Photovoltaic Agricultural Internet of Things Towards Realizing the Next Generation of Smart Farming

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ABSTRACT Serious challenges for to drive agricultural sustainability combined with climate crisis issues have induced an urgent need to decarbonise agriculture. In this paper, we briefly introduce a novel concept of the Photovoltaic Agricultural Internet of Things (PAIoT). This system approach fuses agricultural production with renewable power generation and control via an IoT platform. We discuss PAIoT applications and potential to realize the next generation of smart farming. In addition, we provide a review of key issues on the feasibility of PAIoT and further propose novel techniques to mitigate these key issues.

INDEX TERMS Photovoltaic agriculture, Internet of Things, smart farming.

I. INTRODUCTION

Agriculture is the basic industry which plays an important role in providing support for the construction and development of the national economy. Nowadays, there are three challenges for existing agricultural production as follows: 1) Impacts of climate variability and extreme weather on cereal production [1]; 2) The pressure on food supply as the global population grows [2]; 3) Land area decrease with urbanization [3].

With the increment of the global population and the improvement of people’s living standards, the power consumed also increases rapidly. However, traditional nonrenewable power sources (e.g., fossil fuels) are facing the dilemma of exhausted fossil source and serious greenhouse gas driven environmental pollution. This is driving a continuous search for effective alternatives to traditional power generation. Lately, with the reduction of photovoltaic panel manufacturing cost and the improvement of photoelectric conversion efficiency, photovoltaic power generation has been promoted and applied. Compared with different power methods, e.g., thermal power, hydropower, wind power, nuclear power, and so on, photovoltaic power generation is a highly attractive source of electrical energy, and it is renewable without associated GHG emissions.

In China, total power generation in 2018 was 7,111.77 billion kWh, with a year-on-year growth of 7.7%, i.e., 508.46 billion kWh [4]. If power generation increments are all powered by 10,000 kW photovoltaic plant projects (i.e., located in the area of 40° N, covering an area of 22.02 hectares per plant, 9.855 million kWh as the theoretical power generation per plant [5]), the total area of photovoltaic plants needed to be built is 11,360 square kilometers, which is 14.5 times the size of the land area of New York, USA (i.e., 784.0 square kilometers) [6]. In such case, the huge site area of photovoltaic plants will seriously invade farmland, resulting in a strong competitive relationship with agricultural production, thereby threatening the safety of food production. Then, triggered by addressing these identified critical issues, a new energy agriculture, i.e., Photovoltaic Agriculture (PA), has received extensive attention from governments and academic circles all over the world [7]–[16]. In this new production mode, the combination of both agriculture and energy can effectively alleviate the land competition and further create double incomes on one piece of land at the same time, which can greatly increase the land utilization rate.
Throughout the whole history of agricultural development, the transformation of agricultural production mode is closely linked with the way to use energy by human. Fig. 1 depicts the different coordinate axes for describing the agricultural development: 1) the coordinate axis X1 refers to the perspective of the energy source; 2) the coordinate axis X2 refers to the perspective of the technological revolution; 3) the coordinate axis X3 refers to the perspective of the AI and IoT application. In the middle of Fig. 1, we show the blue dotted line as the agricultural development trend line, above which it illustrates the corresponding agricultural mechanization development trend [17]. Induced by addressing the observed critical issues, this article proposes a future agricultural production mode “Agriculture 5.0” in detail, i.e., a new energy agriculture, in the era of which the PA will be one of the production modes. With the rapid development of smart agriculture and agricultural informatization, an important technology, e.g., Internet of Things (wireless sensor networks), has been widely used in agricultural information collection, agricultural data transmission, agricultural equipment intelligent control, etc. IoT technology is suitable for large coverage area, with a great quantity of deployment. IoT can be easily combined with PA, in which we mainly focus on the wireless technology. Then by deploying wireless sensor network nodes in PA, a completely new agricultural internet of things, i.e., Photovoltaic Agricultural Internet of Things (PAIoT), is formed, whose application prospect and research value has considerable potential.

PA, as an effective production method to effectively alleviate the contradiction between agriculture and energy, can give full play to the advantages of agricultural production and energy production, and generate greater economic value after combining with information technology to form PAIoT. At present, the research issues of PAIoT still need to be further expanded to meet the diversity requirements of this production mode. Therefore, we need to fully consider some key issues that are commonly faced in this production mode. The raising and analysis of these key issues are the important motivational factors of this paper.

Based on the idea from the poster [18], the concept of PAIoT is updated and expanded, with the main contributions of this paper being shown as follows:

1) This paper briefly reviews the recent developments about PA and envisions the future PA, i.e., PAIoT.
2) We provide a review of the key issues that concern the feasibility of PAIoT and further propose the corresponding novel techniques to mitigate these key issues.

For the rest part of this paper, section II describes overview of PA. Section III provides novel techniques to mitigate key issues to enable PA, i.e., PAIoT. And the key issues that concern feasibility of PAIoT are discussed in section V. This paper is concluded in section VI.

II. OVERVIEW OF PA
As early as the 1980s, scholars proposed an idea of PA that combines both photovoltaic power generation with agricultural production in [19]. To date, as a new management mode with a combination of new industry with modern agriculture, PA (as shown in Fig. 2, inspired by [20]), in which the distributed photovoltaic modules are built on certain space (e.g., farmland, pasture, waters.), can realize the planting and breeding under the modules, and power generation on the modules, resulting in sharing cost and full integration between photovoltaic power and facility agriculture, while not changing the nature attributes of land. Fig. 2 depicts that PA not only saves space, and improves the output within the same space, but also facilitate the development of local precision agriculture in scale. Furthermore, it is possible to
fight against smog and balance the regional energy supply in mid-eastern China, where there will be a large area to build photovoltaic power plants.

Based on current researches on the description of PA in [21], PA can be defined as the follows:

1) Build a steel bracket on the farmland, where it will bring the agricultural production benefit by planting crops, raising livestock and poultry raising under the bracket;

2) Place the photovoltaic modules above the bracket, transmit the power to the high-voltage substation by the transmission cable, and sell it on the grid or meet the demand of agricultural production electricity, both of which will generate photovoltaic power generation revenue.

We briefly enumerate a few applications of PA. The steel brackets, above which photovoltaic panels are placed for power generation and below which crops are planted (Fig. 3, ①) and livestock are raised (Fig. 3, ②), are installed in the field. To meet the demands from different users in PA, we can: 1) design a large space for mechanized operation (Fig. 3, ③), further improving the production efficiency; 2) cultivate some crops and vegetables in the space among the photovoltaic panels (Fig. 3, ④), further increasing the income. In addition, there are some other applications of PA, e.g., PV agricultural greenhouse, PV wastewater purification, PV water pumping [21], and PV sightseeing agriculture.

On one hand, the photovoltaic panels can protect the crops and the livestock from disasters, e.g., hail, high temperatures and other severe weather, thereby reducing the agricultural production loss. However, due to the blocking of light, photosynthesis will be affected, leading to some crops’ production reduction, e.g., wheat in [22], while some others’ production does not change by increasing their leaf area to increase photosynthesis, e.g., lettuce in [23]. Although the photovoltaic panel can shelter the crops, the panels will change the distribution of the rain under the panels, resulting in different impact on the crops growth. Then an optimization is needed in the installation of the panels.

On the other hand, the agricultural production process is energy-consuming, in which the electricity consumed is further less than the energy from photovoltaic power generation in [24], [25]. And the remaining electricity can be sold by merging on the grid, decreasing the management cost of PA and increasing the revenue. To improve the deployment density of the photovoltaic panels will increase the benefit from power generation, thus leading to serious agricultural production reduction. Nevertheless, a trade-off between the crops photosynthesis and photovoltaic power generation is also a chance for exploring diversified planting modes, in which we can make different combinations for different crops to guarantee the sufficient photosynthesis for stable yield and quality.

Moreover, it is possible to promote ecotourism on PA based on the local environment, further improving local economic development.

According to the above-mentioned introduction, the increasing researchers are engaged in PA at present, with the continued innovations to enable the photovoltaic power generation applications in agriculture, most of which focus
on the feasibility of combining both photovoltaic power generation and agriculture production while fewest of which is concerned on the combination of both PA and IoT. Indeed, this combination can greatly promote the deep integration between photovoltaic power generation and agricultural production, i.e., intelligent photovoltaic power generation and intelligent agricultural production, remarkably increasing the production efficiency to a high level, which is an obvious characteristic of PA in the future.

III. NOVEL TECHNIQUES TO MITIGATE KEY ISSUES TO ENABLE PA-Yyyyy–Xxxxx-PAIoT

From the above introduction, PA is different from traditional agriculture, whose income sources consist of agricultural production and photovoltaic power generation. Compared with planting energy crops to produce ethanol in agriculture [26], PA shows an advantage of generating cleaner energy without GHG. Therefore, the focus of researches between PA and traditional agriculture is also different. Correspondingly, if an IoT platform is built in PA, it will also present many characteristics different from the traditional agricultural Internet of Things. Now there are many researches on agricultural IoT, e.g., precision agricultural IoT [27], and water quality monitoring [28], in which the main challenges include unsustainable energy supply for nodes and huge investment [29], [30]. However, if an IoT platform is built in PA, there will be no such challenges. Because the energy supply is sufficient and it can fully meet the energy demand of various types of sensor nodes. At the same time, nodes are installed on the bracket of PV electric field, thus reducing deployment costs. In addition, there will be some other advantages:

1) The application of the traditional agricultural IoT mainly focuses on reforming the agriculture with the feature of small-scale [31], which is not good for applying the IoT technology. However, the feature of PA is generally large-scale.

2) The amount of transmission data in future agriculture is huge, including images, audios, videos, etc. No matter what equipment and technology is used, the transmission of such information will consume a lot of energy [32]. Even though there are many researches on Green IoT at present, which further decreases the energy consumption [33], the energy of a node is a bottleneck.

Due to the above analysis, it is necessary to define the new agricultural IoT, to introduce its architecture, and to make a detailed comparison among the new agricultural IoT, traditional agricultural IoT and traditional greenhouse IoT.

A. DEFINITION OF PAIoT

The proposed scheme is very promising to enable PA by combining both PA and IoT. However, there are few researches about the applications of internet of things in PA. Then, motivated by addressing the identified critical issues, this paper has introduced a new agricultural internet of things, i.e., PAIoT, whose definition is as follows including four parts:

1) It can collect on-site information on production areas, e.g., field planting, facility gardening, livestock and poultry
FIGURE 4. Schematic diagram of PAIoT. An early version of this figure has been used in our previous paper, Poster: Photovoltaic agricultural internet of things - the next generation of smart farming, in In Proceedings of International Conference on Embedded Wireless Systems and Networks (EWSN 2019), Beijing, China, 2019.

FIGURE 5. Architecture of PAIoT.
farming. Also, all of sensors and devices were installed on steel structure bracket;

2) WSN nodes get stable energy supply from photovoltaic power generation;

3) Realize multi-scale reliable transmission of agricultural information by using modern information transmission channels;

4) It can perform data fusion and data processing. Intelligent decision and early warning of both agricultural production and photovoltaic panels monitoring are required.

Different from the schematic diagram of PA (Fig. 2) depicted in the form of three-dimension, the schematic diagram of PAIoT (Fig. 4) is described in the form of two-dimension through a two-layer structure. One layer is about the schematic diagram of agricultural production, and the other layer is about photovoltaic power generation and wireless sensor nodes deployment. Moreover, the adoption of this two-layer structure is to facilitate the description of the deployment of wireless sensor nodes in the PAIoT.

**B. ARCHITECTURE OF PAIoT**

Based on the experience of other scholars, we proposed a three-layer IoT architecture [34]–[36]. As shown in Fig. 5, three layers are briefly introduced below:

1) Perception layer: It consists of various sensors applied in scenario of PA, which are used for monitoring key parameters and collecting agricultural big data, e.g., light sensor, temperature and humidity sensor, audio and video sensor, infrared sensor, RFID, GPS, and hall sensor. Moreover, different technologies and special standards are required to meet the demand of PA, including energy management technology, special sensor standard, communication technology, anti-interference technology, and adaptive coding technology. The data processing is finished on the embedded device, and the data is then uploaded to the higher layer.

2) Transport layer: In PA, the main function of transport layer is to transport the collected data to the application layer and to transport the control commands in the form of wireless transmission. And which wireless transmission type is in use depends on the real scenario of PA. In addition, the wireless technology in PA includes ZigBee, Wi-Fi, WLAN, and cellular mobile communications technology (GPRS, 3G, 4G and 5G).

3) Application layer: In this layer, five core application scenarios, which refer to interdisciplinary deep integration in PAIoT, are briefly described to concern feasibility of PAIoT. The interdisciplinary are mainly about agricultural machine, wireless communication, cloud/fog/edge computing, life science, and fault diagnose. With the deep integration of them, the yield and production efficiency will improve while the production cost will reduce. And we will discuss them in detail in the following section.

**C. COMPARISON OF DIFFERENT AGRICULTURAL INTERNET OF THINGS**

As a new agricultural internet of things, based on the definition above, PAIoT shows different characteristics from both

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**TABLE 1. Comparison of different agricultural Internet of Things. (PV: photovoltaic)**

| Item                              | Traditional agricultural IoT | Traditional greenhouse IoT | PAIoT                   |
|----------------------------------|-----------------------------|----------------------------|-------------------------|
| Service objective                | Field agriculture           | Facility agriculture       | Field agriculture and facility agriculture |
| Network coverage area            | Large                       | Small                      | Depending on the construction area |
| Number of network nodes          | Sparse                      | Low                        | Dense                   |
| Node power supply mode           | Small PV cell (Unstable)    | Small PV cell (Unstable)   | Large PV electric field (Stable) |
| PV module status monitoring      | ✗                           | ✗                          | ✓                       |
| Hardware integration of PV module | ✓                           | ✗                          | ✓                       |
| and farmland information acquisition module | ✗                           | ✗                          | ✓                       |
| PV electromagnetic noise channel interference | ✗                           | ✗                          | ✓                       |
| Arrangement cost                 | High (Design the sensor node and purchase the bracket) | Low (Lay on the greenhouse bracket) | Low (Lay on the bracket of PV electric field) |
| Image collector                  | Not inclined to use         | Unique access method       | Unique access method    |
| Information acquisition          | Remote sensing technology   | ✓                          | ✗                       |
|                                  | Drone                       | ✓                          | ✗                       |
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FIGURE 6. Intelligent cleaning and intelligent utilization of water resources.

For all of them, their advantages can greatly promote the development of agricultural Internet of Things, providing reliable technical support for the stable operation.

IV. KEY ISSUES THAT CONCERN FEASIBILITY OF PAIoT

Although PAIoT has many advantages and good application prospects described above, there are still some key issues that concern feasibility of PAIoT.

A. PHOTOVOLTAIC PANEL CLEANING AND COMPREHENSIVE UTILIZATION OF WATER RESOURCES

According to the amount of dust accumulation, photovoltaic panels need to be cleaned in time to ensure power generation efficiency in [9], [37]. Meanwhile, sufficient water supply is also necessary in the whole process of agricultural production to ensure the soil moisture. The combination of both panel cleaning and crops irrigation (Fig. 6) can effectively improves the water resources utilization rate [11].

In PA, the conditions for photovoltaic panel cleaning are inconsistent with the conditions for crops irrigation and livestock farm cleaning. For simplicity, in most time of the day, the cleaning frequency of the panels is not synchronized with the frequency of crops irrigation and livestock farm cleaning. Note that the internet of things technology can effectively solve this problem by taking the following factors into consideration, e.g., cleaning time of the day, cleaning frequency, different water requirements in different growth stages of the crop, different water requirements of different species of crop, soil moisture, and so on. In the PAIoT, the status of
photovoltaic panel power generation is monitored to make judgement whether to clean the panels, and the amount of irrigation water is determined based on the situation of agricultural production, both of which are considered to choose a proper time for the cleaning and the irrigation. And this intelligent cleaning tasks will be finished by the cleaning robots with high efficiency.

### B. NODE DEPLOYMENT AND COST OPTIMIZATION FOR MULTI-FUNCTION AND MULTI-MONITORING STANDARDS

In PA, the photovoltaic module-monitoring node has not been integrated with the agricultural information monitoring node, highly increasing the deployment cost. Therefore, the following constraints need to be considered while deploying the wireless sensor network nodes:

- Ensuring normal communication coverage of the sensor network;
- Monitoring standard arrangement for crops;
- Effective detection range of the sensor;
- Electromagnetic noise interference from photovoltaic power station;
- Irregular farmland boundaries and terrain barriers;
- Tendency layout of farmland key monitoring areas.

The above-mentioned constraints in PAIoT are much more complicated, yet the existing researches can also provide some attractive insights [38]–[40]. Although the existing agricultural information collection system feature complete functions in [41], there are promotion challenges owing to large occupied area and high initial investment. Moreover, in the process of node deployment, the model on network transmission channels and connectivity need to be constructed with three factors (i.e., electromagnetic interference, weather, heterogeneous network.) being taken into account. Then we can improve the invulnerability of wireless sensor networks in PA, further realizing node fault tolerance configuration and global communication redundancy coverage. Finally, we can allow the PAIoT in stable operation (Fig. 7).

### C. TRANSMISSION OPTIMIZATION OF IMAGE DATA ACQUISITION

The multimedia data stream is obtained while monitoring the data of PA, e.g., diseases and insect pests, crop growth, transmission of soil moisture, and the operation status of photovoltaic modules. Note that the irregularities in farmland and terrain, the obstruction of obstacles, and the network bandwidth limitation of the node itself, the network is unable to carry a large amount of data stream information, thus limiting the frequency of sampling of the sensor node, further requiring the transmission optimization of the data in the network [42], [43] (Fig. 8). For simplicity, but without losing too much generality, the optimization for the data from some critical nodes is becoming increasingly important, which will seriously affect the operation status of PAIoT.

Nowadays, there are three methods for data transmission optimization in this network. Firstly, through the node communication quality self-awareness and network layer management, the optimal sampling frequency upper limit of the global image data is obtained with the constraint of network bandwidth and sampling period. Secondly, build an expert system on a dynamic optimization strategy of image acquisition frequency and image quality, and construct an adaptive optimization scheme, which takes into account image sampling quality and image transmission. Thirdly, the deploying nodes with storage and computational capability in terms of Edge Computing, Cloud Computing, and Fog Computing, can support big data processing for large-scale IoT.
D. INFLUENCE OF PHOTOVOLTAIC PANEL POWER GENERATION ON THE ENVIRONMENTAL CLIMATE

In PA, it is the photovoltaic panel that stops the sunlight from shining the crops below and protects the crops below from the natural disasters. Additionally, when generating electricity, the panel heating will affect the temperature of the surrounding environment, resulting in the change of environmental climate (Fig. 9). In other words, after the photovoltaic panels are arranged, the environmental climate parameters (i.e., temperature and humidity [44]) of different area (i.e., the airspace within and outside a certain range above the panel, the airspace below the panel, and the soil below the panel [45]–[48]) will change, leading to various influence on the crop growth. Then, exploring the environmental parameters changing rule of these areas in PAIoT to discover a suitable planting mode is further requested on demand by each researcher in the field of life science.

E. FAULT DIAGNOSIS OF PHOTOVOLTAIC MODULE AND SENSORS IN AGRICULTURAL PRODUCTION

With the faults of photovoltaic module being accurately detected and identified, the technology, i.e., fault diagnosis, will provide effective support for the stable operation of the PAIoT (Fig. 10), especially the power grid maintenance [49], further providing a basis for solving the security and safety problems in PAIoT. We observed that there...
are three common sources of photovoltaic module faults as follows:
- **Shadow**: temporary shadows (e.g., snow, fallen leaves, birds.), site shadow (e.g., terrain, trees.), architectural shadows (e.g., building construction, electric towers.), and self-shadow (e.g., photovoltaic component shadow, other device shadows);
- **Equipment aging**: external high temperatures cause device aging or performance degradation; the performance of photovoltaic modules is inconsistent, causing Hot Spots and accelerating aging; the system is limited by photovoltaic components under poor working conditions; the lack of reverse-control for the equipment;
- **Line damage**: electrical faults (e.g., lightning strike, fuse blow.), other (e.g., intentional attack from human and animal.).

Meanwhile, the effect of the security and safety problems caused by the above-mentioned faults and sensors faults of agricultural production in PAIoT may be not obvious in the short term, particularly in agricultural production where the crop can perform some tolerance to the improper environmental conditions, yet leading to the severe yield reduction after a long time in the future. Then, we observed that every challenge posed for researchers need to be considered seriously while developing novel faults diagnosis technology in PAIoT.

Through the analysis of the above complicated key issues, the PAIoT needs to face more challenges than PA. It also means that the PAIoT can efficiently cope with the actual production, further greatly promoting the development of smart farming in the future.

V. CONCLUSION

With the reduction of photovoltaic panel manufacturing costs and the improvement of photoelectric conversion efficiency, PA has developed rapidly and has good application prospects, increasing the income of agricultural production while solving the problem of energy shortage. This paper briefly introduces the current application of PA, and a new agricultural Internet of Things, i.e., PAIoT, is proposed with the combination of both PA and IoT technology. Through the analysis of key issues that concern feasibility of PAIoT (i.e., photovoltaic panel cleaning and comprehensive utilization of water resources, node deployment and cost optimization for sensor networks for multi-function and multi-monitoring standards, transmission optimization of image data acquisition, influence of photovoltaic panel power generation on the environmental climate, and fault diagnosis of photovoltaic module.), we can know how to better realize the PAIoT, further improving the level of agricultural informatization and promoting the continuous upgrading of the agriculture, which is also the typical application of “smart farming”.

FIGURE 10. Fault diagnosis of photovoltaic module.
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