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ORIGINAL RESEARCH ARTICLE

The integration of traditional agriculture and new energy gives birth to a new model of green development

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ABSTRACT

Under the background of China's double-carbon policy and global climate change, the organic combination of photovoltaic and agriculture has given birth to a new mode of integrated development of traditional agriculture and new energy. This paper summarizes the research and development progress in the field of photovoltaic + agriculture in China from the aspects of the concept of photovoltaic technology, the combination of photovoltaic with agricultural production, and the application of photovoltaic in agricultural production. The research shows that the development of photovoltaic technology has reduced the consumption of non-renewable energy to a great extent, which has brought great advantages to energy supply and green organic agricultural production. Future research can deepen the construction of a perfect and idealized photovoltaic + agriculture model from the theoretical system of photovoltaic combined with agriculture.

Keywords: photovoltaic technology; agricultural production; photovoltaic agriculture; agricultural light complementary

With the continuous progress of urbanization and the new problems of carbon neutralization and carbon emission reduction, global warming and the gradual depletion of non renewable energy have become an unavoidable problem for mankind. The general trend of carbon neutral energy development is to vigorously promote the decarbonization and zero carbonization of power and fuel on the energy supply side, as well as the efficient, re-electrification, and intelligence of energy utilization on the energy demand side through energy reform, so as to build a new power system with new energy as the main body[1]. As a renewable energy source, solar energy has the characteristics of being green, clean, and safe. As a common form of solar resource utilization, solar photovoltaic power generation has been widely recognized and applied all over the world. In the long process of development, it has continuously improved material technology, transportation technology, and production technology so as to promote the cross application of solar photovoltaic technology and other fields. As the largest industry in China, agriculture also has quite a lot of research results in the field of combination with photovoltaic. Under the requirements of China's carbon peak and carbon neutralization, solar photovoltaic technology is bound to be vigorously developed in the agricultural industry. The

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development mode of "photovoltaic + agriculture" will have far-reaching significance for China's green development sustainability and rural revitalization[2].

1. Photovoltaic technology

"Photovoltaic power generation" is generally a modern power generation technology that converts solar energy into electric energy by relying on electronic components such as a solar cell array, battery pack, controller, and inverter according to the principle of the photovoltaic effect. The schematic diagram of a solar photovoltaic power generation system is shown in **Figure 1**. "Photovoltaic" is the abbreviation for solar power generation systems. The whole photovoltaic power generation system has the advantages of convenience and environmental protection[3]. The photovoltaic technology involved is a comprehensive discipline of technology formed by the integration of new materials, new energy, photoelectric technology and chemical technology. Generally, due to the low utilization rate of solar thermal power generation technology, solar photovoltaic power generation technology is more commonly used.

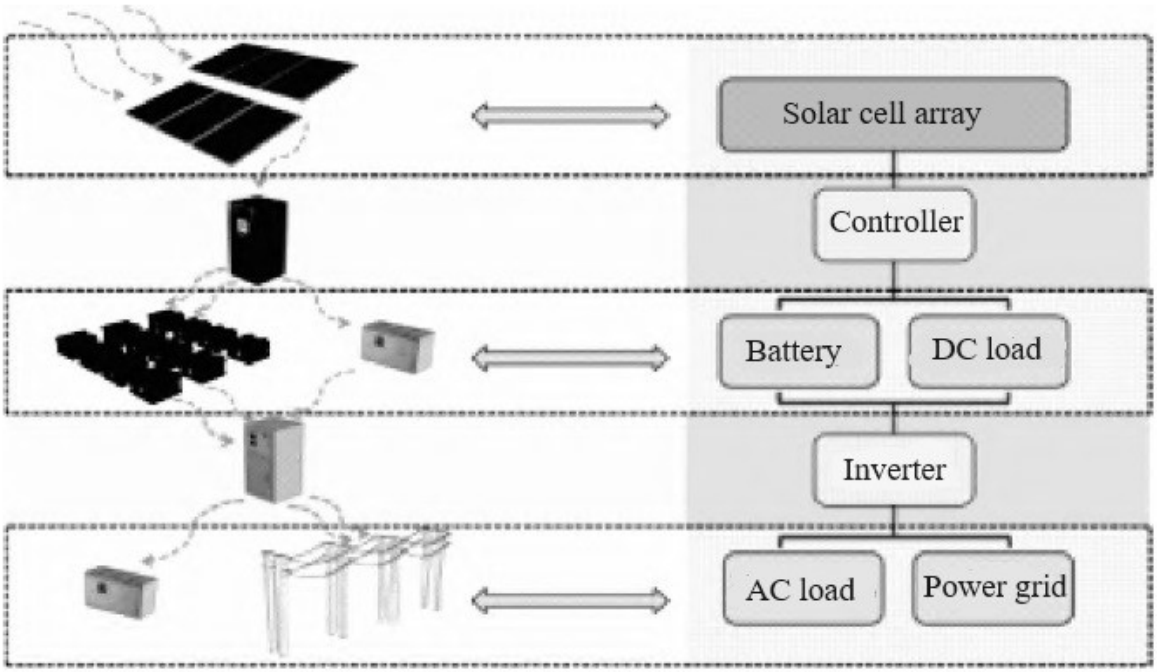

Figure 1. Schematic diagram of solar photovoltaic power generation system.

1.1. Development overview

Photovoltaic power generation technology can be traced back to the photovoltaic effect in 1839, but it was not until 1954 that three scientists in the United States jointly developed the world's first crystal solar cell, which announced the initial maturity of human solar technology[4]. This technology has been researched and developed for more than 100 years since it was put forward. It not only gave birth to a new technology, but also formed a new market. With the development of photovoltaic power generation technology, there are many solar cell modules with different materials and different specifications. At the same time, in order to improve the utilization of power generation, its power generation and transportation mode is also progressing. According to statistics, the worldwide output of solar photovoltaic modules will reach 40 GW·h, and its power generation will also reach 274 tw·h. However, the total amount of photovoltaic power generation only accounts for 1% of the total global power generation. Due to the impact of the development trend of photovoltaic power generation technology, solar power generation will increase significantly in the world in the next 20 years,

accounting for about 21%[5]. By combining the relevant research literature on photovoltaic technology, the author roughly summarizes photovoltaic power generation into several categories, so as to pave the way for a further review of photovoltaic power generation technology combined with agricultural production.

1.2. Classification of solar cells

1.2.1. Crystal solar cell

The first generation of solar cells is crystalline solar cells. At present, the mainstream development direction of the photovoltaic industry is single crystal or polycrystalline Si solar cells in crystalline solar cells. With the promotion of renewable energy demand, the structure of solar cells has been continuously optimized, which has greatly increased the efficiency of solar cells. In this field, Professor Green of Australia led his research team to carry out a series of optimization technologies to keep the efficiency of single crystal Si solar cells in the leading position in the world. However, single-crystal Si solar cells still have the defect of high production costs, and their development is also facing severe challenges. Therefore, polycrystalline Si solar cells came into being and developed rapidly.

1.2.2. Second generation thin film photovoltaic material solar cells

Reducing production costs has always been an unchanging issue for the solar energy industry. Under this requirement, second-generation thin-film solar cells with both efficiency and stability are fabricated by depositing various thin-film photovoltaic materials on the substrate surface of a series of low-cost materials and using the thin-film as the light absorption active region. This will undoubtedly greatly reduce the production cost of solar cells. For example, CIGS photovoltaic cells have the advantages of low carbon emissions, high photoelectric conversion efficiency and environmental friendliness. They can be used in building envelopes instead of traditional building materials[6].

1.2.3. The third generation of idealized solar cells

The third generation of solar cells needs to be innovated in design ideas, battery materials, and process manufacturing so as to create a new generation of photovoltaic modules. Compared with the previous two generations of solar cells, they should have the idealized advantages of being green, high efficiency, long service life, reliability, and low cost. However, due to the development of traditional photovoltaic technology and new materials, the current solar cells still cannot effectively make full use of nearly 50% of the infrared photon energy on earth. The technological innovation of solar cells has encountered a bottleneck that needs to be broken.

1.3. Current transmission mode

In terms of the current transmission mode, photovoltaic power generation is further refined into independent photovoltaic power generation (off-grid photovoltaic power generation) and distributed photovoltaic power generation. The off grid type is equipped with a storage battery, which is a photovoltaic power generation system that can operate independently. Distributed refers to a small-scale photovoltaic power generation system that can meet the needs of special users and support the economic operation of a distribution network. It also has certain requirements for the solar radiation environment. However, at present, grid-connected photovoltaic power generation technology has obvious advantages. It not only saves on construction and maintenance costs but also reduces power generation costs and promotes the diversified development needs of photovoltaic power generation technology[7].

1.4. Composition of power generation energy

In addition to the different solar cells and current transportation modes, photovoltaic power generation also has different composition modes in terms of power generation energy. The power generation system has evolved from the initial solar photovoltaic system to the "hybrid photovoltaic power generation system". Compared with a single solar power generation system, it can further improve the reliability of power generation technology and reduce energy waste. "Hybrid photovoltaic power generation system" means that the composition of power generation energy is not only solar energy. It introduces other available energy into the power generation system so as to effectively deal with uncontrollable factors such as extreme weather and maintain the stability of the power generation system. Among them, "hybrid photovoltaic + wind power generation system" refers to the integration of two different renewable energy power generation systems, wind power generation and photovoltaic power generation, which reduces the energy loss caused by the non-synchronization of solar energy resources and wind energy resources to a certain extent. This power generation system makes the power operation more stable and reduces the dependence of photovoltaic power generation systems on the natural climate. "Solar thermal power generation system" is a kind of collection of thermal energy resources generated by solar energy during the operation of photovoltaic power generation technology. This technology mainly generates power by storing thermal energy. Different from the investment of other technologies, the idealized solar thermal power generation system can be popularized economically on a large scale. On this basis, some researchers have integrated wind power generation and solar thermal power generation to improve the defects of photovoltaic power generation systems or find more effective ways of power generation technology. At the same time, there is also a hybrid power generation system that introduces a photovoltaic power generation system and an electric heater into the above hybrid power system to promote the consumption of new energy. The existence of an electric heater converts excess wind and light energy into thermal energy storage and uses the good scheduleability and controllability of the power station to improve the consumption of new energy[8]. It can be said that through the combination of different energy sources, the hybrid power generation mode effectively controls the load power shortage rate of photovoltaic power generation.

To sum up, the development of photovoltaic technology can directly convert solar energy into electric energy. As a new energy, it has the characteristics of being non-toxic, harmless, healthy, and green, and it meets the requirements of China for sustainable development. The progress of photovoltaic technology has had a great impact on the agricultural production industry. According to the research, it can effectively solve the problems of resource shortages and green production in agricultural production[9].

2. Photovoltaic integrated agricultural production

In the research field, research on the application of solar energy in agricultural production in relevant laboratories can be traced back to the 1960s. The relevant foreign laboratories have studied such contents as air conditioning and agricultural products. The birth of photovoltaic technology has enabled the rapid integration of solar photovoltaics and agriculture. In 1975, the photovoltaic water pump opened the era of the integration of photovoltaic and agriculture, and the standard of photovoltaic integrated agriculture has gradually moved towards modularization and refinement[10]. In general, photovoltaic agriculture is a new industrial model in China. Under this model, the industrial model can be integrated and developed by combining advanced photovoltaic technology and agricultural production technology. It not only includes the operation and management of agriculture but also covers agriculture, cultural tourism, and rural landscape construction[11].

2.1. Development of photovoltaic agricultural production abroad

The research on photovoltaic agriculture abroad mainly focuses on the way of combining photovoltaic with agriculture, the installation mode of photovoltaic modules, and power generation efficiency. The early application research of photovoltaic in agriculture began with the development of aerospace technology. In the early 1980s, the research center of NASA carried out a prediction study on the application of photovoltaic power generation systems to the agricultural sector in the global market. Based on the measurement of energy, economy, solar energy resources, region and other factors, some respondents were selected to analyze the current marketing obstacles of photovoltaic agricultural products in the United States, and relevant plans were formulated[12]. In the later research on photovoltaic integrated agricultural production, scholars mainly focused on the obstacles to the application of photovoltaic systems in agriculture, which are limited to economic, institutional and social impacts. Subsequently, some foreign scholars have successively proposed that translucent or transparent photovoltaic panels can be used to increase the light input of agricultural greenhouses. However, according to the survey, even on sunny days, the blocking of photovoltaic modules will still reduce the temperature in the greenhouse.

2.2. Development of domestic photovoltaic agricultural production

In terms of photovoltaic systems combined with agricultural production, the earliest application of photovoltaic technology in agricultural production has improved land use in the field of agricultural irrigation. Wu and Liu[13] based on the western development strategy, faced with environmental deterioration in the northwest, developed the solar water lifting irrigation system according to local conditions according to different natural conditions in the region, which made full use of the rich natural resources in the West and ensured clean energy power for the development of agricultural production irrigation systems. With the continuous development of China's photovoltaic technology, based on the actual situation of China's photovoltaic technology and agricultural production development, scholars have successively put forward power generation systems such as agricultural light complementarity, fishery light complementarity and forest light complementarity. The cases of domestic agricultural light complementarity are shown in **Figure 2**, and the cases of domestic fishery light complementarity are shown in **Figure 3**. In combination with the current background of rural revitalization, agricultural light complementation has become a major boost to rural revitalization. For example, the agricultural photovoltaic power generation project in Liuwang Town, West Coast new area of Qingdao, which focuses on agricultural light complementation, adopts the modes of fishery light complementation and forest light complementation, and maximizes the use of agricultural facilities for power generation[14]. Based on the local reality, combined with modern photovoltaic technology and agricultural technology, the project has successfully set a model for other rural revitalization projects.

Figure 2. Domestic agricultural light complementary cases.

Figure 3. Domestic fishery light complementary cases.

Figure 4. Tomato production under solar panels in Dornbirn, Austria.

3. Application of photovoltaic in agricultural production

The application of photovoltaic technology in agricultural production has improved land use efficiency. For photovoltaic power generation, fertile agricultural land has been reserved. It has developed rapidly in the production and application of planting, forestry, and animal husbandry worldwide. The tomato production under the solar panels in Dornbirn, Austria, is shown in **Figure 4**, and the photovoltaic panels and sheep on Lanai Island, Hawaii, are shown in **Figure 5**. Peng Meiya of China put forward and summarized the characteristics of photovoltaic agriculture in 2012 and discussed the necessity of developing photovoltaic agriculture in his research. At that time, he summarized the application technologies of photovoltaic agriculture: photovoltaic greenhouses, photovoltaic pig farms, solar insect killing lamps and photovoltaic plant growth lamps[15]. After 2014, the development of photovoltaic agriculture has accelerated in China. Photovoltaic agricultural facility projects focusing on the construction of photovoltaic + agricultural technology have been carried out throughout the country. Correspondingly, photovoltaic agricultural industrial parks and photovoltaic agricultural bases have emerged. As a comprehensive agricultural production mode that can effectively protect the ecological environment and efficiently use energy, photovoltaic agriculture aims to use the existing photovoltaic agricultural technology to produce green organic agricultural products. On the other hand, photovoltaic agriculture has expanded tourism and urban ecology at the same time, which has brought far more value to society than the benefits brought by single agricultural production.

Figure 5. Photovoltaic panels and sheep on Lanai Island, Hawaii.

3.1. System application

As the earliest combination of photovoltaic and agricultural production, irrigation technology has been relatively mature. Wu's application of photovoltaic water lifting in the northwest and Sheng et al.'s[16] application analysis of a photovoltaic water pump system have contributed to the application of photovoltaic agriculture in irrigation. In the field of greenhouse systems, photovoltaic agricultural greenhouse systems mainly include two types: bracket type and flat type. The photovoltaic power generation module of the support greenhouse system is installed in the north of the greenhouse, while the photovoltaic module of the tile greenhouse system is installed on top of the greenhouse. The photovoltaic module needs to have a certain light transmittance to meet the growth needs of crops in the greenhouse[17]. However, such a mode also has some disadvantages. Translucent photovoltaic modules will reduce the efficiency of photovoltaic power generation.

3.2. Agricultural production automation

With the rapid development of Internet of Things technology in China, Internet of Things technology has greatly promoted the progress of agricultural production automation. Photovoltaic agricultural production greenhouses based on Internet of Things technology have gradually become a trend, and photovoltaic technology has also laid the foundation for the continuous improvement of agricultural automation levels. The realization of photovoltaic agricultural greenhouse automation depends on the collaboration of the Internet of Things. Its control system includes a photovoltaic power supply system, a monitoring module, a microcomputer processing center, a wireless network, etc.[18]. In agricultural production automation, farmers can monitor agricultural greenhouses at remote ports at any time, so as to enhance the level of agricultural production and reduce the pressure of agricultural production. On the basis of integrating the green and harmless advantages of photovoltaic technology, automated photovoltaic agriculture further combines the emerging Internet of Things monitoring and processing technology, which has great advantages over traditional agricultural greenhouses. It can not only effectively create an agricultural production environment but also control the real-time data of crop growth more accurately and scientifically.

4. Research review and development direction of new mode of agriculture + photovoltaic

4.1. Research review

- The richness of research focus and research level. "Photovoltaic + agriculture", as a new mode of green agriculture development promoted by the combination of traditional agriculture and new energy, is currently focusing on the development, classification, and energy composition of photovoltaic technology and its combination with traditional agriculture to explore the application scenarios and combination

modes of photovoltaic in planting, forestry, fishery, and agricultural production automation. From the perspective of the research and development process of the new mode of agriculture + photovoltaic, it has experienced from the birth of technology to classified development and finally to the close connection with the landing of agriculture, forming a diversified, rich level research trend from theory to practice.

- The synchronization between the research theme and the development of the times. Under the international and national policy background of "carbon neutrality" in 2021, vigorously promote power technology reform on the energy supply side through energy reform, making photovoltaic technology the focus of scholars. Based on the unchanging background of China as a large agricultural production country, the new energy brought by photovoltaic technology has become a major support for agricultural modernization. At the same time, under the task of comprehensively eradicating poverty, "photovoltaic poverty alleviation" may become one of the important means to realize agricultural modernization.

In conclusion, the advantages of photovoltaic technology have brought the supply of new energy and the conversion of green energy to agricultural production. Technological progress, the improvement of photovoltaic module performance and the reduction of production cost will promote the development of photovoltaic + agricultural industry. The combination of photovoltaic and agricultural industry has a very broad prospect. The proposed combination of photovoltaic agriculture, forestry, fishery and photovoltaic agricultural automation will present more typical cases in the future.

4.2. Development direction

- Focus on promoting photovoltaic technology innovation. Explore the topic of "three generations of ideal light" and summarize the new mode of V battery and photovoltaic hybrid power generation, improve energy utilization efficiency and reduce energy consumption during energy conversion. At this stage, the core of photovoltaic technology still lies in the photovoltaic effect. It relies on electronic components to convert solar energy into electric energy. In addition to the improvement of solar cells, the impact of different electronic components on the efficiency of photovoltaic power generation and the electric energy lost in the transmission process of different components need to be discussed. Photovoltaic power generation technology is relatively mature in energy transmission mode, and there are two energy transmission modes, grid connected and off grid. However, the situation in China is complex, and the environmental conditions in different regions are quite different. The existing energy transportation modes need to be further subdivided and innovated, corresponding to regions with different basic conditions that are conducive to the loss of energy during transportation and lay the foundation for building a new energy transportation network on a larger spatial scale.
- Innovate and develop green energy modes. Further deepening the development and research on the green and clean energy models is an unchanging topic in the development process of the times. It corresponds to China's all-round promotion of green planning, green production, green circulation and green construction, so that development is based on the efficient use of resources, strict protection of ecology, effective control of greenhouse gas emissions, and the carbon neutrality guidance for promoting China's green development. The research on energy mode of photovoltaic power generation system still has a long way to go. At present, the hybrid photovoltaic power generation mode with solar energy as the main energy and wind energy, thermal energy, photo thermal energy and other auxiliary energy as the auxiliary energy is one of the inevitable trends in the development of photovoltaic power generation technology. However, there are differences in the efficiency of hybrid power generation modes composed of different energy sources, which requires a comprehensive horizontal comparative study.
- Establish PV + agriculture logic system. Build a logical framework for the combination of agriculture and photovoltaic, and gradually form a research paradigm for the integrated development of agricultural

modernization and new energy. At present, the domestic research on agricultural PV is mainly focused on the application of agricultural production, and the construction of the theoretical level needs to be further discussed. And the current photovoltaic integrated agricultural industry model is still in the exploration stage. In future research, the integration of traditional agriculture and new energy still needs to break through the current bottleneck. At the same time, the development of PV combined with agriculture needs the support of a more perfect theoretical system. We should consider traditional agriculture in the domestic development process and integrate the system into the collaborative market, economy, planning, and even the environment to build a perfect and ideal PV + agriculture model.

5. Conclusion

The advantages of photovoltaic technology have brought the supply of new energy and the conversion of green energy to agricultural production. With the progress of science and technology, the improvement of the performance of photovoltaic modules and the reduction of production costs will promote the development of the agricultural industry. It can be seen that the combination of the photovoltaic and agricultural industry has a very broad prospect. The proposed combination of photovoltaic agriculture, forestry, fishery, and photovoltaic agricultural automation at this stage will show more relevant effects in the future. The current photovoltaic agriculture industry model is still in the exploration stage[17]. In future research, photovoltaic technology still needs to break through the current bottleneck. At the same time, the photovoltaic agriculture model needs more perfect theoretical system support, and the system will be integrated with collaborative markets, economies, planning, and even the environment to build a perfect and ideal photovoltaic + agriculture model.

Conflict of interest

The authors declare no conflict of interest.

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