

# Case Analysis on Economic Efficiency of Grid-Connected Photovoltaic Power Generation Project with Carbon Emission Measurement

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**Abstract.** Taking the photovoltaic power generation project in Shanghai area as a case, economic benefit of the whole lifetime cycle of the project was analyzed by adopting the levelized cost of electricity (LCOE). Meantime in consideration of the low-carbon economic benefits, the incremental cost analysis method was applied to evaluate the unit carbon-mitigation cost of the project and sensitivity analysis was conducted, in ordering to put forward the guiding suggestions for the investment of photovoltaic power generation projects.

## 1. Introduction

With the intensifying exploitation of renewable energy in worldwide, solar photovoltaic industry is developing by leaps and bounds, which becomes the largest renewable energy industry with the highest investment growth over the world [1]. Compared by conventional coal-fired and oil-fired power generation, photovoltaic (PV) power generation is safe, reliable, noiseless, clean and green, which is also not bound by resource distribution areas while not consuming fuel. It's can avoid the environment damage caused by various pollution derived from conventional coal-fired or oil-fired power generation, such as CO<sub>2</sub>、SO<sub>2</sub>、NO<sub>x</sub> and CO. So PV power generation currently is the project of green power energy supported strongly by Chinese government. The legal system about the environmental protection applied to the power industry will be improved constantly along with moving forward in China's market-oriented reform of the electric power system, so taking into consideration of the environmental cost will become the inevitable trend [2]. In this paper, economic efficiency of PV power generation was analyzed from the carbon emission reduction point of view, meantime in consideration of the total life cycle cost.

## 2. Mathematical Models

The LCOE is one analytical tool that can be used to compare alternative technologies when different scales of operation, investment or operating time periods exist [3-5], which can be consider as one of the main factors to compare the cost of energy generated by a PV power plant with that of a fossil fuel generating unit or another renewable technology [6-8]. The calculation for the LCOE is the net present value of total life cycle costs of the project divided by the quantity of energy produced over the system life.

$$LCOE = \frac{\text{Total Life Cycle Cost}}{\text{Total Lifetime Energy Production}} \quad (1)$$



In consideration of the discount rate, the above LCOE equation can be disaggregated for solar generation as follows [9]:

$$\text{LCOE} = \frac{\text{Initial Investment} - \sum_{n=1}^N \frac{\text{Depreciation}^n}{(1+\text{Discount Rate})^n} \times (\text{Tax Rate}) + \sum_{n=1}^N \frac{\text{Annual Cost}^n}{(1+\text{Discount Rate})^n} \times (1-\text{Tax Rate}) - \frac{\text{Residual Value}}{(1+\text{Discount Rate})^N}}{\sum_{n=1}^N \frac{\text{Initial kWh/kWp} \times (1-\text{System Degradation Rate})^n}{(1+\text{Discount Rate})^n}} \quad (2)$$

The economic efficiency of PV power generation project was analyzed by taking consider into the environmental benefits in this paper, and the benefit about carbon emission reduction compared with traditional power generation's was emphasized on. Thus, this paper serves the greenhouse gas emission of traditional power generation as a basic line, and sets the benefit about carbon emission reduction as the criterion of economic efficiency of PV power generation project. So per-unit cost of carbon emission reduction can be represented as [10]:

$$\text{Per-unit CO}_2 \text{ emission reduction cost} = \frac{\text{LCOE} - \text{Per-unit cost of trational generation}}{\text{Per-unit CO}_2 \text{ emission of PV power generation} - \text{Per-unit CO}_2 \text{ emission of trational generation}} \quad (3)$$

A project of grid-connected PV power generation built in Shanghai area was taken as a case to see whether it made sound economic sense in this paper, while the sensitivity analysis of typical environment factors were made.

### 3. Casd Analysis

By taken grid-connected PV power generation with the installed capacity of 91.5kW built in Shanghai area as an example, per-unit cost of the carbon emission reduction was analyzed in this paper.



The basic information of the case in this paper was as follows: the installed capacity was 91.5kW, the life cycle was 25 years, the initial investment was 739800 yuan, the per-unit cost was 8.80 yuan•W<sup>-1</sup>, the annual cost was 2300 yuan, the average generating capacity was 82.1GWh, the annual load-time 896.9 hours, the discount rate was 8%, the tax rate was 17%, the system degradation rate was 0.8% and the system residual rate was 5%.

Basic information of this project and main parameters for computational analysis are listed in Table I and Table II [4, 11, 12]. The economic efficiency of this project by considering the carbon emission was calculated. The results were shown as follows.

- a) LCOE of the grid-connected PV power generation project is  $0.9991 \text{ yuan} \cdot \text{kWh}^{-1}$ .
- b) Per-unit cost of traditional power generating project is  $0.2590 \text{ yuan} \cdot \text{kWh}^{-1}$ .
- c) Per-unit incremental cost of the project is  $0.7401 \text{ yuan} \cdot \text{kWh}^{-1}$ .
- d) Per-unit  $\text{CO}_2$  emission reduction of the project is  $0.6784 \text{ kg} \cdot \text{kWh}^{-1}$ .
- e) Per-unit carbon emission cost of the project is  $1.0909 \text{ yuan} \cdot \text{t}^{-1}$ .

**Table 1.** Major Parameters in Mathematic Analysis of Pv Project

Parameters	Capacity	Annual load-time	Initial Generating Capacity	Initial Investment	Annual Cost	Discount Rate	Lifetime	System Degradation Rate	Tax Rate	System Residual Rate
value	91.5 kW	896.9 h	82100 kWh	739800 yuan	2300 yuan	10%	25a	0.8%	17%	5%

**Table 2.** Major Parameters in Mathematic Analysis of Trational Generation [10]

Energy	Ratio (%)	Coal (oil) consumption ( $\text{g} \cdot \text{kWh}^{-1}$ )	Standard coal coefficient ( $\text{kg} \cdot \text{kg}^{-1}$ )	Cost ( $\text{yuan} \cdot \text{kWh}^{-1}$ )	Average low calorific value ( $\text{MJ} \cdot \text{kg}^{-1}$ )	Carbon oxidation rate (%)	Carbon content (%)	Carbon emission coefficient ( $\text{kg} \cdot \text{kWh}^{-1}$ )
Coal-fired power	87.6	338	0.7143	0.225	20.93	65	94	0.303
Oil-fired power	1.5	328	1.4286	0.289	41.87	98	85	0.163
coal gas	3.9	$0.1830 \text{ m}^3 \cdot \text{kWh}^{-1}$	1.7143	0.238	50.18	98	35~40	3.1013
Natural gas	7.0	$0.2298 \text{ m}^3 \cdot \text{kWh}^{-1}$	1.3300	0.6894	$35.88 \text{ MJ} \cdot \text{m}^{-3}$	99	15~45	$2.1622 \text{ kg} \cdot \text{m}^{-3}$

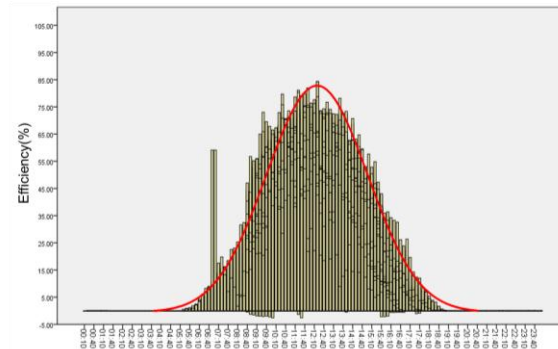
According to the energy program [2016] No.13 published by Shanghai municipal development and reform commission, Shanghai government's implementation of the distributed PV power generation subsidy was classified by power consumptive, i.e. the price for industrial and commercial users was  $0.25 \text{ yuan} \cdot \text{kWh}^{-1}$  and the price for individuals, schools and other users was  $0.4 \text{ yuan} \cdot \text{kWh}^{-1}$ . As well as subsidies from the state ( $0.42 \text{ yuan} \cdot \text{kWh}^{-1}$ ), the LCOE of grid-connected PV power generation project in this paper was  $0.3291 \text{ yuan} \cdot \text{kWh}^{-1}$ , while Feed-in tariffs of coal-fired generation is  $0.4359 \text{ yuan} \cdot \text{kWh}^{-1}$  in Shanghai. Thus, it can be concluded that the return on investment (ROI) of this case has certain advantages in consideration of the subsidies from the government.

#### 4. Sensitivity Analysis

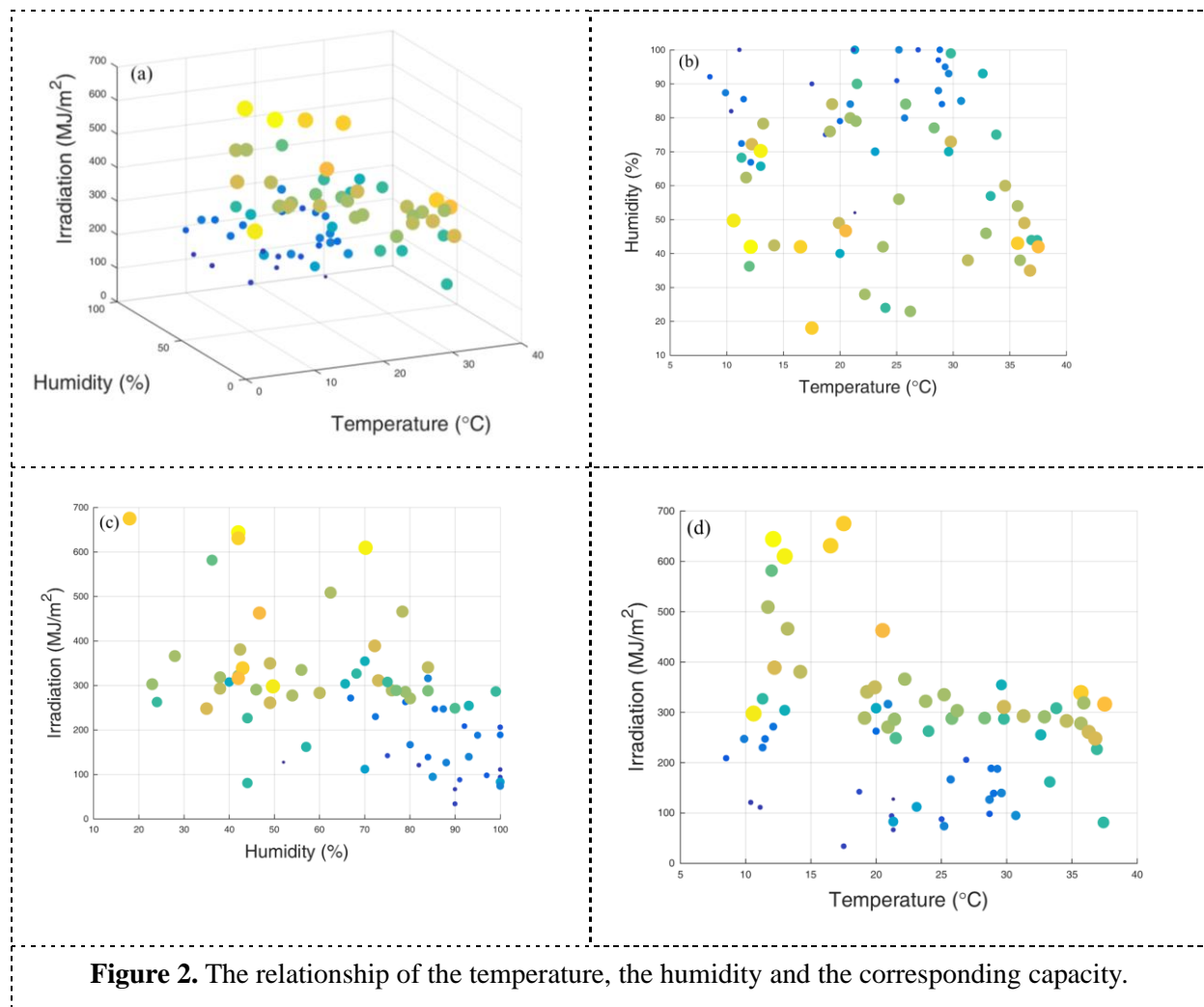
For PV power generation project, its carbon emission cost is affected mainly by the LCOE, which is related to several conditions, such as per-unit cost of the project, amount of solar radiation where the project is located, system efficiency, systematic degradation rate, maintenance costs and the lifetime of key equipment like inverter, etc. For the established grid-connected PV power generation project in this paper, various factors had been defined, for instance, the performance of key equipment and the investment of the project. Consequently, economic efficiency of this project is mainly affected by systematic generating capacity. So the sensitivity effect of environmental factors on the system generating capacity was analyzed based on the actual environment where the equipment was located in this paper.

The electrical efficiency of this PV power generation was analyzed firstly. The data of someday were chosen randomly in order to improve the accuracy of results and the corresponding curve was displayed in Fig. 1. Obviously the random variables follow the normal distribution. The maximum

efficiency appeared around noon and the value was 84.34%. The average efficiency of this plant was 25.21%.



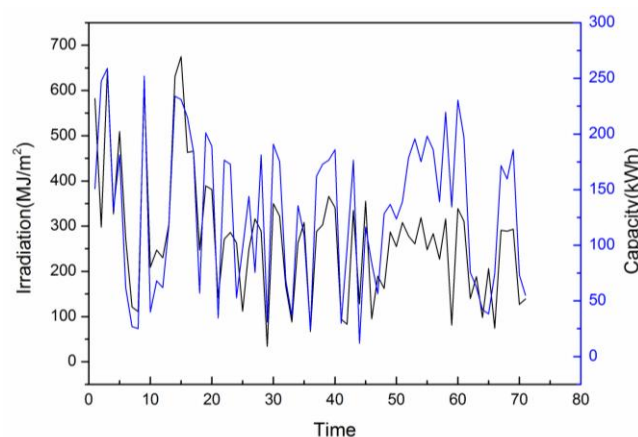
**Figure 1.** The curve of the electrical efficiency of the PV power generation on someday.



**Figure 2.** The relationship of the temperature, the humidity and the corresponding capacity.

According to the climatic characteristics in Shanghai, the electricity generation performance data of equipment is divided by four seasons. That is to say, the environmental data of the temperature, the humidity and the solar radiation in February, May and July, 2016 respectively were chosen to analyze the sensitivity effect on the capacity [13].

The relationship of daily environment temperature, humidity and accumulated solar irradiation, as well as daily systematic generating capacity in February, May and July, 2016 was shown in Fig. 2(a). The lighter color and larger radius of points indicated the larger systematic generating capacity. It had to be pointed out that for daily dynamic change of environmental factors, the environmental temperature and humidity at 14:00 were taken as basic data in this paper, just because those factors reach the optimal value at that moment, which was more representative. The trend of systematic generating capacities almost stayed same with the change of environment humidity in Fig. 2(b). The higher the environment humidity was, the darker and larger radius of points were, which presented the lower the systematic generating capacity. While the radius or color of the points didn't displayed any change rules with the increase of temperature in Fig. 2(b), so the environment temperature had no obvious influence on the systematic generating capacity. The energy of PV power generation is generated from the radiation of solar ray. The solar ray reaches the ground after passing through the earth's atmosphere, so that the higher atmospheric transparency is, the more solar energy transmits to the ground, accordingly which leads to the higher capacity. On the contrary, the higher environmental humidity means the more water vapor contained in the atmosphere, which would deplete the solar energy when solar ray passes through the atmosphere, so the lower systematic generating capacity is obtained. As shown in Fig. 2(c) and (d), the lighter and larger radius points were centralized in the upper of the figures. It was conclude that the higher the value of the accumulated solar irradiation was, the higher the corresponding generating capacity was. It was worth noting that the extreme value of systematic generating capacity appeared around 15°C (namely in winter) and 25°C (namely in spring). By combined with the results of the influence of environmental humidity shown in Fig. 2(b), it was deduced that the phenomenon described above was ascribed to the subtropical monsoon climate in Shanghai where abundant rain and damp air in spring, while dry air in winner. It can be concluded that environmental humidity is one of principal factors affecting the generating performance of equipment. The low environmental humidity in spring and winter displayed the high capacity. Especially, when the environmental humidity is lower than 50%, the generating performance of system is superior.



**Figure 3.** The relationship between accumulated solar irradiation and the corresponding capacity.

According to the results of analysis on the influences of environmental temperature and humidity, it was concluded that solar radiation exactly played a critical role in systematic generating capacity. It was deduced that systematic generating capacity was almost completely consistent with the change trend of solar radiation in Fig. 3(d). The stronger the solar radiation was, the higher the systematic generating capacity was. There was a positive correlation between both of them. So the generating performance of equipment can be improved obviously by perfecting the received conditions for solar radiation and reducing the environmental humidity where the system was built.

## 5. Conclusions



The established grid-connected PV power generation project in Shanghai was taken as a case to calculate the economic efficiency of its whole life cycle, whose LCOE is  $0.9991 \text{ yuan} \cdot \text{kWh}^{-1}$ , in the meantime, the increment cost analysis was adopted to evaluate the carbon emission reduction cost of the project, as well as the analysis on the sensitive factors. It's concluded that if the equipment is installed in dry areas where solar irradiation and airiness are great, it is helpful to exert the performance of systematic power generation. With the increasing popularity of distributed PV power generation, it is bound to impact on the traditional grid, so how to get a relationship of a harmony and balance will become the focus of attention.

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