### Models and methods for low-carbon footprint analysis of grid-connected photovoltaic generation from a distribution network planning perspective

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#### Abstract
Solar energy is a clean energy resource, so the large-scale deployment of photovoltaic (PV) power generation is of great significance for achieving carbon emission reductions in the electric power industry. This paper proposes models and methods for evaluation of the low-carbon benefits of grid-connected PV power generation projects. The carbon emission (or emission reduction) characteristics and the economic benefits of PV generation are analyzed using the following four metrics: generation capacity revenue, PV cost, loss efficiency improvement, and reserve capacity cost. The corresponding low-carbon benefit models and economic benefit models are then established. By combining the low-carbon and economic characteristics of photovoltaic power generation, a model is proposed for evaluating the low-carbon comprehensive benefits (LCBs) of photovoltaic power generation and the concept of a carbon emission payback period (CPP) is put forward. Examples with typical operating data from real-world applications are used to verify the validity of the models and methods proposed in this paper. The analysis results show that photovoltaic power generation has great potential in terms of low-carbon comprehensive benefits compared with conventional power generation.

#### Introduction
“Fighting against fog and haze, and reducing carbon emission” has become a slogan for many energy initiatives aimed at reducing the severe pollution conditions in China. China has pledged to stop increasing CO\(_2\) emissions by 2030 in a joint statement between China and US in 2014. The electric power industry contributes largely to the total global carbon emissions, and this percentage continues to increase every year. Relevant data from China show that the percentage of carbon emissions in total fossil energy from the electric industry has jumped from 21.07% in 1980 to 40% in 2015 [1], with the amount of carbon emissions reaching 764 kg per MWh, which is higher than the world average [2]. Therefore, a drastic reduction in global carbon emissions cannot be realized without a significant contribution from the electric sector, especially in China. It is not an easy task, but there is a potentially huge payoff for reducing carbon emissions in the electric industry.
Renewable energy resources play an important role in emission reduction. Among them, photovoltaic (PV) power generation has huge potential in reducing carbon emissions, since it is abundantly available and has zero pollution. There is currently a rapid deployment of PV systems in China. The installed PV capacity had reached 7742 MW by 2016, and the PV generation capacity is projected to reach 20 GW in 2020 [3]. Therefore, it is important to re-examine and explore both the carbon reduction benefits and economic benefits [4, 5] resulting from large-scale PV integration. These benefits are referred to as low-carbon comprehensive benefits (LCBs) in this paper.

The LCB is a comprehensive index that measures the various effects of integrating photovoltaic generation on achieving low-carbon targets. Carbon emissions are reduced due to higher utilization of clean solar generation over thermal generation. Moreover, carbon emissions are lower in the distribution network as less power is transmitted from the centralized generation to the end of an electric network because of the installation of PV near the load center. On the other hand, additional investment (e.g., a power quality controller) is needed to ensure the power reliability against photovoltaic generation variability, which can be viewed as a negative low-carbon factor. Consequently, the total low-carbon benefit from PV generation should be evaluated and analyzed comprehensively. The proposed “comprehensive benefits” can also be regarded as a specific form of PV carbon footprint. Today, the term “carbon footprint” refers to the amount of carbon emissions (usually in tons) associated with energy generation. In the context of PV integration with a power grid, the carbon footprint means the total emissions related to PV in its total life cycle that includes manufacturing, transportation, operation, and maintenance, which is exactly the so-called LCBs in this paper.

Nowadays, research on low-carbon benefit assessments is still emerging. Most research findings primarily concentrate on three primary aspects: (1) concepts and analysis methods of low-carbon effects on the power grid [6–8], (2) feasible electric low-carbon technologies applied in power system [9–13], and (3) planning and operating targeting the carbon emission reduction [14–19]. As for (1), a number of studies have appeared. Reference [6] proposed the structural identification and evaluation method of CO₂ emission in power system but did not sight into the specific PV carbon emission factors. Reference [7] established a hierarchical and partition low-carbon evaluation model considering PV and other kinds of distributed or traditional generation as the whole generation side, which is not specific enough for evaluation of the PV low-carbon effects. In reference [8] the low-carbon evaluation index system was established for calculating the carbon emissions during the whole life cycle of transmission and distribution system. The index system covers the whole life cycle of power system including planning, operating, maintenance, and scrap recovery. The method in [8] can be modified to evaluate the specific PV low-carbon benefits.

When it comes to (2), there has already been some low-carbon technologies applied in power system such as low-carbon power flow dispatch, voltage control, etc [9–12]. Reference [13] applied the carbon capture and storage (CCS) technology during the operation of power system and the dispatch principle of CCPs was also established. Reference [10] summarized five kinds of low-carbon technologies including low-carbon equipment renewal, low-carbon operation and control, low-carbon planning, low-carbon mechanism, and low-carbon energy consumption patterns.

Since the growing importance of the low-carbon in the power system, the researches on (3) planning and operating targeting the carbon emission reduction are emerging. A model for optimizing spinning reserve requirement of power system under low-carbon economy is established in [14]. The reserve capacity planning in [14] is decided considering the low-carbon emission which has not been studied before. In reference [15], the expansion planning of the transmission system was studied taking the carbon emission costs into account. Besides the planning stage, in [16], the power system optimal operation strategy was developed under the low-carbon economy.

To sum up, low-carbon effects on power system draw more and more attention nowadays. And the photovoltaic (PV) power generation, as the promising appliance in power system, plays important role in carbon emission reduction. However, up to now, the model and the method for evaluating the PV low-carbon benefits are macroscopic [17] and they only consider the positive effects PV provide which is not comprehensive and objective. For example, reference [18] only evaluate the PV low-carbon benefits during the operation stage in which PV generate power with no carbon emitted. However, there are several stages of PV during its life cycle, such as the manufacturing stage which is a high-carbon emission stage [19]. So, the carbon emission characteristic of PV should be analyzed considering the whole life cycle comprehensively which has not been deeply researched.

Therefore, this paper considers the low-carbon benefits of PV integration through its entire life cycle. First, carbon emission (or emission reduction) characteristics and economic benefits are analyzed with respect to the following four aspects: generation capacity revenue, PV cost, efficiency improvement, and reserve capacity cost. Then, the corresponding low-carbon benefit models and economic benefit models are established. Next, a model is proposed for evaluating the low-carbon comprehensive benefits (LCBs) of photovoltaic power generation, as well as the
carbon emission payback period (CPP). The IEEE 14-bus system with typical operating data is used to verify the validity of the models and methods proposed in this paper. The analysis results show that photovoltaic power generation has great potential in terms of low-carbon comprehensive benefits, when compared with conventional power generation. The models and methods provide a new perspective for power distribution network planning toward low-carbon electricity.

**Basic Concept and Evaluation Framework**

In this paper, LCBs are evaluated with respect carbon emission reduction and economic benefit. So the LCB model combines the low-carbon effects and economic benefits of photovoltaic generation.

**Positive and negative factors of low-carbon emissions and the economic benefits**

From a low-carbon perspective, the factors that contribute to a reduction in carbon emission are referred to as positive factors, whereas the factors that contribute to carbon emissions are called negative factors. For example, photovoltaic generation can replace traditional energy generation and reduce carbon emissions, so this is a positive factor. However, the PV industry itself is a high-energy cost industry even though PV generation is a green energy. For instance, the manufacturing and installation of the production and transportation process of solar system materials consume a lot of energy. This indirectly contributes to carbon emissions [20, 21]. Thus, these are negative factors.

From the economic perspective, the factors resulting in economic gains are viewed as positive economic factors. Factors cause or increase additional costs are viewed as negative economic factors. For example, income obtained from PV electricity sale is a positive economic factor, but the initial capital investment is viewed as a negative economic factor.

**Positive and negative low-carbon effects and the low-carbon comprehensive benefits**

Positive low-carbon factors result in emission reductions, called positive low-carbon effects. Negative low-carbon factors result in an increase in emissions, named negative low-carbon effects. The algebraic sum of both positive and negative effects is defined as the low-carbon effects (LEs) of PV generation. The money made from these low-carbon effects through carbon trading is called the low-carbon benefits (LBs) of PV generation.

Similarly, positive economic factors make or save money, called positive economic benefits. Negative economic factors cost money, named negative economic benefits. The sum of all the positive and negative benefits is called the economic benefits (EBs) of PV generation.

The sum of the LBs and EBs of PV generation is defined as the LCBs of PV generation.

**Evaluation framework**

A carbon benefit assessment framework of PV low-carbon comprehensive benefits is shown in Figure 1.

This framework shows that a precise modeling method is applied. First, factors that affect PV LCBs are retrieved from the concepts of the low-carbon and economic benefits. Next, a model for each of the factors was constructed. Finally, the LCBs of the grid-connected PV system are obtained.

**Factors Influencing Low-carbon Benefits**

In this paper, the LCBs of PV are mainly reflected in four aspects including PV revenue, PV cost, revenue as
a result of improvement in network loss, and reserve capacity cost. These four aspects will be discussed separately.

**PV generation benefit**

Traditional energy is consumed less because of PV power generation, thus contributing to a reduction in carbon emissions from fossil fuel generation. Additionally, revenues are obtained from the sale of PV-generated power. Thus, PV generation has positive effects in terms of both low-carbon emissions and revenue. Therefore, more PV generation can lead to more positive LCBs. However, these positive effects need to be evaluated against the cost of PV generation, which are discussed next.

**PV generation cost**

The generation cost of PV includes low-carbon cost and economic cost, both consisting of the initial cost and annual operation and maintenance (O&M) costs.

Although PV generation is clean, the PV industry incurs high-energy costs. A large amount of energy is consumed during the exploitation, smelting, processing and manufacturing of the raw materials needed for various components of photovoltaic activities. The process will lead to the emission of carbon dioxide. Additionally, the annual O&M cost is related to carbon emissions. From this point, the cost of PV generation contributes to the negative factors of low-carbon emissions.

From an economic point of view, capital investment is needed during the early stage before generation, and its operational maintenance costs cannot be ignored. Obviously, with respect to this aspect, PV generation cost is a negative economic factor.

**Improvement in system loss**

Generally, there is a long distance from centralized power plants to load centers: therefore, the losses in transmission systems can be significant. However, PV generation is usually fixed near load centers, and thus power transmission losses can be reduced. From the point of transmission, PV can save the energy. Additionally, when a PV is connected into the grid, the power flow of the distribution system will be improved because of the active power and voltage supports from the connected PV, and the system losses can be reduced.

According to some surveys about current actual power systems, in most cases, PVs can improve the level of system losses, which is equivalent energy savings (less generation) on the generation side. This case is called the positive low-carbon factor and positive economic factor. In other cases, for the certain level of load and PV penetration, PV generation can increase the loss of the system. This is a negative low-carbon factor and a negative economic factor.

**Increase in system reserve capacity**

PV generation is random and intermittent. To ensure the safe and reliable integration and operation of photovoltaic and grid systems, certain reserve capacity is needed to respond to the sudden sharp drop in PV generation and the gap between forecasted and actual demand caused by load forecast errors. For example, if weather conditions cause the active output of the PV generation system to suddenly drop, reserve capacity is needed to fill the sudden decrease in PV generation to maintain grid stability. This kind of reserve capacity will obviously increase the carbon emissions and economic cost. Therefore, the reserve capacity cost is seen as a negative factor in low-carbon emissions and economy. While uncertainties in PV generation are unavoidable, active load management and EV charging can compensate for the uncertainties, thus reducing reserve capacity.

**Evaluation Model of Low-carbon Comprehensive Benefits**

Four aspects of PV LCBs exist as follows: PV revenue, PV cost, revenue due to improvement in network loss, and reserve capacity cost. The analytical models are presented in this section.

**Components of LCEs and EBs for PV generation**

**PV generation benefit**

Assuming the annual PV generation in the \( t \)th year is \( G_t \) [22], can be expressed as (1):

\[
G_t = H_t P_0 R (1 - d)^t
\]

where \( H_t \) represents the solar radiation during the peak hours throughout the entire year. \( H_t \) is obtained from the amount of solar radiation absorbed by the PV plant divided by \( G \), which is the solar radiation on the surface of the earth under standard conditions, equaling 1360.8 \( \text{W/m}^2 \) [23]; \( P_0 \) represents the PV capacity (units: MW); \( R \) is the performance ratio of the PV system (less than 1.0) [24]; and \( d \) is the decay rate of the PV battery.

The low-carbon effect \( C_1 \) when PV generation replaces the traditional generation in the same amount can be represented by (2):
Low-carbon Footprint Analysis of PV

\[ C_1 = G_m H_P R (1 - d) m_i \]  (2)

where \( m_i \) is the CO\(_2\) emission index of the concentrating generation, which means the average amount of CO\(_2\) emitted by the local mixed power industry (using different fuels) per kWh of generation (unit: g/kWh) [25]. Since the PV output has zero carbon emissions, if the electricity output from traditional generation is substituted with PV generation, the carbon emissions will be reduced. Equation (2) indicates the reduced amount of CO\(_2\) emissions because of the power generation of the grid-connected PV in the \( t \)th year, also called the low-carbon effects of PV generation in the \( t \)th year.

The economic income gained from the sale of PV generation is referred to as \( E_1 \), which can be calculated as follows:

\[ E_1 = G_P H_P R (1 - d) P_r \]  (3)

where \( P_r \) is the feed-in tariff of PV. Equation (3) shows the economic benefit of PV generation in the \( t \)th year.

**PV generation cost**

The cost is considered for both the low-carbon and economic aspects.

According to the study, the low-carbon cost of PV generation as \( C_2 \) is mainly from the initial investment cost \( C_0 \) and operation maintenance cost \( C_m \). It can be expressed as (4):

\[ C_2 = C_0 + C_m \]  (4)

The initial carbon investment includes the carbon emission of the raw material production process of photovoltaic systems, photovoltaic equipment manufacturing, and the installation of photovoltaic equipment transportation.

Among the carbon investments, the first two investments are mainly for the generation consumption. They can be evaluated by the amount of carbon emission per kWh of energy produced [26]. With the assumption that the energy consumed by the photovoltaic systems has a unit power \( k \), then the amount of CO\(_2\) emission in the first two stages can be represented by \( k P_r m_c \).

For carbon emissions during transport, it can be assumed that the distance from the place where the PV system is manufactured to the PV power plant is \( s \) (units: km), the entire weight of PV modules is \( W \) (unit: ton or t), the carbon emission intensity ratio of transport is \( g \) (unit: kg/t-km), and the CO\(_2\) emission during this period is therefore \( W g s \).

Therefore, the initial carbon investment \( C_0 \) can be represented by (5):

\[ C_0 = k P_r m_c + W g s \]  (5)

Equation (5) expresses the amount of CO\(_2\) emissions of the PV generation system during production, manufacture, and transportation.

For the carbon cost during PV system operation and maintenance phase, the replacement of the damaged PV panels and routine maintenance of the photovoltaic equipment can be expressed as (6):

\[ C_m = C_0 \beta \]  (6)

where \( \beta \) is the coefficient of the operation maintenance cost of the PV system versus its initial investments [27, 28].

The PV generation economic cost is the sum of the initial investment, construction, operation, and maintenance while the time value of money is considered. In this paper, the PV generation economic cost for the entire PV operational life [29] is calculated as (7):

\[ E_2 = \sum \left[ (I_t \cdot E_{op}) (1 + i)^{-1} \right] \]  (7)

where \( E_2 \) is the economic cost for the entire life of the PV generation project; \( I_t \) is the economic cost in the \( t \)th year; \( E_{op} \) is the cost of operation maintenance including failure costs and replacement costs; and \( i \) is the discount rate.

**Effect of system loss improvement**

The effect of system loss improvement because the connecting PV generation system can be analyzed following the “exist or none” comparison method. Assume that the level of system loss when no PV is connected in the grid is \( W_1 \) and \( W_2 \) is that with PV connections. The improvement can be expressed as \( \Delta W = W_1 - W_2 \). If \( \Delta W \) is the loss improvement amount at a certain time, during the period \( t \), the low-carbon effect due to loss improvement \( C_3 \) is expressed as (8):

\[ C_3 = m_i \int_0^\Delta W(t) \, dt \]  (8)

The equation shows the CO\(_2\) emission reductions due to the loss improvement when PV is connected to the grid. When \( \Delta W > 0 \), the carbon effect is positive. When \( \Delta W < 0 \), the carbon effect is negative.

During the period \( t \), the economic benefit of the system loss improvement \( E_3 \) is expressed as (9):

\[ E_3 = P_r \int_0^\Delta W(t) \, dt \]  (9)

The equation above shows the economic benefit due to the loss improvement when PV is connected to the grid. When \( \Delta W > 0 \), the economic benefit is positive. When \( \Delta W < 0 \), the carbon effect is negative.
System reserve capacity cost
Assume that the reserve capacity index \([30, 31]\) for PV provided by the grid is \(\theta\) and \(P(t)\) is the PV generation at time \(t\). Then, the reserve capacity is \(\theta P(t)\), and the low-carbon and economic effect can be calculated with (10) and (11).

\[
C_i = m_i \int_0^t \theta P(t) dt \tag{10}
\]

Equation (10) shows the equivalent CO\(_2\) emission of the reserve capacity provided for PV.

\[
E_i = P_i \int_0^t \theta P(t) dt \tag{11}
\]

Equation (11) shows the equivalent economic unused cost of the reserve capacity provided for PV.

Actually, the reserve capacity depends on various PV generation factors such as weather conditions, solar battery model, load demand, and reliability standard; therefore, in this paper, the reserve capacity ratio \(\theta\) is defined as the changeable variable that can be adjusted according to real situations.

LCBs of PV generation
LCEs of PV generation
The PV low-carbon comprehensive effects \(C_y\) is obtained by superposing four parts of the positive and negative low-carbon effects, including PV revenues, PV cost, system loss improvement, and reserve capacity, as shown in (12):

\[
C_y = C_i + C_3 + C_4 + C_4 \tag{12}
\]

where \(C_2 = C_i / n\) is the annual carbon emission cost of the PV system, and \(n\) is the calculation life of the PV system. Equation (12) expresses the net CO\(_2\) emission reductions of the PV system for an entire year.

EBs of PV generation
The PV comprehensive economic benefit \(E_y\) is obtained by superposing four parts of the positive and negative economic effects, including PV revenues, PV cost, system loss improvement, and reserve capacity. This is given by (13):

\[
E_y = E_i + E'_i + E_3 + E_4 \tag{13}
\]

where \(E'_i = E_i ((1+i)^{n-1}) / ((1+i)^n - 1)\) is the annual value converted from the present value of (7), which represents the PV cost per year. Equation (13) expresses the economic net income of the PV system for an entire year.

CPP of PV generation
Carbon emission payback period is a concept similar to the payback period (PP) in engineering economics. It is a ratio of the initial carbon investment to the CO\(_2\) emission reductions per year after the PV system is put into operation. This is given by (15):

\[
CPP = \frac{C_0}{C_y} = \frac{C_0}{C_1 + C_2 + C_3 + C_4} \tag{15}
\]

Similar to the payback period, (15) gives the time (in years) that PV needs to compensate for all of the carbon investment using CO\(_2\) emission reduction after the PV system is put into operation. CPP can also be used to indicate PV low-carbon ability.

Case study example
The process of evaluating PV low-carbon comprehensive benefits is illustrated in an IEEE 14 bus system. There are five conventional generators in this system, connected on nodes 1, 2, 3, 6, and 8. Node 1 is the reference node. PV is on node 3.

Assume that the capacity of PV in a district of Tianjin, China, is 10 MW and the load is 260 MW. Also assume the whole investment in 5 years is 1 billion RMB. The annual operation and maintenance expense ratio is 2%, and the payback period (the project life) is 20 years. The connected polycrystalline silicon PV system is fixed as the best dip. The average peak sunshine hours per day are 4.074 h \([22]\), and the system performance ratio is 0.8 \([24]\). The total weight of the PV equipment is 865.76 t. The distance from the place where PV panel component energy originates to the power plant is 400 km. The intensity of the transportation carbon emission of the transportation carbon emission \(g\) is 0.1553 kg/t-km \([22]\). According to the rules of NDRC in 2013, the feed-in tariff in Tianjin is 1 RMB/kWh. The index of the concentrated generation of CO\(_2\) emissions is 0.76 kg/kWh \([32]\), following the 2007 index. The specific parameter settings are listed in Table 1 below.
Low-carbon benefits estimation

PV generation benefits

PV generation benefits are calculated based on the typical day PV output shown in Figure 2. In Figure 2, four typical days representing four seasons are abstracted based on the yearly PV output data. Then using Eqs (1)–(3), the PV generation is 11,896.08 MWh, which corresponds to a reduction in CO₂ emissions of 9,041.021 t. The direct benefit is 11.89608 million RMB.

PV generation costs

The typical electricity consumption in the PV manufacturing stage is as shown in Table 2. Based on the data in Table 2 and Eqs (4)–(6), the CO₂ emission of PV manufacturing and transportation is 19,190 t and 53,781 t, respectively. Thus, the initial carbon investment is 19,243.78 t. When β = 5%, the carbon cost in the maintenance stage is 962.189 t. The low-carbon cost of generation is 20,205.969 t. The overall cost is equally distributed over 20 years, which is the PV project calculation life, and the CO₂ emission every year is 20,205.969/20 = 1,010.298 t.

System loss improvement effects

Three typical days are selected from four seasons, and each typical day is divided into 12 h from 6:00 AM to 6:00 PM. Then, MATPOWER [33] is used to calculate the net loss improvement for each day, and the net loss improvement of every season and a year are then obtained. Table 3 shows the net loss improvement for each day. And Figure 3 shows the net loss improvement for a typical summer day.
improvement of the four typical days. Table 4 shows the net loss improvement of an entire year, which is obtained by evaluating the data of typical days.

From Figure 3, we can see that the net loss improvement of PV keep line with the amount of load and PV output. When it comes to PV output, the more PV output, the more the net loss improvement.

Table 2. Electrical energy consumed in the production of a polycrystalline silicon photovoltaic grid system (kWh/kW).

| Parts           | Component | Frame | Complement | Total |
|-----------------|-----------|-------|------------|-------|
| Power consumption| 2205      | 91    | 229        | 2525  |

Table 3. Variation in net loss for a typical summer day (MW).

| Period | Load | PV output | Net loss with no PV access | Net loss with PV access | Net loss improvement |
|--------|------|-----------|-----------------------------|-------------------------|----------------------|
| 1      | 127  | 2.35      | 2.674                       | 2.617                   | 0.057                |
| 2      | 133  | 3.96      | 3.032                       | 2.922                   | 0.11                 |
| 3      | 168  | 6.71      | 5.110                       | 4.781                   | 0.329                |
| 4      | 178  | 8.82      | 5.830                       | 5.337                   | 0.493                |
| 5      | 186  | 9.66      | 6.368                       | 5.812                   | 0.556                |
| 6      | 150  | 10        | 3.986                       | 3.618                   | 0.368                |
| 7      | 160  | 10        | 4.559                       | 4.132                   | 0.427                |
| 8      | 186  | 10        | 6.368                       | 5.757                   | 0.611                |
| 9      | 209  | 9.46      | 8.105                       | 7.360                   | 0.745                |
| 10     | 212  | 7.19      | 8.519                       | 7.917                   | 0.602                |
| 11     | 181  | 4.61      | 6.019                       | 5.747                   | 0.272                |
| 12     | 214  | 2.50      | 8.707                       | 8.489                   | 0.218                |
| Sum    | –    | –         | 69.277                      | 64.489                  | 4.788                |

Figure 3. Net loss improvement of four typical days representing four seasons.

Table 4. Variation in net loss in four seasons (MWh).

| Season | Net loss improvement |
|--------|----------------------|
| Spring | 280.46               |
| Summer | 430.92               |
| Autumn | 260.78               |
| Winter | 107.21               |
| Total  | 1079.37              |

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outputs, the more load satisfied locally, thus reduces the power transmitted through the power line which leads to decrease the net loss due to the power transmission. When it comes to load demand, the net loss improvement will increase with the load demand raising because PV will feed more load and save more net loss due to the power transmission through the line.

From the results of Table 4, we can observe that in this case, the connection of PV is positive for the grid, and the net losses are reduced; the loss reduction is 1079.37 MWh. The CO₂ emission reduction is 820.321 t, which corresponds to 1.07937 million RMB.

**Reserve capacity costs**

Assume the reserve capacity index is 0.315 in this case and the carbon cost of the reserve capacity is 2260.255 t, which corresponds to 2.97402 million RMB.

**Low-carbon comprehensive benefits and CPP**

The estimations of PV generation income, PV generation cost, system loss improvement benefits, and reserve capacity cost are listed in Table 5.

The PV system yearly low-carbon income is 0.71 million RMB according to the certification emission reduction (CER) of the international carbon trade market. Therefore, as described in (14), the yearly low-carbon economic benefits of the system are 0.71-0.33572 = 0.374 million RMB.

**Results Analysis**

From the results shown above, it can be concluded that the project is not highly feasible from an economic point of view; however, it is feasible from the low-carbon emission point of view [34].

Assuming that the low-carbon benefits of the project are fixed every year, the CPP = 19243.78/6590.789 = 2.9 years, and the emission reduction per kWh of PV compared with the traditional core power generation is 667.45 g/kWh. Thus, the low-carbon potential of the PV system in this case is considerable.

Figure 4 shows the carbon emission of every phase in the PV life cycle. It illustrates that the carbon emission of PV occurs mainly at the operation and manufacture stages. The high percentage of manufacture emission shows that PV manufacturing is a high–energy consuming process. With further technological development, the energy consumption in the manufacturing process will be reduced, and the comprehensive carbon effects of PV will increase considerably.

To measure the uncertainty of the carbon comprehensive benefits caused by the parameter uncertainties in the entire PV life cycle, a sensitivity analysis is performed.

1. Light Intensity: PV carbon benefits accessed in three locations with different light intensity are shown in Table 6. Obviously, the PV system can achieve more low-carbon benefits in a location with higher light intensity, and the CPP will be shorter.

2. Manufacturing Energy Consumption: Figure 4 shows that the carbon emissions in the PV manufacture stage are dominant. With the progress of technology, the energy of the photovoltaic manufacturing stage should be reduced gradually. In this study, it is assumed that the energy consumption in this stage is reduced by 10% (S2), 20% (S3) and 30% (S4) compared with the current energy consumption levels (S1). The comprehensive carbon benefits of the 4 scenarios are shown in Table 7.

3. Life Cycle Length: The length of the PV life cycle is also an important factor affecting the carbon benefits. Table 8 shows that the carbon comprehensive benefits will be improved, and the CPP can be shortened if the PV life cycle length is longer.

The results above show that PV has the great advantage of low-carbon comprehensive benefits compared with conventional power generation.

### Table 5. Low-carbon and economic benefits of PV per year.

| Items                  | LCEs (tons) | EBs (10,000 RMB) |
|------------------------|-------------|------------------|
| PV incomes             | +9041.021   | +1189.608        |
| PV costs               | −1010.298   | −1033.715        |
| System loss improvement| +820.321    | +107.937         |
| Reserve capacity costs | −2260.255   | −297.402         |
| Total                  | +6590.789   | −33.572          |

### Table 6. PV Carbon benefits under different light intensity.

| Units              | Location 1 | Location 2 | Location 3 |
|--------------------|------------|------------|------------|
| Peak sunshine hours| h          | 5.86       | 4.074      | 2.45       |
| PV capacity        | MW         | 10         | 10         | 10         |
| PV efficiency      | %          | 80         | 80         | 80         |
| Annual power generation | MWh       | 17111.2    | 11896.08   | 7154       |
| Emission reduction | t/year     | 11903.61   | 7940.1     | 4336.14    |
| Emission intensity | g/kWh      | 695.66     | 667.45     | 606.11     |
| CPP                | year       | 1.7        | 2.6        | 4.7        |
From the perspective of the low-carbon benefits of PV, compared with traditional thermal power generation, PV has good environmental benefits due to its characteristics of zero CO₂ emission during the power generation process. With the application of new technologies in the future, the initial carbon investment of PV will be greatly reduced, which will result in a great increase in the PV low-carbon benefits.

From an economic benefits perspective, using PV as a kind of distributed power generation can reduce the power flow in the distribution lines during operation in order to reduce the power loss, which leads to considerable economic benefits. Although at present, due to the huge investment in the construction of PV, the economic benefits of the entire PV life cycle are not obvious; however, with the development of PV cell panel manufacturing technology, as well as the gradual improvement of the permeability of PV power generation, the photovoltaic construction costs will further decline, and the economic benefits of PV will be more obvious.

**Conclusions**

Low-carbon emission is the visible result of carbon emission/reduction, and it should be better assessed, especially for utility grid-connected PV generation. Based on the low-carbon and emission reduction requirements, this paper proposed a comprehensive, quantitative approach for evaluating the low-carbon comprehensive benefits of PV generation, from the perspective of the entire life cycle and power distribution network planning.

1. Using the life cycle low-carbon concept, the characteristics of carbon emission (reduction) and economic benefits of grid-connected PV were discussed with respect to PV generation benefit, generation cost, system loss improvement benefit, and reserve capacity cost.
2. Based on the low-carbon positive factors and negative factors, the low-carbon positive effect and negative effect were proposed and examined. The comprehensive low-carbon effect was divided into PV generation cost, generation income, net loss improvement, and reserve capacity cost. A model was also established to include low-carbon and economic aspects, which favor future detailed analysis regarding distribution network low-carbon benefits.
3. Using PP in engineering economics, the concept of CPP was proposed to provide a new comprehensive analysis approach regarding PV generation projects. This concept can be extended for other types of new grid-connected energy resources.

**Table 7.** Carbon benefits under different manufacturing energy consumption.

| Units                  | S1          | S2          | S3          | S4          |
|------------------------|-------------|-------------|-------------|-------------|
| Energy consumption     | MWh         | 2.525*10⁴   | 2.273*10⁴   | 2.02*10⁴    | 1.768*10⁴   |
| Initial carbon investment | t          | 19,374      | 17455.01    | 15,536      | 13,617      |
| Emission reduction     | t/year      | 7940.1      | 8036        | 8132        | 8227.95     |
| Emission intensity     | g/kWh       | 667.45      | 675.52      | 683.59      | 691.65      |
| CPP                    | year        | 2.56        | 2.58        | 2.24        | 1.9         |

**Table 8.** Photovoltaic carbon benefits under different life cycle lengths.

| Units                  | 18 years  | 20 years  | 22 years  | 24 years  | 26 years  |
|------------------------|-----------|-----------|-----------|-----------|-----------|
| Annual carbon costs    | t         | 1130.15   | 1017.1    | 924.67    | 847.61    | 782.41    |
| Emission reduction     | t/year    | 7827.17   | 7940.1    | 8031.65   | 8109.71   | 8174.91   |
| Reduction intensity    | g/kWh     | 657.96    | 667.45    | 675.23    | 681.71    | 687.19    |
| CPP                    | year      | 2.59      | 2.56      | 2.53      | 2.50      | 2.48      |
The methodology in this paper mainly provides a macroanalysis of a low-carbon footprint for PV integration into a power generation grid from the viewpoint of power distribution network planning; the analysis time scale is 1 year. The authors will carry out a more detailed analysis based on more detailed time scale simulations in the future.

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Conflict of Interest

None declared.

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