

# Economic Comparison of Scheduled and Unscheduled Photovoltaic Systems

## Case Study of Xi'an Jiaotong University Library

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**Abstract**—Solar energy, a clean energy with a high utilization value, is an important pillar of the future energy structure. The photovoltaic industry, as the core of the solar energy industry, has attracted the attention of governments and enterprises in various countries. The application of solar photovoltaic energy has become crucial in the design of green buildings. A photovoltaic power generation system is divided into off-grid and grid-connected systems. The grid-connected photovoltaic system can be further divided into scheduled and unscheduled photovoltaic systems depending on the energy storage equipment. On the basis of the current technical level and cost of photovoltaic systems, this work uses Xi'an Jiaotong University Library as an example. The economy of scheduled and unscheduled photovoltaic systems is compared through investigation and calculation.

**Keywords**—photovoltaic system; scheduled photovoltaic system; unscheduled photovoltaic system

### I. INTRODUCTION

In 1839, the French physicist A.E. Becquerel discovered that illumination can cause potential differences among different parts of semiconductor materials. This phenomenon is called the "photovoltaic effect."

The first solar cell, which consisted of a layer of selenium covered with a thin film of gold, was fabricated by Charles Fritts in 1884, but it exhibited poor efficiency. In 1954, the American scientist Charbin made the first practical monocrystalline silicon solar cell at Bell Laboratories in the United States. This solar cell gave rise to a practical photovoltaic technology that converts solar energy into electrical energy. The working principle of the solar cell is the photovoltaic effect.

After the industrial revolution, the application of fossil energy resulted in a rapid increase in productivity and remarkable industrial civilization. However, the pollution caused by fossil energy continues to perplex mankind. Therefore, the demand for clean energy has increased. With the current deterioration of the environment, the difficulty of exploiting fossil energy and the decrease in reserves are becoming increasingly urgent. As a solution to these issues, the photovoltaic power system that directly uses solar energy is regarded as an important part of the future energy structure by the governments of many countries, and various policies have

been established to protect the development of this industry (Table 1)<sup>[1]</sup>.

TABLE I. POLICIES TO PROTECT THE SOLAR INDUSTRY

Countries	Policies
Germany	Feed-in Tariff Law, Financial Support, Tax Preference, R&D Support
United States	Tax Preference, R&D Support, Education and Publicity
Japan	Financial Support, Tax Preference, Education and Publicity

In accordance with its national conditions, China has absorbed the merits of the policies of other countries, encouraged the photovoltaic industry through the feed-in tariff law, and achieved good results.

### A. Different Types of Photovoltaic Systems

TABLE II. TWO TYPES OF PHOTOVOLTAIC SYSTEMS

Types	Applied Range
Off-Grid Photovoltaic System	No Grid Area, Signal Station, Lighthouse, Street Lamps, Traffic Lights
Grid-Connected Photovoltaic System	Domestic Photovoltaic System, Photovoltaic Power Station

An off-grid photovoltaic system mainly consists of photovoltaic module, inverter control, energy storage system, and fixed system units. The electricity generated by illumination can be stored directly in the battery to provide energy for the load under the condition of insufficient light at night or during the day. This system is usually built in no-electricity areas and special places where a public power grid cannot be built, such as mountain areas, wastelands, and plateaus. By contrast, a grid-connected power generation system connects the generated power to the corresponding voltage-grade power grid. The integration of this power generation system is the focus of the solar energy industry in China. In particular, a photovoltaic power system combined with different buildings on the grid roof is the main direction of China's future photovoltaic industry<sup>[2]</sup>.

### B. Introduction of Xi'an Jiaotong University Library

Xi'an Jiaotong University Library has two parts. The north building with a building area of 11,200 m<sup>2</sup> was built in July 1961, and the south tower with a building area of 18,000 m<sup>2</sup> was constructed in March 1991. The building area of the west campus library is 10,340 m<sup>2</sup>. The total area of the library is 39,540 m<sup>2</sup> and includes 3,518 seats. The use of photovoltaic power generation was not considered during the design and construction of the building, and energy saving design standards were relatively low. This problem is common in the majority of old buildings in the city. From the estimation of the energy consumption of the library according to the energy consumption standard of GB/T 51161-2016 civil buildings, Xi'an is a hot-summer and cold-winter area, and the energy consumption guide value for this library type is 55 kW·h/m<sup>2</sup>·a (without heating). The heating energy consumption guide value is 3 kW·h/m<sup>2</sup>·a. Thus, the estimated annual energy consumption of this library is 2,293,320 degrees, and the electricity cost is approximately 1,147,000 RMB (0.5 RMB/degree). The university library must develop new energy and use energy saving methods to achieve energy savings. Among all new energy types, solar energy has the most promising future. If eligible university libraries can use solar energy, then the problem will be solved. Solar energy provides considerable economic and environmental benefits by promoting energy saving and emission reduction in colleges and universities and by advocating low-carbon life.

## II. DESIGN OF PHOTOVOLTAIC SYSTEMS

### A. General Introduction of Solar Energy

Solar energy is inexhaustible, and all existing forms of energy on Earth are derived from solar energy. Although the energy of solar radiation to the Earth's atmosphere is only 2,200,000,000 of its total radiation energy, it has reached 173,000 TW, which means that the sun's energy per second on Earth is equivalent to 5,000,000 tons of coal, and the energy is large. The annual average amount of sunshine in China is greater than 2,000 h in more than two-thirds of the area, and the annual average daily radiation is greater than 4,000 MJ/m<sup>2</sup>, which is better than that of Europe and Japan and similar to that of the United States. Xi'an Jiaotong University is located at longitude 108° 54' E and latitude 34° 16' N. In May, the maximum radiation value is 5.36 kW·h/m<sup>2</sup>/day, that is, 19.396 MJ/m<sup>2</sup>/day. In December, the minimum radiation value is 2.62 kW·h/m<sup>2</sup>/day, that is, 9.432 MJ/m<sup>2</sup>/day. The annual average radiation amount is approximately 4,500 MJ/m<sup>2</sup>. Xi'an Jiaotong University is the second solar-energy-rich area in China. Abundant solar energy resources are conducive to the promotion of solar power generation at a reduced cost [3].

### B. Scheduled and Unscheduled Photovoltaic Systems

A solar photovoltaic power generation system is mainly composed of a solar panel, controller, inverter, and battery.

(1) Solar panels convert sunlight directly into direct current (DC) and are the most basic unit of photovoltaic power generation systems. Multiple solar cells connected together by

wires on metal brackets are combined into a solar cell array to produce the required voltage and current.

(2) The controller can adjust the battery voltage by adjusting and distributing the input and output power of the system.

(3) Inverters are devices that convert DC to alternating current (AC). Solar cells and batteries are DC power sources. Thus, an inverter needs to convert DC power to 50 Hz AC current for AC load.

(4) In a photovoltaic system, the battery stores and adjusts the power generated by the system because of the inconstancy of sunshine. The battery converts DC power to chemical energy and then to electric energy for release as the load [4].

A grid-connected photovoltaic system can be divided into scheduled and unscheduled photovoltaic systems according to whether the battery energy storage links are configured or not.

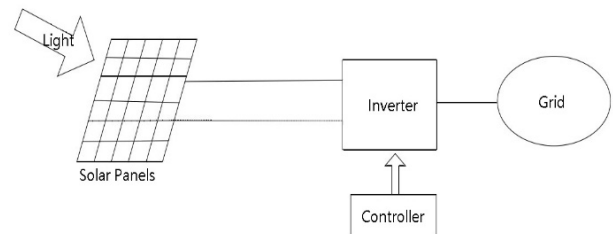


FIGURE I. STRUCTURE OF AN UNSCHEDULED PHOTOVOLTAIC SYSTEM

An unscheduled photovoltaic system consists of photovoltaic panels, a controller, a grid-connected inverter, and a transformer, as shown in Figure 1. In an unscheduled photovoltaic power station, grid-connected inverters use photovoltaic cells when the power grid is normal. The generated DC energy can be directly converted into AC power with the same frequency and the same phase as the grid voltage and sent to the power grid. When the network is powered off or no light is present, the system automatically stops sending electricity to the grid.

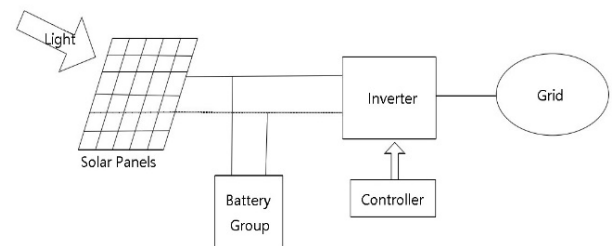


FIGURE II. STRUCTURE OF A SCHEDULED PHOTOVOLTAIC SYSTEM

The typical structure of a scheduled photovoltaic system includes photovoltaic panels, a grid-connected inverter, a battery energy storage link, a controller, and a transformer, as shown in Figure 2. The energy storage system is the regulation and control link of the photovoltaic grid-connected generation system. It is used when the power is sufficiently good to

generate electricity. Some electric energy can be stored, and when necessary, a part of the stored electric energy can be released at an appropriate time to stabilize the photovoltaic power supply. The output and effect of electrical balance can be adjusted. The scheduled photovoltaic system is superior to the unscheduled photovoltaic system in terms of function. However, the energy storage battery has several serious disadvantages, namely, short battery life, high cost, and large weight [5].

### III. COMPARISON OF SCHEDULED AND UNSCHEDULED PHOTOVOLTAIC SYSTEMS

#### A. Formula and Calculations<sup>[6, 7]</sup>

(1) The design formula used to calculate the total capacity of a solar cell module:

$$W_0 = \delta H / QR\eta$$

where  $W_0$  is the total capacity calculation value of the anode battery module in kWp;  $H$  is the annual electricity simultaneous rate, which is 0.9 in this study;  $Q$  is the annual energy consumption to satisfy the load, with a value of 2,293,320 kW·h;  $R$  is solar energy annual radiation, which is 1,250 kW·h/m<sup>2</sup> in Xi'an;  $\delta$  is the ratio of solar annual irradiance on the surface of solar panels to solar annual radiation on the ground surface, with a value of 1.2; and  $\eta$  is the total efficiency of the system after considering various loss factors, with a value of 0.7.

$$W_0 = 1,965.7 \text{ kWp}$$

(2) The capacity of the battery is calculated, and the calculation formula is expressed as follows:

$$C = E_0 D / D_d \eta_i$$

where  $C$  is the calculated value of the capacity of the battery in kW·h;  $E_0$  is the average daily electricity consumption in kW·h;  $D$  is the guarantee period, which is usually 3 days;  $D_d$  is the battery discharge depth, which is usually 0.7; and  $\eta_i$  is the inverter efficiency, which is usually 0.85.

$$C = 31,679.3 \text{ kW·h}$$

(3) The capacity of the inverter is calculated, and the appropriate controller is selected.

$$C_N = K_n P$$

where  $C_N$  is the power capacity of the inverter;  $K_n$  is the safety factor, which is usually 1.2, and  $P$  is the load power. The control of the photovoltaic power generation system is mainly embodied in the control of the charger and inverter because of the output and storage of the solar cell. The load and self-discharge of the battery are uncertain. Thus, fuzzy control can be adopted.

$$C_N = 2,358.84 \text{ kW}$$

#### B. Investment Comparison

The difference between scheduled and unscheduled photovoltaic systems is the presence of a battery, and the cost of the unscheduled photovoltaic system can be approximately calculated by the cost of the scheduled photovoltaic system (Table 3). Table 4 shows that the advantages of the current unscheduled photovoltaic system are numerous.

TABLE III. INVESTMENT IN THE SCHEDULED PHOTOVOLTAIC SYSTEM IN XI'AN JIAOTONG UNIVERSITY LIBRARY

Items	Solar Panel	Battery Group	Controller and Inverter	Cables	Holder and Switch Box	Construction	Total Investment
Unit Price (RMB/kW)	2250	400	150				
Quantity (kW)	1965.7	31679.3	2358.8				
Investment (Million RMB)	4.428	12.672	0.354	1.625	1.95	2.6	23.629
Percentage	18.7	53.6	1.5	6.9	8.3	11.0	

TABLE IV. INVESTMENT IN TWO TYPES OF PHOTOVOLTAIC SYSTEMS

Types	Investment
Scheduled Photovoltaic System	23.629 M RMB
Unscheduled Photovoltaic System	10.957 M RMB

#### C. Generating Cost Comparison

Similarly, the unit power cost of the unscheduled photovoltaic system can be approximately estimated by reducing the cost of the battery of the scheduled photovoltaic system. Table 6 shows that the current unscheduled photovoltaic system has the same advantages in unit price.

TABLE V. GENERATING COST OF THE SCHEDULED PHOTOVOLTAIC SYSTEM IN XI'AN JIAOTONG UNIVERSITY LIBRARY

Items	Solar Panel	Battery Group	Controller and Inverter	Cables	Holder and Switch Box	Construction	Aggregate
Investment (Million RMB)	4.428	12.672	0.354	1.625	1.95	2.6	23.629
Lifetime (Years)	20	15	10	20	20	20	
Annual Investment (Million RMB)	0.2214	0.8508	0.0354	0.08125	0.0975	0.13	3.1
Generated Capacity (kW·h)	2,293,320						
Generating Cost (RMB/ kW·h)	0.0965	0.371	0.0154	0.0354	0.0425	0.0567	0.6175

TABLE VI. GENERATING COST OF THE TWO TYPES OF PHOTOVOLTAIC SYSTEMS

Types	Generating Cost
Scheduled Photovoltaic System	0.6175 RMB/kW·h
Unscheduled Photovoltaic System	0.2465 RMB/kW·h

TABLE VII. ANNUAL COST COMPARISON IN THREE SITUATIONS

Types	Generating Cost (RMB/kW·h)	Purchasing Cost (RMB/kW·h)	Subsidies (RMB/kW·h)	Unit Spending (RMB/kW·h)	Annual Consumption (kW·h)	Annual Spending (Million RMB)
Scheduled Photovoltaic System	0.6175	0	0.37	0.2475	2,293,320	0.5676
Unscheduled Photovoltaic System	0.2465	0.5109	0.65	0.1074		0.2463
Present Status	0	0.5109	0	0.5109		1.1717

#### D. Annual Cost Comparison

At present, the non-commercial electricity price for schools and government agencies is 0.5109 RMB/kW·h in China.

According to the subsidy policy of the Chinese government in 2018, the price of photovoltaic power generation in the first, second, and third solar-energy-rich areas is 0.55, 0.65, and 0.75 RMB/kW·h, respectively. Xi'an belongs to the second solar-rich-energy area, and the photovoltaic electricity price is 0.65 RMB/kW·h.

In addition, according to China's subsidy policy in 2018, the subsidy for self-generation and self-use with surplus energy connected to the grid is 0.37 RMB/kW·h according to the generating capacity.

Notably, the annual power cost of the scheduled photovoltaic system is 321,300 RMB more than that of the unscheduled photovoltaic system, but it is half that when compared with the present cost of 1,171,700 RMB. Generally, the photovoltaic power generation system has obvious economic benefits.

#### IV. CONCLUSION

According to the example of Xi'an Jiaotong University Library, the total investment for the scheduled photovoltaic system is much higher than that for the unscheduled system judging from the one-time investment in construction.

According to the unit price, the scheduled photovoltaic system is also much more expensive than the unscheduled system. However, the scheduled photovoltaic system has many advantages, including strong self-sustaining capability to ensure emergency electricity consumption. The subsidy is high, and the price is acceptable with regard to the annual cost of electricity consumption.

Therefore, we conclude that the scheduled photovoltaic system has a simple structure and good economic effect. It is worthy of recommendation. The unscheduled photovoltaic system is more stable than the scheduled photovoltaic system, but it is more expensive. The configuration of batteries is the key to its economic performance.

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