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Valuing the carbon assets of distributed photovoltaic generation in China

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ABSTRACT

Distributed photovoltaic generation has advantages in energy savings and emissions reduction, but its economic value is still unclear. This paper examines the carbon value of distributed photovoltaic generation, analyzes the influencing factors and further illustrates how these factors affect the value. First, it introduces the method of carbon asset valuation to distributed photovoltaic generation, which produces lower carbon emissions than most other energy sources. Second, based on mean estimates of the internal determining factors for the carbon assets of distributed photovoltaic generation, this paper provides an estimated value of the carbon assets. Third, under uncertain conditions and accounting for the time factor, it uses Monte Carlo simulation to analyze the sensitivity of the carbon asset value of distributed photovoltaic generation. The results indicate that (1) distributed photovoltaic generation has a carbon asset value; (2) the carbon asset value of distributed photovoltaic generation is determined by the carbon reduction level, the power generation capacity and the carbon price; and (3) carbon price fluctuations affect the carbon asset value of distributed photovoltaic generation much more than the power generation capacity. This paper provides academic support to promote carbon asset trading in distributed photovoltaic generation and for distributed photovoltaic generation to reduce carbon emissions.

1. Introduction

Distributed photovoltaic generation has received considerable attention recently, as it plays an increasingly important role in energy savings and emissions reduction. Distributed photovoltaic generation serves the current demand for not only electrical energy but also increased electrified heating, cooling and transport, so it has sound advantages for achieving the sustainability objectives of energy policy at low cost (Hancevic et al., 2017; Bell and Gill, 2018). Driven by technological advancements and policy encouragement, distributed photovoltaic generation has had developed rapidly in China in recent years (Dong et al., 2016; Nerini et al., 2016; Anaya and Pollitt, 2017; Feng et al., 2017; He et al., 2017). Its cumulative installed capacity reached 6.06 GW at the end of 2015, and the average annual increase will be 12.79 GW during the 13th Five-Year Plan of China, which implies that there is a very substantial development space for distributed photovoltaic generation in the future.

Although the economic value of distributed photovoltaic generation is recognized, and it has developed rapidly in many countries such as China, its potential environmental value in energy savings and emission reduction is still very ambiguous (Holtmeyer et al., 2013; Zhao et al., 2015; Brouwer et al., 2016; Luo et al., 2016). To analyze the potential environmental value of distributed photovoltaic generation, this paper applies the theory of carbon asset valuation advanced by Han et al. (2015) to value the carbon asset of distributed photovoltaic generation. We further analyze the influencing factors on the carbon asset value of distributed photovoltaic generation and illustrate how these factors affect the value.

Carbon assets refer to the economic and environmental value of carbon reduction in all green production or consumption processes, so such assets are quite extensive. However, the study of carbon assets is limited to only a few fields; to the best of our knowledge, there are still no specific studies on the carbon asset value of distributed photovoltaic generation. Because distributed photovoltaic generation provides considerable benefits with regard to energy conservation and carbon reduction, its carbon asset value should be considered. This paper examines the carbon asset value of distributed photovoltaic generation, which will contribute to the understanding of the economic and environmental effects of distributed photovoltaic generation and the literature on the assessment of carbon assets' value.

According to Han et al. (2015), the value of carbon assets depends on the abetment ability of the project, its production amount and the carbon price in the market. Distributed photovoltaic generation has overwhelming superiority in energy savings and emissions reduction, as

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during the 13th Five-Year Plan of China, the carbon dioxide emissions from solar power are expected to be 33–50 g/kW h and those from coal are expected to be 796.7 g/kW h. As the market size of distributed photovoltaic generation in China expands, the National Energy Bureau has encouraged distributed photovoltaic generation as part of voluntary carbon reduction systems. The public carbon price will be formed in the carbon trading market launched by the State Council of China in 2018. All these conditions make it possible to study the influencing factors on the carbon asset value of distributed photovoltaic generation in China, which will increases the understanding of how the carbon asset value of distributed photovoltaic generation is determined and how it changes.

The reminding of this paper proceeds as follows: Section 1 reviews the literature related to the carbon assets of distributed photovoltaic generation. Section 2 introduces the methodology to evaluate the carbon assets of distributed photovoltaic generation and derives the influencing factors in theory. Section 3 introduces the data and variables used in the paper. Section 4 presents the empirical results with some analysis. Section 5 discusses the findings from the empirical results and the economic and environmental significance of understanding the carbon assets of distributed photovoltaic generation. Section 6 concludes and discusses the implications of the paper.

2. Literature review

The economic value of carbon assets, as a new type of resource in finance or environmental studies, has been gradually recognized by scholars. Ortas and Álvarez (2015), for example, depicted the co-movement of carbon assets and energy commodities through wavelet decomposition, which illustrates the efficiency of the European Union Emissions Trading Scheme (EU-ETS). By examining the time-varying correlations between carbon allowance prices and other financial indices during the third phase of the EU-ETS, Zhang et al. (2017) found that carbon assets were relatively independent of other financial assets and thus argued for the diversification benefits of including carbon assets in financial portfolios. The relation between the price of energy commodities and that of carbon assets is also a popular topic in academia (Reboredo, 2014; Kanamura, 2016; Wen et al., 2017; Wang and Guo, 2018; Uddin et al., 2018). Knowing the value of carbon assets is the basis for their exchange in the market and for inducing the participants to engage in low-carbon behavior. However, only a few of papers have evaluated the carbon value of environmental protection embedded in economic activities.

Scholars have gradually recognized the economic value of carbon reduction behavior when calculating the carbon emissions emitted by a source or sequestered in a biomass sink. Bebbington and Larrinaga-González (2008) primarily took a monetary perspective and emphasized the valuation of assets and liabilities in reference to carbon emission and sequestration accounting. To evaluate organizational capabilities in carbon emissions management, Ratnatunga et al. (2011) introduced a metric called an Environmental Capability Enhancing Asset (ECEA) as the underpinning for converting non-monetary CO_2 emissions and sequestration measures into monetary values. Stechemesser and Guenther (2012) examined the measurement of emissions and removals and their implications for finance. They examined monetary aspects from an organizational perspective and described the internal and external application of carbon asset from an accounting perspective. Ascui and Lovell (2013) additionally highlighted that carbon assets can accumulate for mandatory or voluntary purposes and at different scales, for example, on a global, national or organizational scale. On this basis, Song et al. (2013) established a pricing model for evaluating carbon asset values in electricity markets. Han et al. (2015) introduced carbon asset theory into traditional high-tech evaluation methods and applied the method the authors developed to the carbon asset evaluation of wind energy technology. Wang et al. (2015) applied carbon asset theory to the comprehensive energy infrastructure and proposed that there is often a lack of explicit assessment when cost and environmental performance is taken into account. Although carbon asset valuation has been utilized in the forest system, the traditional power market, bank credit, wind power technology and other fields, there is still no research specifically on the carbon value embedded in distributed photovoltaic generation.

Scholars have also discussed the influencing factors for carbon assets when they study the carbon assets of an institution or a technique. Song et al. (2013) considered the influence of market demand, generation costs, baseline of carbon emissions and carbon emissions reduction costs on carbon asset values in electricity markets. Based on the carbon asset theory they advanced, Han et al. (2015) examined the carbon asset value of a high-tech innovation, which is determined by the baseline standard emissions of the industry, the emissions level when adopting a reduction technology, the enterprise's production and the price of carbon. Wang et al. (2015) applied the theory of carbon asset assessment to the comprehensive energy infrastructure and proposed that there is often a lack of explicit assessment when cost and environmental performance are considered. These studies provide references for our evaluation of the factors affecting the carbon value embedded in distributed photovoltaic generation.

Furthermore, how do the influencing factors affect carbon assets? Song et al. (2013) conducted a sensitivity analysis to assess the impact of these factors on the value of carbon assets. Using Sobol' sensitivity analysis method of variance, Han et al. (2015) evaluated the influencing factors for carbon asset values from high-tech innovation and found that carbon asset values vary across different technologies, in different industries and over time. Wang et al. (2015) conducted a descriptive analysis of simulated integrated energy interactions in an energy plan to illustrate the impact of technical emissions on integrated energy. Based on these studies, we further develop the sensitivity analysis method and then analyze how the influencing factors affect the value of carbon assets embedded in distributed photovoltaic generation.

By valuing the carbon assets in distributed photovoltaic generation and advancing new methods to analyze the influencing factors and their sensitivity to this type of asset, this paper, on the one hand, further develops the theory of carbon asset valuation. On the other hand, it also adds to the knowledge base related to the value of distributed photovoltaic generation.

A few scholars have discussed the economic value of distributed photovoltaic generation. Mitscher and Rüther (2012) analyzed the economic competitiveness of grid-connected, distributed solar photovoltaic generation through small-scale rooftop installations in Brazil. Holdermann et al. (2014) analyzed how the variation in specific investment costs and the discount rate affect the economic viability of distributed photovoltaic generation in residential and commercial sectors in Brazil. Burtt and Dargusch (2015) examined the cost-effectiveness of subsidies paid for by electricity consumers to support the installation of roof-top photovoltaic systems by households in Australia. Zhang (2016) studied the business models and financing mechanisms used for the distributed solar photovoltaic deployment in China and discussed the challenges and policies involved. Hancevic et al. (2017) quantified the potential effects that the massive adoption of distributed photovoltaic generation systems would have on household expenditures and welfare, subsidy reductions, pollution and water resource usage for Mexican residents. Nomaguchi et al. (2017), using a case study of the diffusion of photovoltaics in a Japanese dormitory town, analyzed subsidy policies for a distributed photovoltaic generation system for companies and citizens in the integrated planning of low-voltage power grids. Camilo et al. (2017) analyzed the financial and technical effects of distributed photovoltaic generation for consumers in Brazil. More broadly, the economic effects of other types of distributed generation, including the benefits, costs and risks, have also been examined (e.g., Huang and Söder, 2017; Bell and Gill, 2018). In addition to the above studies, the impacts of carbon reduction on the value of distributed photovoltaic generation have gained attention recently.

When analyzing the capacity constraints on distributed solar photovoltaic generation in the US Midwest, Cook et al. (2018) noted the relevance of carbon emissions factors as well as electricity generation and hourly solar capacity factors. Further, from the perspective of emissions reduction benefits, He et al. (2018) established dynamic subsidy models for distributed photovoltaic generation. The authors found that the reduction in unit costs together with gradual technological progress would reduce the emissions reduction benefit subsidies and, subsequently, the internal rate of return of distributed photovoltaic generation projects. Based on these studies, we apply the concept of carbon asset theory to distributed photovoltaic generation. Our results provide a supplement for the economic analysis of distributed photovoltaic generations and a wider perspective for understanding its social, ecological and environmental value.

3. Theory and methodology

3.1. Carbon asset valuation of distributed photovoltaic generation

The value of carbon emissions reductions, referred to as the carbon trading mechanism, has changed for enterprises, consumers, projects and technologies in accordance with the provisions of the "Kyoto Protocol" agreement, in which most countries promised to achieve carbon reduction targets within a certain period. The government assesses the maximum carbon footprint of each enterprise within a given range and divides it into several carbon emissions shares, each of which is a carbon emissions right. In the primary market for carbon emissions rights, the government adopts bidding, auction or other method to sell carbon emission rights to the enterprises. Enterprises can discharge carbon up to a given share, and trade the excess shares in a secondary market.

Scholars proposed the concept of carbon assets from different perspectives, which led to a reduction in carbon emissions (Han et al., 2015). Bigsby (2009), for example, defined carbon assets as the ability of natural resources, such as forests, to store carbon. Lin (2010) defined carbon assets as CDM (Clean Development Mechanism) assets due to the implementation of a low-carbon strategy. Wan and Zhu (2010) considered carbon assets as resources that can bring economic benefits to enterprises by maintaining the amount of greenhouse gases emitted into the atmosphere at less than the baseline required by the government. Based on these principles, Han et al. (2015) defined the extra value of carbon assets owned by an enterprise due to the use of advanced technology as follows:

$$V^T = (M^T - C^T)\bullet Y\bullet P \tag{1}$$

In this formula, V^T represents the carbon asset value per unit of time for an enterprise adopting a low-carbon technology. M^T, which is used as the baseline level of emissions, is the industry standard emissions per unit of output. C^T is the emissions level per unit of output of a target enterprise when adopting a specific type of emissions reduction technology. Y is the enterprise's production per unit of time. P is the public price of carbon.

To simplify the analysis, we define D^T, and set it equal to $(M^T - C^T)$. Then, Formula (1) changes into:

$$V^T = D^T\bullet Y\bullet P \tag{2}$$

According to the definitions of M^T and C^T, the meaning of D^T is the amount of carbon emissions reduction per unit of output for an enterprise adopting a new low-carbon technology. As a result, Formula (2) suggests that it can determine the carbon asset value of a new low-carbon technology for an enterprise based on three factors, i.e., the amount of carbon reduction from adopting a new low-carbon technology, the enterprise's production per unit of time and the public price of carbon.

Similarly, the carbon asset value per unit of time for a distributed photovoltaic generation project, which normally has advantages with regard to low-carbon production, is dependent on the amount of carbon reduction per unit of electricity generation, the production per unit of time and the public price of carbon. Accordingly, the methodology for determining the carbon asset valuation for distributed photovoltaic generation is similar to that for determining the carbon asset valuation for an enterprise or a household that adopts a new low-carbon technology. Then, the valuation formula for the carbon assets of distributed photovoltaic generation according to Formula (2) can be obtained:

$$V = D\bullet Y\bullet P \tag{3}$$

where V represents the carbon asset value of distributed photovoltaic generation, D is the amount of carbon reduction per unit of electricity generation from distributed photovoltaic generation, Y is the amount of electricity generation per unit of time, and P is still the public price of carbon.

The carbon emissions reduction per unit of power generation (D) represents the difference between carbon emissions sourced by distributed photovoltaic generation and the baseline carbon emissions level per unit of power generation. Various types of energy are available for power generation, such as hydropower, thermal power, nuclear power, and wind power, which are the main types of power in China. The various types of energy each have specific conversion values for carbon emissions reduction per unit of generation. In this case, the more effective way to measure the carbon asset value of distributed photovoltaic generation is to measure the carbon asset value of carbon emissions reduction in distributed photovoltaic generation compared to the production of various energy sources under uncertainty, and then make a horizontal comparison between the energy differences and a longitudinal comparison of the variables' sensitivity.

The carbon price is the unit value of carbon mitigation. The carbon price is determined by the supply and demand of carbon quotas, and it fluctuates over time in the public trading market. When the carbon limit supply exceeds the demand, the carbon price is lower. When the supply is less than the demand, the carbon price rises. The China Carbon Price Survey 2015 notes that the carbon price steadily increased to 40 Yuan/ton carbon dioxide equivalent in the national carbon emissions trading system.

The carbon market, however, is still an emerging market. There is uncertainty regarding the amount of carbon emissions reduction from distributed solar power generation that can be traded in a carbon market. Moreover, the baseline of carbon emissions is uncertain, as various types of energy are available for power generation, such as hydropower, thermal power, nuclear power and wind power. The baseline is the cause of the uncertainty surrounding the true amount of carbon reduction, even though the carbon emissions from distributed power generation are certain. In this case, a more effective method is to measure the value of the carbon assets of distributed photovoltaic generation under uncertainty. Under this condition, the carbon asset value of distributed power generation is written as

$$V = p\bullet D\bullet Y\bullet P \tag{4}$$

where p is the probability that carbon emissions reductions generated by distributed power generation can be realized through the carbon market, and the meanings of the other variables are the same as those in Formula (3).

The analysis takes into account the factor of time, i.e., the carbon value of distributed photovoltaic generation at different times. Formula (4) reflects the functional relationship between V and the independent variables. Based on this, we introduce the time index t to consider the influence of time on the carbon assets of a distributed photovoltaic generation station and determine how the value of carbon assets varies over time. The formula for the value of the carbon assets of distributed photovoltaic generation at time t is

$$V_t = p_t\bullet D\bullet Y_t\bullet P_t \tag{5}$$

where the carbon asset value V_t is the value of the carbon assets of distributed photovoltaic generation at time t, p_t is the probability that carbon emissions reductions can be realized through the carbon market at time t, D is the carbon emissions reduction per unit of power generation, Y_t is the generation capacity of a distributed photovoltaic generation station at time t, and P_t is still the carbon price, determined by the carbon asset trading market at time t. The variable D in Formula (5) is the same as that in Formula (4) because the carbon emissions reduction per unit of power generation does not change in the short term. As a valuation model of the carbon assets of distributed photovoltaic generation, Formula (5) has advantages in calculating the value of the carbon assets of distributed photovoltaic generation at different times.

3.2. Sensitivity analysis of the influencing factors

To reflect the relationship between the carbon asset value of the distributed photovoltaic generation and its various influencing factors, the sensitivity analysis method is used in this paper. A sensitivity analysis measures the sensitivity of dependent variables to variations in one or more independent variables under uncertain environmental conditions. According to our former analysis, the carbon asset value of distributed photovoltaic generation is affected by the probability that the value of the carbon emissions reduction will be realized through market transactions, the carbon emissions reduction per unit of power generation, the power from distributed photovoltaic generation and fluctuations of the carbon market price. A sensitivity analysis can precisely quantify the sensitivity of the various influencing factors to the value of the carbon assets of distributed photovoltaic generation.

The method used to conduct the sensitivity analysis in this paper is as follows: First, we take the logarithms of both sides of Formula (5)

$$\ln V_t = \ln p_t + \ln D + \ln Y_t + \ln P_t \tag{6}$$

Then, we take the derivative with respect to time t from Formula (6). Since we set D as a constant, the resulting formula is

$$V_t'/V_t = p_t'/p_t + Y_t'/Y_t + P_t'/P_t \tag{7}$$

where V_t' is the marginal change in the carbon asset value with respect to time; p_t' is the marginal change in probability p during period t; Y_t' is the marginal change in Y during period t; and P_t' is the marginal change of P during period t. V_t'/V_t, p_t'/p_t, Y_t'/Y_t and P_t'/P_t are the variance ratio of V_t, p_t, Y_t and P_t, respectively. We can rearrange Formula (7) to write

$$(p_t'/p_t)/(V_t'/V_t) + (Y_t'/Y_t)/(V_t'/V_t) + (P_t'/P_t)/(V_t'/V_t) = 1 \tag{8}$$

Thus, the sensitivity index of p_t, Y_t and P_t to V_t can be constructed respectively as

$$S_p = (p_t'/p_t)/(V_t'/V_t) \tag{9}$$

$$S_Y = (Y_t'/Y_t)/(V_t'/V_t) \tag{10}$$

$$S_P = (P_t'/P_t)/(V_t'/V_t) \tag{11}$$

Formulas (9), (10) and (11) are used to value the sensitivity of the carbon asset value of distributed photovoltaic generation to the probability that carbon emissions reductions can be realized, the annual generation capacity of distributed photovoltaic generation and the carbon price respectively. This approach will illustrate the effects of the factor fluctuations on the carbon asset value of distributed photovoltaic generation and determine the main factors affecting the carbon asset value.

3.3. Mathematical distribution of the influencing factors

The Monte Carlo simulation method is used to simulate the mathematical distribution of the carbon assets of distributed photovoltaic generation in this paper. Monte Carlo simulation is a statistical simulation process that transforms random values into vectors of a probability distribution and then extracts various vector groups for inspection. The key of this method is to recognize the characteristics of the distribution of the variables at different times.

According to the latest regulation on the design standards for photovoltaic power station, named GB50797-2012, the capacity of a distributed photovoltaic generation station is mainly based on the location of the site, the photovoltaic power station system's design and the layout and environmental conditions of photovoltaic among other factors. In general, the average annual generation capacity of a distributed photovoltaic generation station can be calculated in the following four ways:

(1) Standard method: $E_p = HA_1 \cdot PAZ \cdot K_2$

E_p: Power generation by the Internet (kW h);
HA_1: Annual total solar radiation of a horizontal plane (kW h/m^2);
PAZ: System installed capacity (kW); and
K_2: Coefficient of comprehensive efficiency (with values ranging from 75% to 85%).

(2) Component area method: $E_p = HA_2 \cdot S \cdot K_1$

HA_2: Annual total solar radiation of an inclined plane (kW h/m^2);
S: Total area of components (m^2); and
K_1: Component conversion efficiency.

(3) Standard sunshine hour method: $E_p = H \cdot PAZ \cdot K_2$
H: Local standard sunshine hours (h).

(4) Empirical coefficient method: $E_p = PAZ \cdot K$

K: Empirical coefficients (based on local sunshine conditions, usually with the values ranging from 0.9 to 1.8).

Because the generation mode of a distributed photovoltaic generation station is one of the power generation methods in the power industry, the carbon emissions level per unit of power generation will be synchronized with the industry as a whole. Therefore, there is reason to believe that Y_t'/Y_t is close to zero. Similarly, assuming that Y_t obeys a normal distribution, then

$$Y_t \sim \mathrm{N}(\mu_{Y_t}, \sigma_{Y_t})$$

Then, Y_t'/Y_t also obeys normal distribution, that is

$$Y_t'/Y_t \sim \mathrm{N}(\mu_Y, \sigma_Y)$$

P_t'/P_t is the change rate of P_t over time t, that is, the market return of carbon assets over time t, which is denoted as R_t; thus,

$$P_t'/P_t = R_t$$

With regard to carbon assets, $0 \le p_t < 1$, $p_t'/p_t > 0$. Assuming that the carbon assets of distributed photovoltaic generation are available in the early stage and that the probability of trading in the carbon market is p_0,

$$p_t = p_0 + b \cdot t, \quad t < (1-p_0)/b$$

where b is a coefficient. Thus, the distribution of p_t'/p_t that can be obtained at $t < (1-p_0)/b$ is

$$p_t'/p_t \sim \mathrm{N}(\mu_p, \sigma_p), \quad \mu_p = b/(p_0 + b \cdot t)$$

China's national emissions reduction policy forms the market demand. Since November 2011, the government has officially launched several carbon emissions trading pilots in Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong and Shenzhen. Therefore, we can refer to the historical returns to simulate the market return on carbon assets from a certain type of energy generation. The distribution of R_t is simulated by historical data according to

$R_t \sim N(\mu_R, \sigma_R)$

In summary, Formula (4) shows that the rate of change of three random variables that affect the value of the carbon assets of distribution power plants follows a normal distribution. That is, the rate of change Y_t'/Y_t of the generation capacity of distributed photovoltaic generation Y follows $Y_t'/Y_t \sim N(\mu_Y, \sigma_Y)$ over time t. The market return P_t'/P_t based on carbon price P follows $R_t \sim N(\mu_R, \sigma_R)$ over time t. The rate of change p_t'/p_t of the probability p with which the carbon emissions reductions of solar energy relative to other energy sources can be realized through carbon asset market transactions follows $p_t'/p_t \sim N(\mu_p, \sigma_p)$, $\mu_p = b/(p_0 + b \bullet t)$ over time t.

4. Data and variables

This section describes the data on the three factors influencing the carbon asset value of distributed photovoltaic generation, which are the carbon emissions reduction per unit of power generation for distributed photovoltaic generation, the generation capacity of distributed photovoltaic generations and the price of carbon.

4.1. D: Carbon emissions reduction per unit of power generation

Carbon emissions reduction per unit of power generation is one of the factors influencing the carbon asset value of distributed photovoltaic generation. This factor depends on the carbon emissions from solar power generation and the benchmark of the carbon emission level for solar power generation, which is partly based on the carbon emissions levels of other energy-generation approaches. China's energy endowment ensures that coal will remain its major energy source for a long time. Therefore, this paper first selects the typical carbon emissions data from representative thermal power generation as a comparison. Using solar photovoltaic power generation as a zero reference and considering the entire life cycle assessment, including coal mining and transportation processes, we are concerned only with the production process of thermal power plants. Standard coal is defined as any amount of fuel that produces heat of 29.27 MJ. It emits 0.785 kg of carbon dioxide when a thermal power plant produces 1 kW h, where 1 kW h = 3.6 MJ. When the energy production from distributed photovoltaic generation is converted to 1 kg of standard coal, we can calculate its carbon emissions reduction per unit of power generation compared with the emissions of thermal power plants, which is $D_1 = 0.785$ kg/kW h (referencing GBT2589-2008).

Although thermal power accounts for a considerable portion of China's power generation, new energy sources have developed rapidly in recent years. Table 1 shows the full generation capacity of Mainland China in 2015 and 2016. Compared to 2015, the proportion of thermal power generation had the smallest change from the previous year, with an increase of only 2.4%. However, photovoltaic power generation showed a significant increase of 72% over 2015, which suggests that China's energy structure is gradually changing and that the degree of dependence on thermal power generation is decreasing in the development of the electric power. Therefore, it is necessary to evaluate the carbon asset value of distributed photovoltaic generation by comparing power plants' average carbon reduction. According to the Chinese Life Cycle Database developed by Sichuan University and IKE Co. Ltd., China's grid power (the average value of power after mixing) for 1 kW h of carbon emissions is approximately 0.96 kg. Based on this value, we obtain the per unit carbon emissions reduction for distributed photovoltaic generation in relation to the average of all power plants, which is $D_2 = 0.96$ kg/kW h.

Table 1
Total capacity of different types of power generation in Mainland China in 2015 and 2016. Source: China Electricity Council. http://www.cec.org.cn/guihuayutongji/tongjxinxi/.

Power generation	2016	2015	Year-on-year change (± ,%)
Total of power generation	59,897	56,938	5.2
Hydropower	11,807	11,117	6.2
Thermal power	42,886	41,868	2.4
Nuclear power	2132	1714	24.4
Wind power	2410	1853	30.1
Solar power	662	385	72

Note: The rate of increase or decrease is shown in the year-on-year change (± , %) column. The rates of all types of power generation increased in 2016 compared to those in 2015; the unit is kW h.

Table 2
Parameters of distributed grid connected polysilicon battery board. Source: The home photovoltaic project in Guangdong Province of China, from the Web site of Jinko Solar Co Ltd.

PAZ	$S(M^2)$	K_1	K_2
100 kW	1650 × 992 mm	≥ 97.8%	80%

Note: PAZ is the installed capacity of relevant system, S is the total area of the components, K_1 is the components' conversion efficiency and K_2 is the coefficient of comprehensive efficiency. Their units are shown in the table.

4.2. Y: Generation capacity of distributed photovoltaic generation

Power generation capacity is another factor influencing the value of the carbon assets of distributed photovoltaic generation, which is determined by the component area, the amount of solar radiation and the conversion efficiency. Table 2 presents the equipment parameters of a solar panel. The installed system's capacity is 100 kW, the total area of the components is 1650 × 992 mm, the components' conversion efficiency is greater than 97.8%, and the coefficient of comprehensive efficiency is 80%.

Using data from the China Meteorological Administration, we can obtain the total annual solar radiation from the average horizontal solar energy of the national land surface. Taking Guangdong Province, a province in southern China as an example, the total annual solar radiation from horizontal solar energy is 1050–1400 kW h/m^2. Here, we take the average, $HA_1 = 1225$ kW h/m^2. The total annual solar radiation of the national average's best inclined plane was 1712.7 kW h/m^2. The best slope solar energy in Fujian, Guangdong and other regions has a total annual radiation exposure between 1000 and 1400 kW h/m^2, and taking the average, $HA_2 = 1200$ kW h/m^2. The annual sunshine hours in Guangdong are 1400–2200 h. Converted to the average standard sunshine hours, this value is $H = 3.52$ h, and the empirical coefficient is $K = 1.35$.

Table 3 shows the annual electricity output derived from the four calculation methods for the average generation capacity of photovoltaic power plants described above. The standard method yields the result that the generation capacity of distributed photovoltaic generation is 98,000 kW h. The result of the component area method is 1536.76 kW h. The electricity generated by the standard sunshine hour method is 102,784 kW h. The value obtained by the empirical coefficient method is 135 kW h. The result calculated by the standard sunshine hour method is close to the actual normal value.

4.3. P: Price of carbon

The price of carbon, which is determined by market supply and demand, is another factor influencing the carbon asset value of distributed photovoltaic generation. Based on the 2016 Guangdong carbon emissions trading market, the average carbon price in each month is 16.99, 15.81, 15.22, 13.18, 14.67, 11.65, 9.66, 11.90, 13.74, 10.90, 11.62 and 15.66, respectively (China Carbon Emissions Trading, http://

Table 3
Average generation capacity of photovoltaic power plants calculated by different methods.

Standard method	Component area method	Standard sunshine hour method	Empirical coefficient method
1225 × 100 × 0.8 = 98,000	1200 × 1.65 × 0.992 × 97.8%× 80%= 1536.76	3.52 × 100 × 365 × 80%= 10,2784	100 × 1.35 = 135

k.tanjiaoyi.com/). By taking the average, the mean carbon price is P_t = 13.42 Yuan/kg.

According to preliminary estimates by the National Development and Reform Commission of China, the carbon price of 300 Yuan per kilogram is a price standard that satisfies low-carbon, green objectives. As a standard specification, the mean market return $\mu_R = 0.045$, which is within the range of 0.04–0.05. The standard deviation is $\sigma_R = 0.087$.

5. Empirical results and analysis

5.1. Carbon asset value of distributed photovoltaic generation

We substitute the variables from the previous section into Formula (2). As shown in Section 3.1, the carbon emissions reduction per unit of distributed photovoltaic generation using solar power generation relative to thermal power generation is $D_1 = 0.785$ kg/kW h. Relative to the use of other integrated energy sources, this value is $D_2 = 0.96$ kg/kW h. The generation capacity of distributed photovoltaic generation is Y = 102784kW h. The carbon price is P = 13.42 Yuan/kg. We can obtain the carbon asset value results of V_1 = 1,08,2798 Yuan and V_2 = 1,32,4187 Yuan. V_1 is the carbon asset value of distributed photovoltaic generation relative to that of thermal power energy, and V_2 is the carbon asset value of distributed photovoltaic generation relative to the value of integrated energy. The above results are obtained when the variables D, Y and P are all at their mean values. This represents a method to calculate the carbon asset value of distributed photovoltaic generation from a static perspective.

Then, we change variables Y and P with a variation range of ± 10%. When the variables are at the top of the range, the new values are Y_1 = 1,13,062.4 and P_1 = 14.76. When the variables are at the bottom of the range, the new values are Y_2 = 92505.6 and P_2 = 12.08. Hence, eight combinations are generated. By substituting the different variable values of each combination into Formula (2), we again obtain the carbon asset value of distributed photovoltaic generation, and Table 4 presents the results.

As shown in Table 4, when both Y and P increase by 10%, the carbon asset value of distributed photovoltaic generation relative to thermal power generation is V_{11} = 1,310,009, which is an increase of 21% compared with V_1. The carbon asset value of distributed photovoltaic generation relative to integrated energy generation is V_{21} = 1,602,049, which is an increase of 21% over V_2. When Y decreases by 10% but P increases by 10%, V_{12} = 1,071,825, which is a decrease of 1% compared with V_1. In addition, V_{22} = 1,310,767, which is also 1% less than V_2. When Y increases by 10% but P decreases by 10%, V_{13} = 1,072,148, which represents a 0.98% decrease relative to V_1. In addition, V_{23} = 1,311,162, which has the same fluctuation as V_2. When both Y and P are reduced by 10%, V_{14} = 877,212, which has an 18.99% wave propagation compared with V_1. In addition, V_{24} = 1,072,769 is a 18.99% decrease relative to V_2.

Table 4
The static fetch point results of the carbon asset value of distributed photovoltaic generation.

Variable	Y_1	Y_2
P_1	$V_{11} = 0.785\ Y_1P_1 = 1310009$	$V_{12} = 0.785\ Y_2P_1 = 1071825$
	$V_{21} = 0.96\ Y_1P_1 = 1602049$	$V_{22} = 0.96\ Y_2P_1 = 1310767$
P_2	$V_{13} = 0.785\ Y_1P_2 = 1072148$	$V_{14} = 0.785\ Y_2P_2 = 877212$
	$V_{23} = 0.96\ Y_1P_2 = 1311162$	$V_{24} = 0.96\ Y_2P_2 = 1072769$

The results in Table 4 suggest that the carbon emissions reduction per unit of generation or the generation capacity with a simultaneous increase in the growth ratio has a greater impact on the carbon asset value of distributed photovoltaic generation than that with a simultaneous decrease in their growth ratios. As long as the carbon emissions reduction per unit of generation or the generation capacity decreases, their effects to the carbon asset value of distributed photovoltaic generation decline.

The static point selection method has advantages in calculating the value of the carbon assets of distributed photovoltaic generation explicitly. However, this method is suitable for valuing the carbon assets of distributed photovoltaic generation only at a static point in time. It cannot reflect the relationship between the value of carbon assets of distributed photovoltaic generation and the various influencing factors. A sensitivity analysis for each factor is needed to properly analyze the influencing factors on the value of the carbon assets of distributed photovoltaic generation. Such an analysis should take into account the time variation within a certain range of fluctuation that influences the carbon asset value of distributed photovoltaic generation to determine the main factors affecting the carbon asset value.

5.2. Sensitivity of the influencing factors

To reflect the relationship between the value of the carbon assets of distributed photovoltaic generation and the various influencing factors, we use the sensitivity analysis method as described in Section 2.3. This method uses Monte Carlo simulation to randomly sample the power generation capacity Y and the carbon price P to fluctuate within a range of ± 10%, which will form a normal distribution for the change rate.

Suppose $b = 0.015$, $p_0 = 0.25$, $\sigma_Y = 0.25$, $\sigma_R = 0.087$, μ_Y is valued between −0.1 and 0.1, and μ_R is valued between 0.04 and 0.05. Based on the analysis of the relevant variable distribution, the following assumptions can be summarized:

$$p_t'/p_t \sim \mathrm{N}(0.015/(0.25 + 0.015\bullet t),\ 0.1)$$

$$Y_t'/Y_t \sim \mathrm{N}(\mu_Y,\quad 0.25)$$

$$R_t \sim \mathrm{N}(\mu_R,\quad 0.087)$$

Then, the effects of Y and P on V can be investigated based on the empirical simulations of the influence of changes in p_t'/p_t, Y_t'/Y_t, and R_t on V_t'/V_t according to Formulas (9), (10) and (11). The results are shown in Fig. 1, Fig. 2, Fig. 3 and Fig. 4.

Fig. 1 indicates that when $\mu_Y = 0$ and $\mu_R = 0.04$, i.e., the generation capacity remains stable and the carbon price declines, the sensitivity of the carbon asset value of distributed photovoltaic generation to the generation capacity changes a small amount (with a value of 1.2), but the sensitivity of the carbon asset value of distributed photovoltaic generation to the carbon price increases substantially (with a value of 7.9) as time passes.

Fig. 2 illustrates that when $\mu_Y = 0$ and $\mu_R = 0.05$, i.e., the generation capacity remains stable and the carbon price increases, the sensitivity of the carbon asset value of distributed photovoltaic generation to the generation capacity changes a small amount, while the sensitivity of carbon asset value of distributed photovoltaic generation to the carbon price decreases substantially (with a value of 20.9) as time passes.

Fig. 3 demonstrates that when μ_Y = -0.1 and $\mu_R = 0.045$, i.e., the generation capacity declines and the carbon price remains stable, the sensitivity of carbon asset value of distributed photovoltaic generation

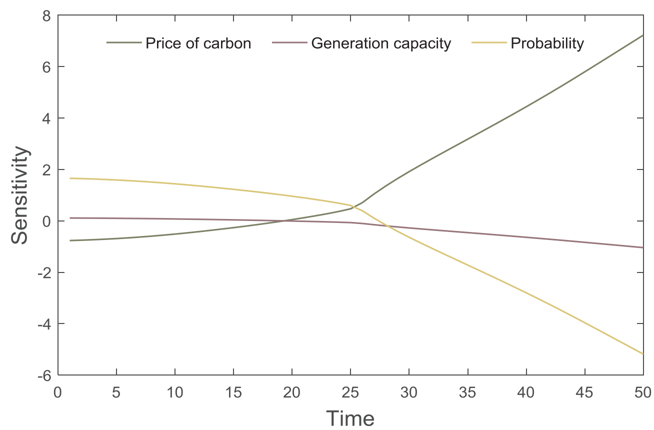

Fig. 1. The value of V varying with t when μ_Y is constant and μ_R increases −10%.

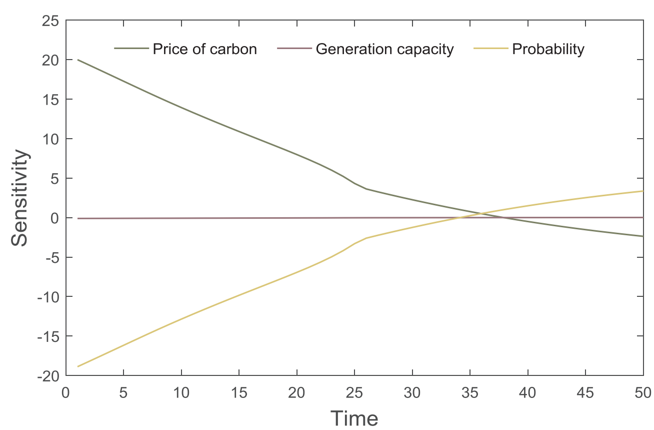

Fig. 2. The value of V varying with t when μ_Y is constant and μ_R increases + 10%.

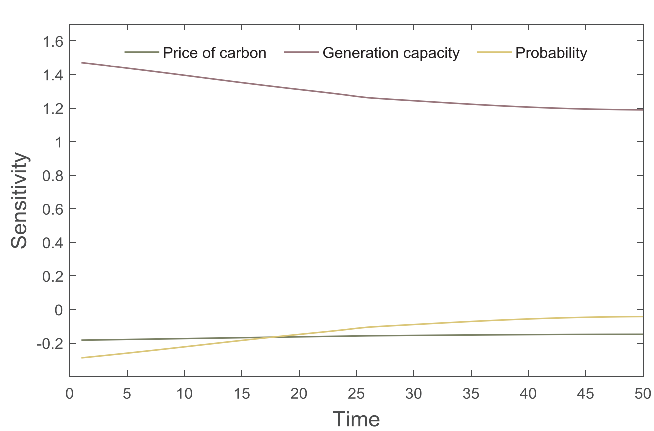

Fig. 3. The value of V varying with t when μ_R is constant and μ_Y decreases −10%.

to the generation capacity declines at a value of 0.3, while the sensitivity of the carbon asset value of distributed photovoltaic generation to the carbon price increases a small amount as time passes.

Fig. 4 shows that when $\mu_Y = 0.1$ and $\mu_R = 0.045$, i.e., the generation capacity increases and the carbon price remains stable, the sensitivity of the carbon asset value of distributed photovoltaic generation to the generation capacity increases at a value of 0.1, but the sensitivity of the carbon asset value of distributed photovoltaic generation to the carbon price changes only a small amount as time passes.

The empirical analysis leads to the result that the carbon price and

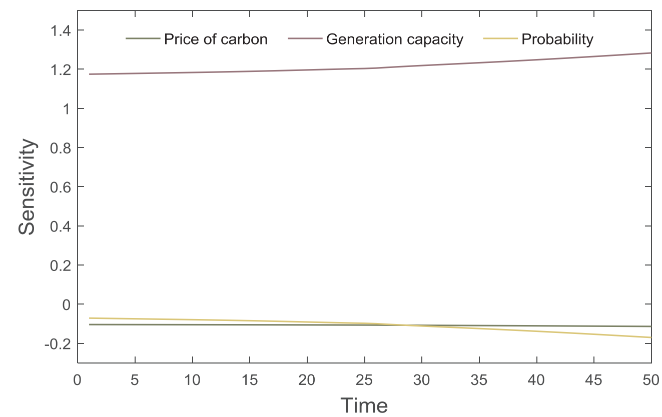

Fig. 4. The value of V varying with t when μ_R is constant and μ_Y increases + 10%.

the generation capacity of distributed photovoltaic generation have strong impacts on its carbon asset value over time and that the impact of the carbon price is greater than that of the generation capacity. As time goes by, the impacts of the carbon price and the generation capacity on the carbon asset value of distributed photovoltaic generation tends to be stable unless the carbon price declines. The empirical results imply that the distributed photovoltaic generation industry and even other environmental related industries should pay more attention to changes in carbon prices, which would require appropriate measures to control the risk of carbon asset transactions.

6. Discussion

6.1. Carbon emissions reduction per unit of power generation

As one of the basic factors influencing the carbon asset value of distributed photovoltaic generation, the carbon emissions reduction from distributed photovoltaic generation depends on the carbon emissions of solar power generation and the benchmark carbon emissions level for solar power generation. We set the carbon emissions of solar photovoltaic power generation as a zero reference in our empirical analysis. This approach considers only the energy production process. It does not consider the entire life cycle assessment for coal mining or the transportation processes for thermal power plants. If we include more detail, calculating the amount of the carbon emissions reduction will be slightly more complex. The rule for calculating the carbon emissions reduction from distributed photovoltaic generation using the carbon emissions from solar power generation minus a benchmark, however, is universal.

6.2. Generation capacity and the carbon asset value of distributed photovoltaic generation

The generation capacity, which is another factor that affects the carbon asset value of distributed photovoltaic generation, is obtained by calculating the average annual power generation capacity of a solar panel in our empirical analysis. However, due to the uncertainty involved with solar radiation and conversion efficiency, the generation capacity fluctuates within a certain range. Controlling for other assessment factors, the sensitivity of the generation capacity to the carbon asset value of distributed photovoltaic generation over time can be obtained: the sensitivity increases when it is randomly chosen within the + 10% range, but decreases when the generation capacity is randomly chosen within the −10% range. This result suggests that the sensitivity of the generation capacity to the carbon asset value of distributed photovoltaic generation increases when the generation capacity increases and decreases when the generation capacity declines.

6.3. Carbon price and the carbon asset value of distributed photovoltaic generation

The price of carbon, as another of the factors affecting the value of carbon assets when evaluating distributed photovoltaic generation, can be estimated using data sourced from the carbon emissions trading network. However, the carbon price fluctuates frequently in the carbon emissions market. By assuming that the range of fluctuation is ± 10% and controlling for other assessment factors, we obtain the sensitivity of the carbon price to the carbon asset value of distributed photovoltaic generation over time: the sensitivity increases as time passes when the carbon price is randomly chosen within the −10% range, but it decreases when it is randomly chosen within the + 10% range. Compared with the generation capacity, the carbon price is more sensitive to the carbon asset value of distributed photovoltaic generation, which suggests that the carbon price is more important to the carbon asset value of distributed photovoltaic generation.

7. Conclusions and policy implications

This paper introduces the concept of carbon assets into distributed photovoltaic generation and applies the method of carbon asset valuation to it. This paper also analyzes the influencing factors and their sensitivities for the carbon value of distributed photovoltaic generation. The study develops the theory of carbon asset valuation and applies it to assessing of the carbon asset value of distributed photovoltaic generation. Moreover, it adds to the knowledge base regarding the social, environmental and economic value of distributed photovoltaic generation. The specific conclusions are as follows:

First, the concept of carbon assets and its valuation method, which has been used to study the extra value of forest systems, traditional electricity markets and bank credit, can also be applied to distributed photovoltaic generation. Because distributed photovoltaic generation emits little carbon dioxide in its power production process, there are advantages with regard to carbon reduction, particularly compared with traditional power generation methods such as centralized coal, petroleum or thermal power generation, which means that distributed photovoltaic generation has carbon asset value.

Second, according to the valuation model in our analysis, the carbon asset value of distributed photovoltaic generation is dependent on the carbon emissions reduction per unit of generation, the generation capacity and the public price of carbon. The carbon emissions reduction provided by distributed photovoltaic generation is determined by the carbon emissions of solar power generation minus a benchmark, which is partly a result of the carbon emissions levels of other energy-generation methods other than distributed photovoltaic generation. The generation capacity fluctuates based on the uncertainty of solar radiation and the conversion efficiency. Because fluctuations in the carbon emissions market occur frequently, the carbon price causes the carbon assets of distributed photovoltaic generation to change in a timely manner and to have public value.

Third, the carbon asset value of distributed photovoltaic generation increase as long as one of the influencing factors, including carbon emissions reductions per unit of power generation, the generation capacity and the public price of carbon, increases. Moreover, these factors have different degrees of impact on the carbon value of distributed photovoltaic generation. Generation capacity and the amount of carbon reduction are the key factors that determine the carbon asset value of distributed photovoltaic generation.

Fourth, the influencing factors, including the carbon emissions reduction per unit of power generation, the generation capacity and the public price of carbon, have different sensitivities to the carbon assets of distributed photovoltaic generation. Fluctuations in the carbon price have greater impacts on the carbon asset value of distributed photovoltaic generation than that in the carbon emissions reduction per unit of power generation or the generation capacity.

Based on the above conclusions and the methodology and empirical analysis of this study, as well as the existing policies and economic performance of distributed photovoltaic generation in China, we propose the following policy implications:

By applying the concept of carbon asset theory to distributed photovoltaic generation, this study provides a wider perspective for understanding its social, ecological and environmental value and eventually provides a supplement for the economic analysis of distributed photovoltaic generations carried out by Zhang (2016), Hancevic et al. (2017), Nomaguchi et al. (2017) and Camilo et al. (2017) among others. Distributed photovoltaic generation, treated as an emerging renewable energy type, is concerned continuously by the government in China, who cares about the development of distributed photovoltaic generation in a competitive market mechanism and its functions in supporting the poor. The finding of carbon asset of distributed photovoltaic generation will provide more theory basis for the government to implement subsidy policies. The electricity price for photovoltaic power stations should be higher when thinking about its carbon asset value, which reflects its contribution to energy savings and carbon emissions reduction. The poor supported by photovoltaic power station and the related enterprises should get much more financial subsidies according to the carbon asset value of distributed photovoltaic generation. This study also provides theory support for the government to encourage distributed photovoltaic generation with carbon asset value as part of voluntary or mandatory carbon reduction systems.

An issue important for the government and related enterprises and households is how to add the carbon asset of distributed photovoltaic generation, because of its economic value and its benefits to energy savings and carbon emissions reduction. By analyzing its affecting factors, this study implies the ways to improve the carbon asset value of distributed photovoltaic generation. The government should choose a reasonable carbon-emissions baseline for distributed photovoltaic generation to increase its carbon-reduction grade. The government also should provide a much higher price for carbon allowances by setting a reasonable quota for distributed photovoltaic generation. There should be ways for enterprises and households related to increase and realize this value through a carbon exchange mechanism or a carbon-reduction subsidy system.

This study also enriches the methodologies for the government and enterprises to evaluate the carbon asset value for distributed photovoltaic generation as well as other kind of renewable energies. According to our methodology for valuing the carbon asset of distributed photovoltaic generation, all the influencing factors, including the carbon emissions reduction per unit of power generation and the carbon price, should be considered. In the long term, both the government and enterprise should focus more on the generation capacity and carbon reduction amount, which refers to the carbon-emissions baseline set by the government and low-carbon technologies advanced by enterprises. In the short term, it should focus more on the carbon price, to which the carbon assets of distributed photovoltaic generation are more sensitive than the generation capacity and the carbon reduction amount. As a generalization, this methodology and its implications have chances to be more widely used in wind, hydro, geothermal, tide and other renewable energy generations.

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