

10.65231/ijmr.v2i2.130

Stochastic Process in the Concentrating System of a Solar Power Plant for Greenhouse Agriculture

Jian Liu

Belarusian National Technical University, 220013, Minsk, Belarus

KEYWORDS

ABSTRACT

*Greenhouse farming;
Photovoltaic system;
Stochastic processes;
MATLAB simulation;*

Agricultural greenhouses are usually located in the suburbs or remote areas away from towns, and generally speaking, the cost of transmission and power supply is high, and some remote areas do not even have electricity supply. However, traditional greenhouses contain many different electrical equipment and facilities, and a stable power supply is essential for the normal, economical and efficient operation of the greenhouse. Modern agricultural greenhouses also need to be equipped with complete lighting systems, temperature and humidity control systems, ventilation systems, carbon dioxide concentration control systems, irrigation sprinkler systems, etc., which are difficult for traditional greenhouses to achieve smoothly. Traditional greenhouses are usually covered with plastic film, which usually needs to be replaced every year, and the discarded plastic film does not meet the requirements of energy conservation and environmental protection. The problem of "thermal insulation" in greenhouses has also been plaguing greenhouse growers. From the perspective of planting cycle, traditional greenhouses are generally only planted twice a year, and the economic benefits are limited.

1.Solar Power Systems: Background and Significance

1.1.Background of solar power generation system

Energy has always been the driving force and source of the survival and development of human society. With the continuous development and progress of society, fossil energy reserves are also increasingly depleted. According to official statistics, China imported 150 million tons of crude oil last year alone. At the current rate of consumption, China's existing energy reserves can only last for 50 years at most. Fortunately, with the continuous advancement of science and technology, mankind has discovered a variety of new energy sources such as nuclear energy, geothermal energy, tidal energy, wind energy, and solar energy. Under the limitations of fossil energy and the pressure of environmental protection, countries around the world have stepped up their efforts to support the development and utilization of these green renewable energy sources.

Under the limitations of fossil energy and the pressure of environmental protection, most countries in the world have increased their support for the development of green new and renewable energy. Especially since the beginning of the 21st century, the demand for energy in countries around the world has been growing. The installed capacity of renewable energy power generation in Germany, Denmark and other countries has reached a high level. In order to promote the development of renewable energy, countries not only continue to increase investment in the research and development of renewable energy technology, but also take measures at the legislative and policy levels to support the development and utilization of renewable energy and accelerate its development, making it an important alternative energy source for energy diversification, climate change and sustainable development.

Considering many factors such as energy supply, solar energy is undoubtedly an ideal green energy source for sustainable development. At the same time, solar energy is about to become one of the most important energy sources in the 21st century. Solar energy is the energy radiated by the sun into space, which is the energy produced by continuous

* Corresponding author. E-mail address: liujianwork163@gmail.com

Received date: February 01, 2026; Revised manuscript received date: February 10, 2026; Accepted date: February 20, 2026; Online publication date: February 28, 2026.

Copyright © 2026 the author. This is an open access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>).

Research Article

nuclear fusion reactions inside the sun. The solar energy that reaches the Earth's surface is about $82 \times 100,000$ kilowatts, and the energy density is about 1 kilowatt/square meter. Solar power generation is mainly divided into thermal power generation and photovoltaic power generation. Due to its wide distribution, inexhaustible availability, safety and cleanliness, solar energy has gradually become an ideal new generation of renewable energy for mankind, and it is the energy that humans can ultimately rely on [1].

1.2. Importance of solar power generation system

Solar power generation is one of the important forms of solar energy utilization, which directly converts solar energy into electricity. Among the various power generation methods, photovoltaic power generation is the mainstream. Photovoltaic power generation converts the light energy that hits the solar cells directly into electrical energy output.

In order to encourage the development and utilization of solar technology, governments around the world have actively formulated various preferential policies to promote the development of solar photovoltaic power generation. In 1996, with the support of the U.S. Department of Energy, the U.S. government launched the "Photovoltaic Building Program" with an investment of \$2 billion. In 1997, the U.S. government took the lead in announcing the launch of the "Million Solar Roof Program". In 2002, the total production capacity of photovoltaic cells in the United States reached 112.9 megawatts. The plan aims to reduce the cost of electricity generation to 7.7 cents per kWh by 2010, reduce CO₂ emissions by 3.511 million tons per year and create 71,500 new jobs. The program is currently approved by the California Department of Implementation[2]. The Japanese government announced the "Sunshine Plan" as early as 1974 and proposed the "New Sunshine Plan" in 1993, aiming to promote the comprehensive and long-term development of solar energy research programs. Japan has successively issued a series of regulations on incentives for the research and application of renewable green energy such as solar energy, which has greatly promoted the development and application of Japan's photovoltaic industry. In 2002, Japan's total photovoltaic cell production reached 254 megawatts, ranking first in the world with a growth rate of 48.6%. It is planned that by 2010, more than half of the new residential roofs will be equipped with photovoltaic solar systems. The

German government is one of the first and most active countries in the world to advocate and encourage photovoltaic applications [3]. In 1990, the German government took the lead in launching the "Thousand Roof Solar Program". In 1993, Germany took the lead in implementing the "Thousand Roofs Plan" supported by government investment and approved by power companies, and expanded to the "Rooftop Photovoltaic Plan" in 2001. In 1998, the German government further proposed the "100,000 PV Roof Plan" and developed dedicated PV modules integrated with buildings. The "100,000 solar roofs plan" was implemented in January 1999. The Renewable Energy Act promulgated by the German government came into force on April 1, 2000. In addition, Italy, India, Switzerland, France, the Netherlands, and Spain have similar programs and are investing heavily in technology research and development and accelerated industrialization [4].

From a global perspective, photovoltaic power generation has completed the initial research and development and large-scale application demonstration stage, and is currently developing in the direction of mass production and large-scale application. It has evolved from a small power supply to today's grid-connected power generation to serve the public power system. Its range of applications also covers almost all areas of electricity consumption. In addition, photovoltaic centralized power generation and photovoltaic buildings have developed rapidly and gradually become the main force in the market.

1.3. Overview of solar power generation system

Solar power generation systems are a new type of power generation system that uses the photovoltaic effect of semiconductor materials to directly convert solar radiation energy into electricity. The so-called photovoltaic effect refers to the phenomenon that after an object absorbs light energy, the distribution state and concentration of non-conductive carriers inside it change, resulting in current and electromotive force.

A key component of this technology is the solar cell. Solar cells can be encapsulated and protected in series to form a large area of solar cell modules. Combined with power controllers and other components, photovoltaic power generation devices can be formed. The advantage of photovoltaic power generation is that it is less geographically restricted because the sun shines on the earth;

Photovoltaic systems also have the advantages of safety and reliability, no noise, low pollution, no fuel consumption, no need to erect transmission lines, local power generation, and short construction period.

Light energy conversion equipment, or photovoltaic cells, is a device that uses the photovoltaic effect to convert light energy into electricity. At present, the photovoltaic conversion devices widely used in photovoltaic power generation projects are mainly silicon photovoltaic cells, including monocrystalline silicon, polycrystalline silicon and amorphous silicon cells. The production technology of monocrystalline silicon photovoltaic cells has matured and has entered the stage of large-scale industrial production. Now we use crystalline silicon as an example to describe the photovoltaic power generation process. As shown in Fig. 1, N-type silicon is obtained after phosphorus doping of P-type crystalline silicon to form PN junctions. When the light hits the surface of the photovoltaic cell, some photons are absorbed by the silicon material. The energy of the photons is transferred to the silicon atoms, causing electrons to transition into free electrons, which collect on either side of the PN junction, creating a potential difference. When the external circuit is turned on, under the action of this external voltage, the current will flow through the external circuit to produce a certain output power.

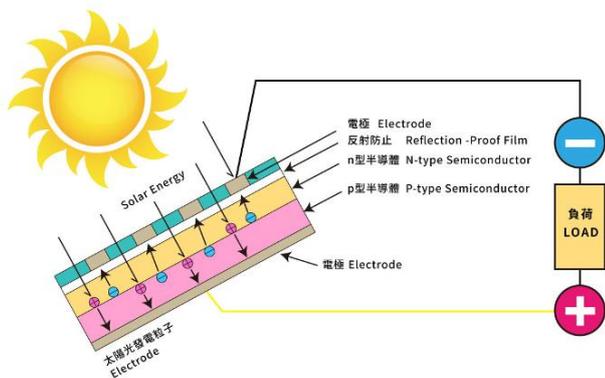


Fig.1. Principle of the photovoltaic effect

2. Modeling and simulation of solar power generation systems

2.1. Solar array modeling

The basic characteristics of solar cells can be expressed in terms of the relationship between current and voltage. The relationship between current and voltage also depends on a range of other parameters, especially those related to the

intensity of sunlight on the solar cell surface and the temperature of the cells. Figure 2 shows the equivalent circuit of an ideal photovoltaic cell.

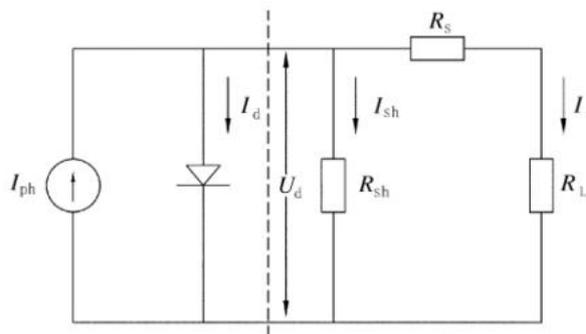


Fig.2. Photovoltaic cell equivalent circuit

It consists of series and parallel resistors, diodes, and photo-generated current sources. I_{ph} is the photogenerated current. When the light intensity is constant, it can be equivalent to a constant current source because the photogenerated current does not change with the working state of the photovoltaic cell. When the two ends of the photovoltaic cell are connected to the load, the voltage at the load side acts on the PN junction, generating a current I_L opposite to the direction of the photogenerated current. The series equivalent resistor R_s represents the obstruction of current flow in the battery, and its value depends on the PN junction depth, semiconductor material purity, and contact resistance [5]. The larger the series resistance, the greater the line loss, and the lower the output efficiency of the photovoltaic cell. The bypass resistor R_{sh} is inversely proportional to the battery's floor leakage current. The relationship between the output voltage and current of the photovoltaic array is as follows:

$$I = I_{ph} - I_D \left(e^{\frac{q(U+I R_s)}{A k T}} - 1 \right) - \frac{U + I R_s}{R_{sh}}$$

In the formula, A is the ideal coefficient of the diode, the Boltzmann constant $k=1.38 \times 10^{-23} \text{ J/K}$, $q=1.6 \times 10^{-19} \text{ C}$ is the electron charge; θ is the temperature, R_{sh} and R_s are the parallel and series resistances, respectively. Since the photogenerated current I_{ph} is proportional to the instantaneous light intensity of the photovoltaic cell E_{TP} , A will change +0.1% with increasing temperature when the temperature zero point is 298K (25) [6]. Therefore:

$$I_{ph} = 5.46 \times 10^{-3} E_{TP} [1 + 0.001(T - 298)] \tag{3-2}$$

Assuming $E = 100 \text{ Mw/cm}^2$ the temperature of the entire unit is 30°C higher than the air temperature. Find the temperature expression of the device:

$$T = T_a + 0.3E_{TP} \times 1000 \tag{3-3}$$

By establishing the equation system through the above formula, the ideal output characteristics of the photovoltaic array can be obtained.

Establish a simulation model based on the equivalent circuit of photovoltaic modules. Figure 3 shows the packaging model diagram of photovoltaic modules.

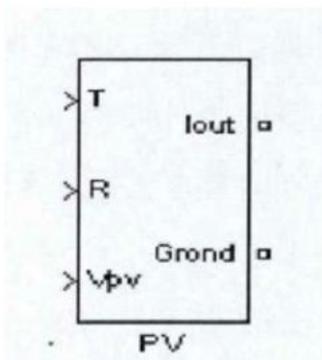


Fig.3. Photovoltaic cell packaging model diagram

In the above figure, T is the battery temperature, R is the light intensity, and V and I are the output voltage and output current of the photovoltaic array, respectively. This is a universal PV module packaging model. By inputting different parameters inside the component, the I-V characteristics and PV characteristics under different conditions can be simulated. Fig. 4 shows the simulation model of the output characteristics of photovoltaic modules [7].

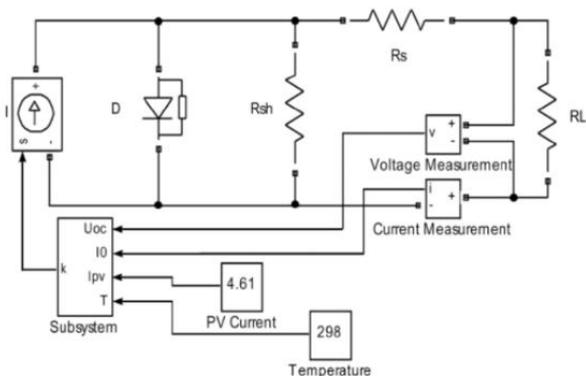


Fig.4. Solar PV module simulation model

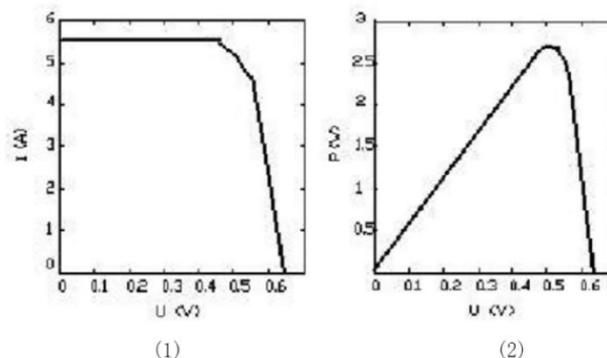


Fig.5. SOutput characteristic curve of a photovoltaic array
The photovoltaic cell model was simulated using the MATLAB environment. At this time, the light intensity is 100Mw/cm² and the atmospheric temperature is 25°C. As shown in Fig. 5, curve 1 is the simulation result of the output voltage-current characteristics of the photovoltaic array, and curve 2 is the simulation result of the output power-voltage characteristics of the photovoltaic array [8].

2.2. Analysis of solar greenhouse power generation technology

There are many types of traditional greenhouses, which can be classified according to roof truss material, lighting materials, appearance and heating conditions, such as: plastic greenhouse, Boer greenhouse; single-body greenhouse, multi-span greenhouse; single-roof greenhouse, multi-storey greenhouse; heated greenhouse, unheated greenhouse, etc. The typical structure is shown in Fig. 6 [9].

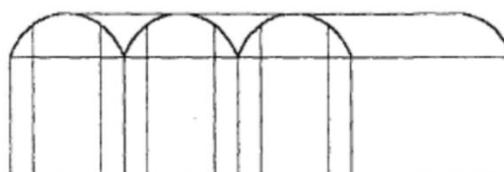


Figure.6. Typical structural form of a traditional greenhouse
The disadvantages of traditional greenhouses are as follows: Not suitable for long-term use, Greenhouses covered with plastic film usually need to be replaced every 1 to 2 years, which increases maintenance costs. At the same time, the replaced and discarded plastic film will cause secondary pollution and does not meet the requirements of energy conservation and environmental protection. Various environmental parameters in the greenhouse are controlled to prevent plants from growing too slowly. Traditional greenhouses have poor control over

parameters such as temperature, humidity, and light, which affects the growth rate of plants. The temperature in the greenhouse in summer is too high, which prevents many vegetable varieties from growing properly. Poor greenhouse insulation performance in winter also affects the cross-season growth of many crops [10].

High energy consumption and poor environmental performance. Greenhouses are an important means for farmers to increase their yield and income. However, many parts of China have large temperature differences throughout the year, as well as large temperature differences between day and night. In order to ensure the normal growth of various crops, a variety of methods need to be used for constant temperature control. When the temperature is low in winter, some areas use the method of burning coal in the greenhouse to heat up, but this not only consumes resources but also pollutes the environment; When the temperature is high in summer, it is necessary to cover the greenhouse with a sunshade net and ventilate it with a fan. In remote areas, there is a lack of mains electricity, and the power supply of various equipment in the greenhouse mainly relies on diesel engines, which consumes both traditional resources and lacks environmental performance.

In view of the many shortcomings of traditional greenhouses, the introduction of solar power generation technology into the greenhouse system can not only solve the power supply problem of greenhouses and increase yield, but also establish an image of energy conservation and environmental protection, and shape the ecological and environmental protection concept of new modern agricultural vegetable greenhouses [11].

With the development of building-integrated photovoltaic (BIPV) technology, photovoltaic power generation systems are combined with greenhouses to give full play to the advantages of photovoltaic systems and make up for various defects and shortcomings of traditional greenhouses.

When the photovoltaic power generation system is combined with the greenhouse, it not only provides the required electricity for the greenhouse, but more importantly, the photovoltaic power generation system is fully integrated into the architectural design concept of the greenhouse. Its functional parameters are indispensable for greenhouses and are also an important part of building a new concept of green ecology.

The photovoltaic modules used in photovoltaic greenhouses need to be integrated into the greenhouse building materials,

completely replacing the original building materials, rather than simply being attached to the original building. From a structural point of view, photovoltaic modules comply with various building codes, and many factors such as technology, practicality, aesthetics and safety are fully considered at the beginning of planning and design.

Photovoltaic modules need to have light transmission. While they generate electricity, they need to ensure that greenhouse plants receive the necessary light and block some of the harmful light, such as ultraviolet rays. Photovoltaic systems can ensure the light intensity and duration required by plants, promote the growth of various plants in the greenhouse, and increase their growth rate. In addition to powering various conventional and automated monitoring facilities in the greenhouse, the photovoltaic system can also provide LED auxiliary lighting to promote plant growth and solar energy for various insect repellent and insecticidal facilities.

Photovoltaic greenhouses need to have the characteristics of heat preservation, ventilation and convenience. On the one hand, the photovoltaic module itself can block part of the excess sunlight from entering the greenhouse, play a role in shading and energy saving, make the greenhouse warm in winter and cool in summer, suitable for plant growth; On the other hand, photovoltaic modules can convert the received solar energy into electricity required for greenhouses, playing a green, environmentally friendly, economical, and efficient role. Since the greenhouse itself has requirements for ventilation, light transmission and other functions, photovoltaic greenhouses need to meet the needs of ventilation irrigation, spraying, heat dissipation, sealing and insulation, temperature and humidity regulation, carbon dioxide concentration adjustment, plant pollination and natural ecology.

Photovoltaic greenhouse systems must be efficient and economical. It not only powers various necessary facilities in the greenhouse, but also meets the daily electricity needs of greenhouse growers. For large-scale photovoltaic vegetable greenhouses, it can not only solve their own electricity problems and save related costs, but also transmit excess electricity to the national grid. In addition to the original agricultural greenhouse construction subsidies and related agricultural subsidies, you can also enjoy national and local government subsidies, such as photovoltaic power generation subsidies for distributed photovoltaic power plants and income from electricity sales to power companies. In addition, photovoltaic greenhouses have good energy

conservation and emission reduction effects and high environmental benefits. They avoid environmental pollution caused by the use of traditional energy sources and reduce the cost of emission reduction, pollution control and environmental protection. Its economic, environmental and social benefits are very considerable. At the same time, photovoltaic greenhouses can also be built into modern agricultural ecological demonstration parks integrating production, environmental protection, demonstration education and tourism. The photovoltaic greenhouse is designed to have a service life of not less than 25 years, high quality and good safety [12].

According to the geographical location, regional characteristics and functional needs, as well as the scale and form of photovoltaic greenhouses, photovoltaic greenhouses can be divided into the following categories:

Independent photovoltaic greenhouse: In areas where power supply is insufficient or non-existent, small greenhouses often use freestanding photovoltaic greenhouses. Its working principle is shown in Figure 7.

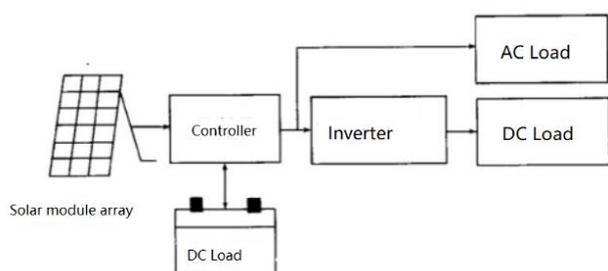


Figure.7. Schematic diagram of an independent photovoltaic greenhouse

The system is mainly composed of transparent photovoltaic modules, photovoltaic controllers, batteries, off-grid inverters, etc. The photovoltaic module converts sunlight into direct current, and the photovoltaic controller controls the charging and discharging of the cells. The PV controller can directly provide DC power output to the greenhouse DC load, or convert the DC power into 380V/220VAC AC power through an off-grid inverter to power the greenhouse AC load.

Grid-connected photovoltaic greenhouse: In areas with electricity, photovoltaic greenhouses are usually grid-connected. Grid-connected photovoltaic greenhouses can be divided into 380V low-voltage side grid-connected type and grid-connected type that is boosted to 10KV, 35KV or higher voltage levels by step-up transformers according to different voltage levels at grid-connected points. Considering

the application characteristics of photovoltaic greenhouses, their structural forms generally include single photovoltaic greenhouses and combined photovoltaic greenhouses, and the roof forms are oblique ridge and zigzag. Taking a zigzag roof photovoltaic greenhouse as an example, its structure is shown in Fig. 8 and Fig. 9 [13].

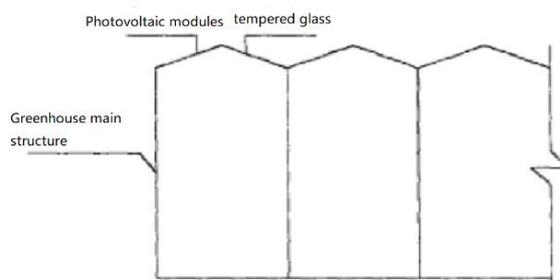


Figure.8. Photovoltaic greenhouse height

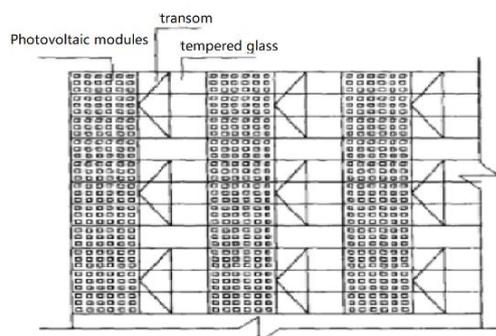


Fig.9. Floor plan of the photovoltaic greenhouse

Photovoltaic translucent modules are installed on each southern slope of the zigzag roof, which can be arranged continuously or at intervals as needed; The north slope is fitted with traditional tempered glass and is equipped with beamed windows. Photovoltaic modules can not only replace the original building materials, but also serve as power generation units to achieve true photovoltaic building integration.

The greenhouse roof structure needs to comprehensively consider factors such as structural weight and strength, pay attention to lightweight, comply with local climatic conditions, and meet relevant design specifications. The installation combination of photovoltaic modules and greenhouse structures mainly adopts aluminum profile open frame structures [14].

The photovoltaic modules installed in the greenhouse must first meet the various building and technical specifications related to the greenhouse, as well as the technical specifications of the photovoltaic system itself. Depending on the installation site, wind and snow loads will vary, and

the strength requirements of the components will also vary. For areas with large wind and snow loads, thicker double-glazed transmitting modules are usually used as needed; For areas with low wind and snow loads, thinner double-glazed translucent components can also be used. Single-layer glass + transparent TPT modules are also a viable option. The cell type can be crystalline silicon or thin-film cell. The structure of the greenhouse photovoltaic module is shown in Figures 10 and 11.

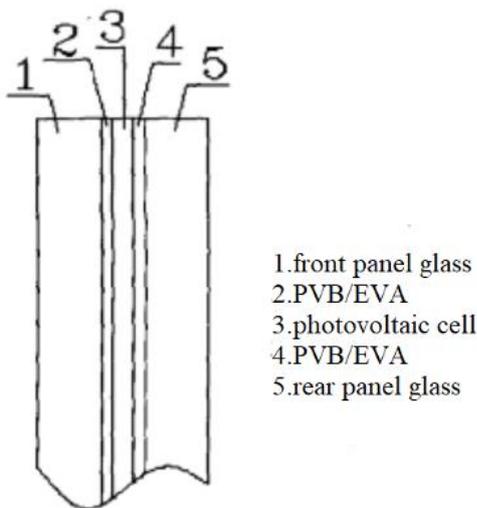


Fig.10. Double-layer clear glass photovoltaic module

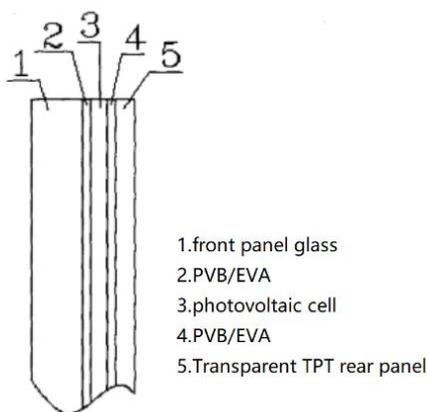


Fig.11 Single-layer transparent glass photovoltaic module.

One of the characteristics of double glazing components is light transmission, so different light transmittance can be customized according to the lighting needs of greenhouses and different plants. For crops, the 400~520nm (blue light) and 610~720nm (red light) bands in the solar spectrum are more suitable for plant growth. The relationship between solar spectra and plant photosynthesis is shown in Figure 12 [18].

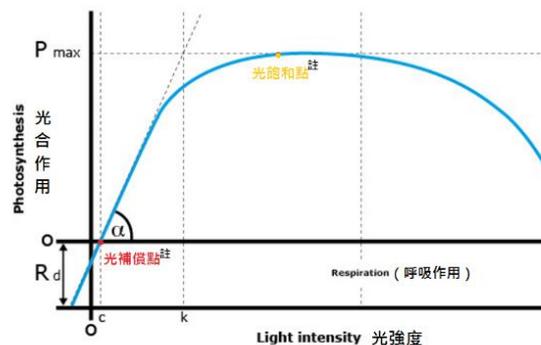


Fig.12. Relationship between solar spectra and plant photosynthesis

Here are the photovoltaic modules designed according to the demand of crops for the solar spectrum: For double-glass modules using thin-film photovoltaic cells, thin-film cells have good spectral characteristics and are able to transmit visible light from 400 to 800 nanometers. They can effectively block UV and infrared rays, preventing UV rays from causing damage to plants during the day. In addition, they prevent overheating in the greenhouse and prevent indoor infrared rays from radiating outward at night, providing good thermal insulation. Thin-film cells have good light transmission and can be customized with any percentage of light transmittance according to needs. At present, the light transmittance of commercially available light-transmitting thin film modules is 10%, 20%, and 30% [19].

For double-glass modules using crystalline silicon photovoltaic cells, they cannot promote plant growth by increasing the sun's spectral transmittance due to their lack of spectral properties. Crystalline silicon photovoltaic cells have the advantages of high power generation efficiency, low cost of W_p modules, and high installed capacity per unit area. Its light transmittance can be adjusted and customized as needed without affecting the light needs of the plants. The following example illustrates the design selection process.

Conclusion

This paper analyzes the principle and structure of photovoltaic power generation system to complete the modeling and simulation of photovoltaic power generation system. In the MATLAB/SIMULINK simulation environment, based on the IV mathematical function relationship of photovoltaic cells, the working principle of solar cells is analyzed, the simulation model of photovoltaic

cells is established, and the output characteristics of photovoltaic cells under different light intensities and temperatures are studied and analyzed. The simulation results verify that the output characteristics of photovoltaic cells are nonlinear, and change with the change of external environment. The main circuit of the photovoltaic power generation system is modeled.

At present, the efficiency of photovoltaic power generation systems is still not ideal and needs to be further improved. Therefore, it is imperative to enhance the application functionality of the system. If the functions of grid-connected power generation, independent control, seamless switching of grid-connected/independent working modes, multi-machine parallel connection, and multi-machine group control are integrated, it can be flexibly combined into various application systems, making them more versatile and multi-functional, thereby improving system efficiency. In recent years, photovoltaic power generation technology has become the focus of global attention, and photovoltaic power generation systems have been applied on a large scale at home and abroad. Although this paper conducts in-depth research on some key problems of photovoltaic power generation system through theoretical analysis and simulation, there are still many problems that need to be solved urgently.

REFERENCES

- Zhang, X., & Cao, R. (2021). Photovoltaic grid-connected power generation and its inverter control. *Photovoltaic Grid-Connected Power Generation*, (3), 16-17.
- Ren, X. (2021). Solar photovoltaic power generation engineering technology. *Solar Photovoltaic Power Generation*, 16(4), 35-37.
- Zhao, Z. (2020). Solar photovoltaic power generation and its application. *Solar Photovoltaic Power Generation Applications*, 23(4), 103-105.
- Yang, G., Qiang, S., Zhang, Y., & Zheng, Y. (2021). Solar photovoltaic power generation system and its application. *Solar Photovoltaic Power Generation System*, 19(2), 31-38.
- Wang, D. (2018). Solar photovoltaic power generation technology and system integration. **Solar Photovoltaic Power Generation Technology*, (127), 44-48.
- Li, C., & Yang, X. (2020). Solar and wind energy grid connection technology. **Solar Power System*, (8), 76-113.
- Cui, R., Zhao, C., & Wu, D. (2021). Grid-connected photovoltaic power generation system. **Grid-Connected Photovoltaic Power Generation System Technology*, 27*(1), 5.
- Zhou, Z., & Ji, A. (2019). Design and construction technology of off-grid solar power system. **Solar Power Generation System Design*, (8), 22.
- Lu, M., Cen, H., & Guo, T. (2021). Research on the optimal allocation of greenhouse composite energy supply. **Research on Agricultural Mechanization*, (1)(215), 66-69.
- Liu, K., Feng, L., & Yang, W. (2017). Greenhouse microclimate characteristics and their relationship with macroclimate. *Acta Meteorological Society*, 24.
- Liu, Y. (2011). Modeling and simulation of photovoltaic grid-connected power generation system. *Power Generation System Modeling*, 24.
- Pugachev, V. S. (2020). Grid-connected control technology for photovoltaic power generation. *CNKI*, (17), 183-215.
- i China PV Power Application. (2022, September 26). Retrieved September 26, 2022, from <https://take-profit.org/statistics/imports/china/>
- Irwin, D. A. (2021). Operation control strategy of three-phase grid-connected photovoltaic power generation system. *World Development*, (139), 105-106.
- Zhou, X., Guo, R., & Ma, Y. (2021). Control technology of photovoltaic grid-connected power generation system. *Control Technology*, 30(6), 15-27.
- Wu, C., Zhang, J., & Chen, Y. (2020). Time solar photovoltaic grid-connected power generation and lighting system. *Lighting System*, (3), 29-36.
- Wang, Z., Wang, R., Shi, T., & Wu, F. (2018). Modeling and simulation of grid-connected photovoltaic power generation system. *Rural Electrification*, 8(2), 95-108.
- Lai, S. (2021). Research on the optimal allocation of greenhouse composite energy supply. *Research on Agricultural Mechanization*, (7), 16-20.
- Li, Y. (2017). Greenhouse microclimate characteristics and their relationship with macroclimate. *Meteorology*, (11), 61-65.