed PV systems in China's five cities according to two aspects: technical feasibility and cost-effectiveness.

4.1. Technical feasibility analysis

To analyze the technical feasibility of distributed PV systems, several groups of capacity configurations were input into the HOMER software to simulate the actual residential electricity usage. All feasible system configurations that satisfy the different

Table 4
Different levels of electricity load and related retail electricity price.

City	Different levels of electricity demand (kWh/month)		Retail electricity price (yuan/kWh)	Daily average electricity load (kWh/day)
Chongqing	low	0–200	0.5200	6.67
	medium	200–400	0.5700	10.00
	high	>400	0.8200	13.33
Guangzhou	low	0–240	0.5802	8.00
	medium	240–400	0.6302	10.67
	high	>400	0.8802	13.33
Beijing	low	0–230	0.4883	7.67
	medium	230–500	0.5383	12.17
	high	>500	0.7883	16.67
Yushu	low	0–150	0.3771	5.00
	medium	150–230	0.4271	6.33
	high	>230	0.6771	7.67
Lhasa①	average	–	0.5400	8.00

Note: ①The missing data is because the formulation of a unified retail electricity price in Lhasa does not take different levels of electricity demand into account.

[3] Data source: HOMER software.

Table 5
The optimal system configurations in the distributed PV systems of five cities.

City	Electricity demand	PV capacity (kW)	12 V battery (quantity)	Inverter capacity (kW)
Chongqing	low	3	1	1
	medium	5	1	3
	high	7	1	3
Beijing	low	3	1	1
	medium	3	1	3
	high	5	1	3
Guangzhou	low	3	1	1
	medium	5	1	3
	high	7	1	3
Yushu	low	3	1	1
	medium	3	1	1
	high	3	1	1
Lhasa	average	3	1	1

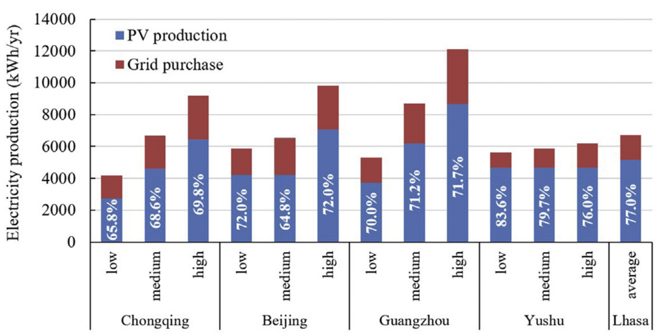

Fig. 4. The proportion of PV power generation in the five cities.

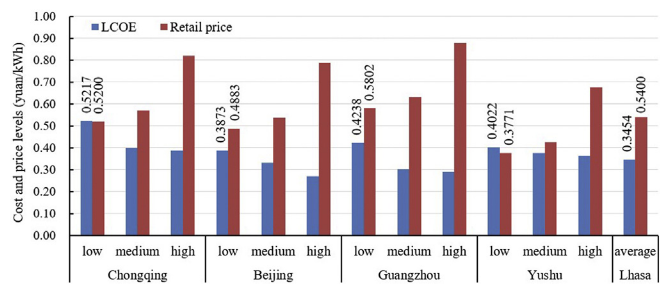

Fig. 5. Cost-effectiveness analysis of the distributed PV systems in the five cities.

residential electricity demands were selected to calculate the value of NPC and LCOE. Table 5 displays the optimal distributed PV system with the minimal NPC under different electricity demands in each city. In the case of low electricity demand, the system configurations are similar, including a PV module with 3 kW capacity, a 12 V battery, and 1 kW inverter. However, the configurations of distributed PV systems are influenced by solar radiation and electricity demand. The distributed PV systems in a city with low solar radiation must have a PV module with high capacity. For example, in Chongqing, the capacity of a PV module must increase to 7 kW to satisfy the high electricity demand. In contrast, the distributed PV system in Yushu has the same PV module of 3 kW capacity for different levels of electricity demand because of high solar radiation.

The electricity generated by distributed PV systems comes from PV module operation and power grid purchases. As shown in Fig. 4, the PV production of the five distributed PV systems accounts for more than 65% of the total power generation in those cities. It is worth noting that the percentage of PV production in Yushu and Lhasa are both over 75% because the solar radiation in these two cities are plentiful, which can provide a large share of electricity to users. However, the technical feasibility of the distributed PV system must depend on the services of grid operators.

For electricity consumption, the surplus electricity sold to the public grid accounts for about 30% in each of the five PV systems, which means that the efficiency of the distributed PV systems in the five cities are similar. However, the quantitative difference of the surplus electricity can also affect the results of net-metering policy effectiveness, considering the coal-fired benchmark price and the LCOE of PV systems.

4.2. Cost-effectiveness analysis

The cost-effectiveness analysis aimed to investigate the economy of the distributed PV system without net-metering policy. Under the low, medium, and high levels of the residential electricity demand, the LCOE of the distributed PV systems across the five cities ranges between 0.4022 and 0.5217, 0.3017–0.3997 and 0.2700–0.3870 yuan/kWh, respectively. As shown in Fig. 5, with an increase in electricity demand, the LCOE of the distributed PV system in each city shows a declining trend. High electricity demand can help reduce the LCOE through improving the capacity size and operation efficiency of the PV system, which also illustrates the large economies of scale of solar PV systems (Hittinger et al., 2015; Lee and Callaway, 2018). Chongqing, with the poorest solar radiation, has the highest LCOE (0.5217 yuan/kWh) among the five cities. Generally, a high solar radiation will lead to a low LCOE of PV systems (Fuentealba et al., 2015; Silva-Pérez, 2016). However, the lowest LCOE of the distributed PV systems does not appear in Lhasa or Yushu, which both have rich solar radiation. This is because the local electricity demand is low due to low economic development. Although the regional solar radiation and on-grid electricity are sufficient, PV modules with a small capacity are not necessary to generate more power for users' consumption. Therefore, the total power generation of the distributed PV system is slightly lower and the cost is relatively higher than those of big cities. In contrast, Beijing and Guangzhou, as two of the most developed cities in China, have a lower LCOE because of their high electricity demand most of the year. Therefore, local or residential electricity demand should be considered in the actual application of distributed PV systems and related policy design.

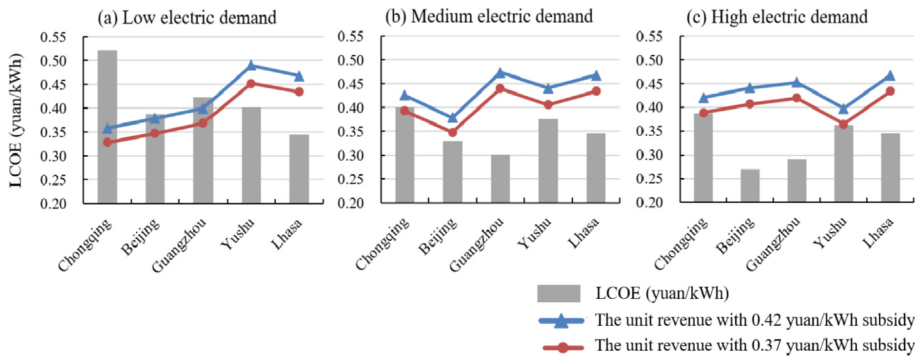

Fig. 6. Revenue analysis of the distributed PV systems in the five cities.

5. The assessment and design of China's net-metering policy

5.1. The assessment of policy effectiveness

Although the LCOE of the distributed PV system is lower than the retail electricity price, power consumers still prefer the traditional power grid because of the high quality of service. Thus, the Chinese government implemented the net-metering policy to stimulate power consumers to invest in distributed PV systems. By calculating the revenue of users, the effectiveness of the net-metering policy was examined. As shown in Fig. 6 (a), under the condition of low electricity demand, the LCOE of distributed PV systems in Chongqing, Beijing, and Guangzhou is higher than the unit revenue of users, which means that the net-metering policy cannot help users cover their electricity bills. It is worth noting that the low solar radiation in Chongqing leads to the high LCOE of the distributed PV system. It is difficult for the net-metering policy to play a role in this area. In contrast, Yushu and Lhasa, with rich solar radiation, have high unit revenues that cover the electricity bills of users, which verifies the effectiveness of the net-metering policy in these areas. In addition, the unit revenue of the distributed PV system in Yushu is the highest among the five cities. The net-metering policy can play an active and precise role in the policy of PV poverty alleviation which is implemented in this city.

Under the condition of medium and high electricity demand, as shown in Fig. 6(b) and (c), the unit revenues of users are all higher than the LCOE of the distributed PV systems in the five cities. The net-metering policy is very effective when the residential electricity demand is at a higher level. Specifically, high electricity demand can improve the operation of the PV system and reduce the LCOE, especially in China's first-tier cities like Beijing and Guangzhou. Meanwhile, the users can also sell more electricity to the power grid and make a profit.

With the growth of electricity demand, the unit revenue of users in Beijing and Guangzhou shows a remarkable improvement. It can be concluded that electricity demand is a vital factor to influence the effectiveness of the net-metering policy when the local solar radiation is poor.

As shown in Fig. 6, the reduction of the net-metering policy subsidy (from 0.42 to 0.37 yuan/kWh in 2017) can still ensure sufficient revenue for users to cover their electricity bills or the costs of PV power generation. Thus, with the increase of the financial gap of China's PV subsidy, the reduction of the net-metering subsidy is necessary and accurate for policy sustainability and effectiveness.

5.2. A reasonable net-metering subsidy policy

According to China's National Energy Administration, the cumulative financial gap caused by renewable energy subsidies has been as large as 110 billion yuan in 2018. To alleviate the financial tension, the net-metering policy should be designed properly to cover the costs of the distributed PV system. As shown in Fig. 7, the reasonable subsidies in different scenarios of electricity demand fluctuates from 0.05 to 0.27 yuan/kWh, which are much lower than the past net-metering policies (0.42 and 0.37 yuan/kWh), except for Chongqing. That means that there is still a large margin for the decrease of China's net-metering subsidy.

Specifically, in the scenario of low electricity demand, Chongqing is the only city whose reasonable net-metering is higher than current subsidies. However, the reasonable net-metering subsidy is closely related to solar radiation. The richer the local solar radiation is, the lower the reasonable metering subsidy becomes. For example, Lhasa with rich solar radiation, has the lowest reasonable net-metering subsidy (0.11 yuan/kWh). Therefore, the net-metering subsidy policy in China should be designed considering the regional differences in solar radiation. Currently, China's feed-in tariff policy has been implemented according to different levels of solar radiation in three areas. However, the net-metering policy is

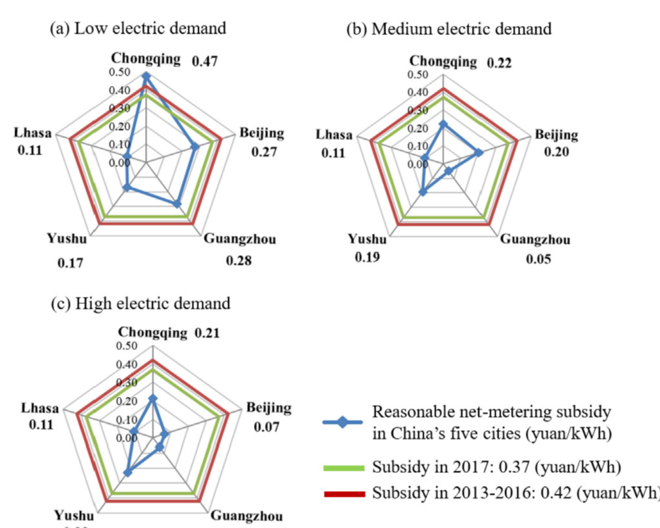

Fig. 7. Reasonable net-metering subsidies covering the LCOE of the distributed PV systems.

designed according to the national unified standard, which will increase the subsidy pressure.

In the scenario of medium and high electricity demand, the reasonable net-metering subsidies in the five cities are much lower than the current subsidy even though the subsidy has been adjusted to 0.37 yuan/kWh in 2017. Also, compared to the scenario of low electricity demand, the reasonable subsidies in the five cities also show a declining trend. Therefore, the reasonable net-metering subsidy should be designed considering the effect of electricity demand. For the areas that have high residential electricity demand, the net-metering subsidy of distributed PV systems should be adjusted lower to avoid excessive subsidies.

6. Conclusions

This study examined the actual application of China's distributed PV systems using a techno-economic evaluation. Based on the cases of five cities, the simulation of the HOMER model demonstrated that the existing techniques make the implementation of distributed PV systems in different areas feasible, with 3–7 kW PV modules needed to meet the different scenarios of electricity demand. In comparison with the regional retail electrical price, the cost of PV power generation is relatively lower. The LCOEs of the distributed PV systems in each area range between 0.2700 and 0.5217 yuan/kWh. This fluctuation of investment costs is closely related to the solar radiation and electricity demand, both of which can affect the efficiency of the PV system. As a result, in two regions in China, it has been demonstrated to be advantageous to install distributed PV power generation to ensure users' investment cost at a lower level: one is the western remote areas with rich solar radiation, like Tibet and Qinghai province, and the other is the eastern developed areas with higher residential electricity demand, such as Beijing and Guangdong province. However, some problems should be addressed in these two regions respectively, such as the excessive PV electricity production and the insufficient consumptive ability of grid equipment.

To assess the effectiveness of China's current net-metering policy, the metering subsidies across five regions have been added to the calculation of users' unit revenues. The results implicate that the formulation of net-metering policy should not only consider the regional divergence of solar radiation, but also take different levels of electricity demand into account. For example, under the condition of low electricity demand, the users' unit revenue in Yushu and Lhasa with rich solar radiation are higher than in other cities. In contrast, with a rise in electricity demand, the increase in residential revenues in Chongqing, Beijing, and Guangzhou exceeds the LCOE of distributed PV systems. Thus, it can be concluded that the current metering subsidy can completely cover the investment cost of distributed PV systems and make residents' PV systems profitable. Therefore, it is necessary to decrease the metering subsidy to relieve the financial pressure on the government. However, there is one notable exception in Chongqing. Because it has the poorest solar radiation and the highest LCOE of the distributed PV system, the net-metering policy is unsuitable for this area.

Currently, China's feed-in tariff policy has been implemented in three areas with various levels of solar radiation, but the net-metering policy schemes are uniform across China. According to China's actual situation, the divergence of regional revenue and cost from PV power generation raises questions about the disunity of the reasonable metering subsidy, considering the local solar radiation, electricity demand, and economic development. In this study, a reasonable metering subsidy is designed to range from 0.05 to 0.27 yuan/kWh, which is much lower than the current metering subsidy.

With the continuous decline of metering subsidies, the economic attractiveness of distributed PV installation to householders has been strangled. If there are no follow-up incentive policies, the sustainable development of PV industry would be uncertain. Thus, further research should focus on the transformation of the development pattern for renewable energies. For example, shifting the development direction from supportive policy driven to free market competition will not only require more enterprises to actively participate in clean energy projects, but will also be conducive to the early realization of PV grid parity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Xinyu Jia: Investigation, Software, Formal analysis, Writing - original draft. **Huibin Du:** Project administration, Validation, Funding acquisition. **Hongyang Zou:** Conceptualization, Methodology, Visualization, Supervision. **Gang He:** Writing - review & editing.

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