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Design of Carbon Monitoring System Platform for Agricultural Energy Internet

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Abstract: As global climate change and carbon emission issues become increasingly severe, the agricultural energy Internet plays a crucial role in achieving low-carbon development. The merging of new energy with modern agriculture is progressively being realized, making effective carbon monitoring and accounting especially critical. This paper presents a novel design for a carbon monitoring system platform for the agricultural energy Internet, using aquaponics greenhouses as the research object. Addressing the difficulties presented by the diversity and magnitude of agricultural carbon sources, the paper proposes a carbon accounting model applicable to such greenhouse environments. This model aims to enhance energy utilization efficiency and reduce carbon emissions through precise accounting and monitoring. Subsequently, a carbon monitoring system applicable to the agricultural energy Internet is designed. This system enables real-time and accurate monitoring and assessment of carbon emissions and absorption in agricultural parks. The platform, developed using a B/S architecture with a separation model between front-end and back-end employing Vue and Spring Boot frameworks, provides a comprehensive solution for monitoring and managing carbon emissions in agricultural energy.

Keywords: Agricultural Energy Internet, carbon footprint, aquaponics, system design

1. Introduction

Agricultural Energy Internet (AEI) represents an expansion of the energy Internet into the agricultural domain, centered on the electric power system and prioritizing distributed renewable energy integration, utilizing information and communication technology along with Internet of Things (IoT) technology, to accomplish the comprehensive management and control of the agricultural and energy systems founded on the interconnection of various types of energy and to provide a series of specific services for the agricultural production through the related IoT platform, whose essential feature is the deep coupling of information-matter-energy [1]. As modern agricultural industrial parks evolve, traditional energy consumption modes, characterized by high pollution and energy use, no longer align with economic and social developmental needs [2, 3]. It is critically important to develop the park's AEI to foster the synergistic, effective, and enduring advancement of new energy and modern agriculture [4]. The development of energy agriculture to minimize emissions of greenhouse gases in the agricultural production process has emerged as the primary research direction of AEI considering China's commitment to reducing carbon emissions [5, 6]. AEI possesses attributes of high comprehensive energy efficiency and low-carbon emission and holds a significant role in promoting the evolution of agricultural production and energy systems towards intelligent, intensive, and high energy efficiency.

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In China, the share of carbon emissions attributable to agricultural production activities surpasses that of any other country, contributing to 17% of the nation's total carbon emissions, compared to 7% in the United States and 11% worldwide [7, 8], and the effect of reducing agricultural carbon emissions is significantly better for China than for other countries. Therefore, China urgently needs to change its energy supply mode, lower carbon emissions from agriculture, and achieve the development of the energy system towards decarbonization. The cross-sector integration between the energy Internet and agriculture has transitioned into a new mode of energy ecology in modern agricultural parks, and as a product of the intensive integration of energy and agriculture, the construction of the AEI is not only conducive to promoting China's rural revitalization but also an important means of achieving "carbon neutrality." Low-carbon, clean, and intelligent has become the prevailing direction for the evolution of modern agricultural energy [9, 10]. AEI can improve energy efficiency, optimize the energy structure, and serve a crucial function in diminishing carbon emissions. On the one hand, the carbon dioxide released during energy generation is used for agricultural production, addressing both the decarbonization of the energy system and carbon dioxide fertilization challenges concurrently, realize the benign cycle of carbon emission from electricity generation and carbon sequestration in agriculture, and then foster the simultaneous growth of increased agricultural production and efficiency and decarbonization of energy [11, 12]; on the other hand, the cultivation of agricultural biomass resources can address issues related to environmental contamination and energy scarcity of agricultural wastes, effectively reducing carbon emissions and facilitating the decarbonization development and the green, low-carbon energy transformation [13, 14].

In the cross-border integration of the agricultural energy sector, carbon monitoring is crucial for the effective and sustainable functioning of agricultural energy systems. This process involves measuring and evaluating carbon emissions, enabling real-time assessment of the carbon footprint in agricultural energy systems. Such assessment is critical for gauging energy efficiency and providing a scientific foundation for the management and optimization of these systems [15, 16]. The progression of the AEI has progressively facilitated the merging of new energy with modern agriculture. The existing obstacles separating the energy and agricultural industries are gradually broken. However, the absence of precise carbon monitoring makes it difficult to comprehensively assess the environmental effects of the AEI, thereby hindering the achievement of carbon emission reduction goals. Carbon monitoring is essential to assess the effectiveness of agricultural practices and energy technologies in reducing carbon emissions and increasing carbon sequestration. By leveraging accurate monitoring data, we can refine agricultural production methods and energy conversion technologies, thereby reducing energy consumption, enhancing energy efficiency, and optimizing resource utilization. Therefore, the application of carbon monitoring in AEI is not only a product of technological innovation but also a key catalyst for the advancement of the deep integration of agriculture and energy fields.

In conclusion, establishing an efficient and accurate carbon monitoring real-time monitoring system for the carbon emissions from agricultural energy systems and assessing energy use efficiency is vital. It provides a scientific basis for managing and optimizing agricultural energy systems, reducing carbon emissions, and supporting the achievement of "carbon peak" and "carbon neutral" goals. Therefore, this study aims to provide insights into the design and development of a carbon monitoring system specific to the AEI, with the technology roadmap as illustrated in Figure 1.

Initially, we conducted a detailed site survey of the aquaponics greenhouse and collected basic data of the agricultural park. We then mapped out the carbon pathways of the park and determined the appropriate carbon accounting methods. Based on these methods, we built carbon accounting models capable of accurately calculating various carbon emission sources and carbon sequestration sources within the greenhouse. Subsequently, we analyzed the required functional modules of the system and designed the overall system architecture, determining the system workflow. Finally, by analyzing and evaluating the data from the carbon monitoring platform and the park's operational data, we can provide scientific low-carbon management recommendations for the park, supporting the transition to low-carbon development in agricultural parks.

2. Related Work

Zhang et al. [17] studied smart logistics' precise tracking and analysis of carbon emissions, selected the emission factor approach for analyzing carbon emissions in the smart logistics process, and constructed a theoretical framework for a smart logistics supply chain that accounts for carbon emissions. Liu et al. [18] presented a system for monitoring carbon emissions in real time for the prefabricated buildings industry chain and meanwhile developed three different data display platforms according to the user's needs. Zhang et al. [19] proposed a neighborhood and street scale carbon emission real-time estimation model and designed an intelligent low-carbon monitoring platform that integrates conventional carbon management practices with IoT technology. Liu and Zhang [20] developed a real-time carbon emission monitoring system by incorporating information and communication technology, offering a framework for monitoring and managing carbon emissions. Pau et al. [21] propose a big data architecture aimed at advanced services in the building sector, aiming to enhance services within the building sector. The platform integrates various data sources and provides a unified framework for data management, analysis, and visualization to improve energy efficiency and reduce greenhouse gas emissions in buildings.

However, existing platform designs have concentrated on the industrial sector and mass production environments, with limited research being conducted on carbon emission monitoring platforms within the agricultural energy sector. Considering the substantial contribution of agriculture to global carbon emissions and its concomitant challenges posed by climate change, there is an imperative need to develop and implement a platform for an AEI carbon monitoring system that accurately implements carbon monitoring in agricultural greenhouse environments, thereby enabling agricultural producers to comprehend and effectively manage their carbon footprints.

3. Practical AEI

Section 3 introduces the theoretical basis of carbon accounting for the AEI, discussing the diversity of carbon emission sources in agricultural parks and clearly outlining the research framework for carbon cycling in these environments. Through a detailed analysis of the carbon emissions in an aquaponics greenhouse, we propose a carbon accounting model specifically for this greenhouse. This model is designed to accurately calculate carbon emissions within the greenhouse, aiming to enhance energy utilization efficiency and reduce carbon emissions.

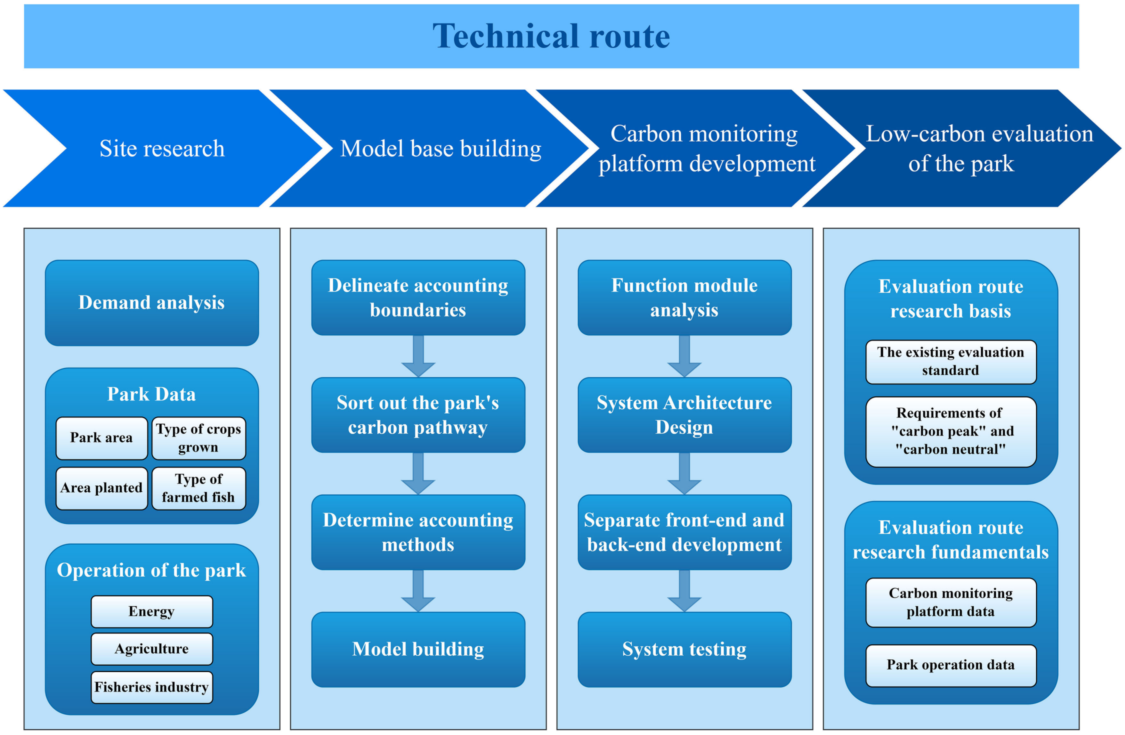
3.1. Theoretical basis of carbon accounting for AEI

Addressing the scarcity of accounting models for agricultural emission sources, especially considering the vast variety and volume of carbon emissions within agricultural parks, the comprehensive and accurate monitoring and evaluation of carbon emissions at each production link within an agricultural park becomes an imperative research topic. This paper mainly analyzes the carbon emission and carbon absorption situation of the park grounded in the concrete circumstances of the aquaponics greenhouse in Zhuozhou and puts forward a set of carbon accounting system schemes applicable to this kind of greenhouse, which can achieve the purpose of improving the energy utilization efficiency and reducing the carbon emission through the emission reduction potential of the new energy source and the photosynthetic carbon absorption capacity of the greenhouse crops. A schematic of the system's accounting is shown in Figure 2.

3.2. Carbon accounting models

In this study, carbon accounting models are divided into three main categories based on their actual sources, as shown in Table 1, and then subdivided into each module. The system will perform carbon accounting through the following three models, which are based on the documents referenced in Table 2.

Figure 1
Technology roadmap



3.2.1. Carbon emissions accounting model

The primary sources of carbon emissions include emissions from purchased grid electricity, respiration of farmed fish, plant and soil respiration, and waste disposal. These are accounted for as follows:

a. *Carbon emissions from purchased electricity:* A large number of equipments in the agricultural park consume electricity, and in the morning or evening, the electricity generated by PV is not enough to maintain the operation of the equipments, so it is necessary to obtain electric power supplied by the grid, and most of the electricity from the grid comes from some thermal power plants, which will indirectly emit CO2. Carbon emissions from purchased electricity are shown in the following equation.

$$E_{CO_2} = AD_{\text{electricity}} \cdot EF_{\text{electricity}} \tag{1}$$

where E_{CO_2} is the carbon emissions from purchased electricity; $AD_{\text{electricity}}$ is the volume of electricity acquired from the grid; $EF_{\text{electricity}}$ is the grid emission factor.

b. *Fish respiratory carbon emissions:* Fish, as poikilothermic animals, are significantly influenced by water temperature, which affects their respiration rate and consequently alters their oxygen consumption rate. Changes in water temperature affect the basal metabolic rate, energy intake, nutrient digestion, and energy storage in fish. Specifically, an increase in temperature usually elevates the metabolic rate, leading to a higher oxygen consumption rate. This relationship between temperature and respiration rate allows fish to adapt their physiological functions to environmental changes [25]. Considering only aerobic respiration, fish respiratory carbon emissions can be found by following equations.

$$W_{OX} = Z \cdot L_s \cdot OCR \times 10^{-6} \tag{2}$$

$$E_{CO_2\text{-breathe}} = W_{OX} \times \frac{44}{32} \tag{3}$$

where W_{OX} is the respiratory oxygen consumption of the fish; Z is the overall weight of farmed fish; L_s is the survival percentage; OCR is the oxygen consumption rate. $E_{CO_2\text{-breathe}}$ is the carbon emission from fish respiration.

c. *Plant respiration carbon emissions:* The empirical equation for respiration of plant communities per unit of floor area is presented in the equation below and enables further calculation of carbon emissions from plant respiration.

$$p_r = f_1 \cdot i \cdot t_1^b \tag{4}$$

$$E_{CO_2} = A \cdot p_r \tag{5}$$

where E_{CO_2} is the carbon emission from plant respiration; p_r is the intensity of carbon dioxide respiration of the crop community per unit greenhouse area; A is the area under cultivation; f_1 is the plant leaf area index; t_1 is the leaf surface temperature; i, b is the coefficient.

d. *Soil respiration carbon emissions:* Soil respiration modeling per unit of floor area is presented in the equation below and enables further calculation of carbon emissions from soil respiration.

$$p_s = p_{s0} \cdot 3^{\frac{T}{10}} \tag{6}$$

$$E_{CO_2} = \mathrm{A} \cdot p_s \tag{7}$$

Figure 2
Schematic diagram of carbon accounting

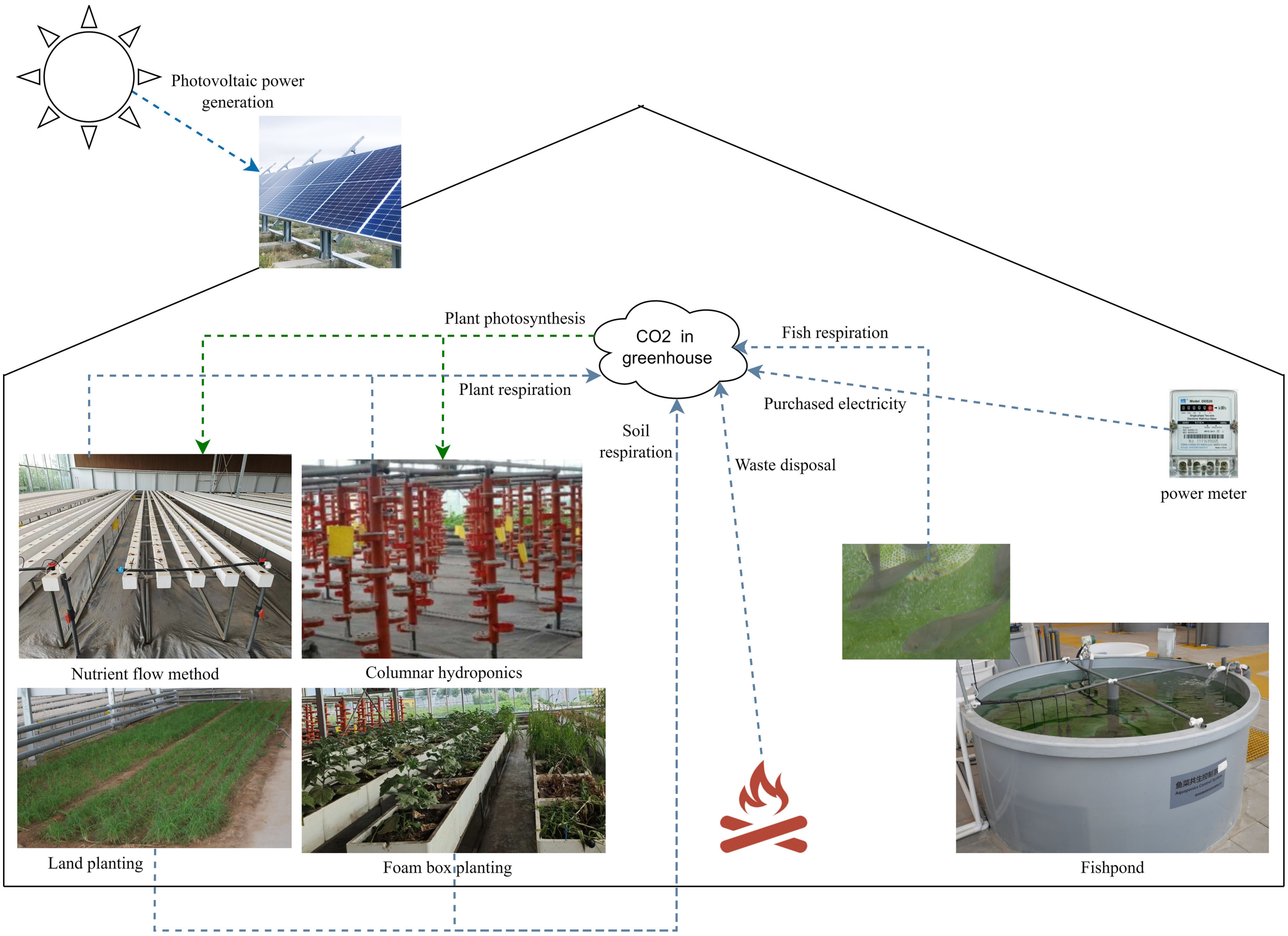


Table 1
Summary of carbon accounting models

Type of carbon accounting	Sources of carbon accounting	Formula number
Carbon emissions	Purchased electricity	(1)
	Fish respiratory	(2),(3)
	Plant respiration	(4),(5)
	Soil respiration	(6),(7)
	Waste disposal	(8)
Carbon sequestration	Plant photosynthesis	(9)–(14)
	Soil carbon sequestration	(15),(16)
Carbon emission reductions	Photovoltaic power generation	(17),(18)

where p_s is the amount of change in carbon dioxide due to soil respiration; p_{s0} is the amount of carbon dioxide released from the soil at 0°C; T is the soil temperature.

e. *Waste disposal carbon emissions:* The equation for calculating carbon emissions from waste disposal is presented below.

$$E_{CO_2} = \mathrm{A} \cdot M_B \cdot C_f \cdot G_{ef} \cdot 10^{-3} \tag{8}$$

where E_{CO_2} is the CO2 emission; A is the area burned away; M_B is the mass of fuel that can be burned; C_f is the combustion factor; G_{ef} is the emission factor.

3.2.2. Carbon sequestration accounting model

Carbon sequestration mainly consists of plant photosynthetic carbon sequestration and soil carbon sequestration:

Table 2
Documents referenced in carbon accounting

Name of carbon accounting	Documents referenced
Purchased electricity	"Guidance on accounting methods and reporting of corporate greenhouse gas emissions – power generation facilities" [22]
Photovoltaic power generation	"Baseline emission factor of China's regional power grid for emission reduction projects in 2019" [23]
Waste disposal	"2006 IPCC Guidelines for National Greenhouse Gas Inventories" [24]
Soil carbon sequestration	

a. *Plant photosynthetic carbon sequestration:* Plants in the greenhouse sequester carbon, and their carbon sinks are an important form of absorbing carbon dioxide in the park. The model for calculating photosynthetic carbon sequestration per unit of floor area in greenhouse plants is presented in the equations below, which allows for calculating the amount of photosynthetic carbon uptake by plants in the greenhouse.

$$G(t_1) = \frac{2(t_1 + a)^2(t_\mathrm{m} + a)^2 - (t_1 + a)^4}{(t_\mathrm{m} + a)^4} \tag{9}$$

$$p_t = p_{max}G(t_1) \tag{10}$$

$$p_m = \frac{p_t}{1 + \frac{k_1}{E_a}} \tag{11}$$

$$p = \frac{(c_\mathrm{i} + k_\mathrm{c} + rp_\mathrm{m}) - \sqrt{(c_\mathrm{i} + k_\mathrm{c} + rp_\mathrm{m})^2 - 4c_\mathrm{i}rp_\mathrm{m}}}{2r} \tag{12}$$

$$p_p = f_1^{\frac{1}{2}} \cdot p \tag{13}$$

$$E_{\mathrm{CO_2}} = A \cdot p_p \tag{14}$$

where $E_{\mathrm{CO_2}}$ is the carbon dioxide absorbed by plant photosynthesis; $G(t_1)$ is the temperature coefficient; t_1 is the leaf surface temperature; a is a constant related to the type of plant response to temperature; t_m is the foliar temperature at which the maximum photosynthetic rate is reached; p_t refers to the maximum rate of photosynthesis when the foliar temperature reaches t_1; p_m refers to the maximum photosynthetic rate of the plant species studied; k_1 is the rate constant related to light intensity; E_a is the photosynthetically active radiation illuminance; k_c is the rate constant related to carbon dioxide concentration; c_i refers to the indoor carbon dioxide concentration; r refers to the sum of leaf resistance; p is the intensity of carbon dioxide uptake per unit area of plant leaf; p_p is the intensity of carbon dioxide absorption by the crop per unit greenhouse area; f_1 is the plant leaf area index; A is the planted area.

b. *Soil carbon sequestration:* Soil carbon sequestration applicable to this system can be obtained from the following equations.

$$C = \frac{\left(SOC_0 - SOC_{(0-T)}\right)}{D} \tag{15}$$

$$SOC = SOC_{\mathrm{reference}} \cdot F_{LU} \cdot F_{MG} \cdot F_I \cdot A \tag{16}$$

where C is the yearly variation in carbon pools in mineral soils; SOC_0 is the soil organic carbon pool in the last year of the inventory period; $SOC_{(0-T)}$ is the soil organic carbon pool at the start of the inventory period; T is the number of years in the separate inventory period; D represents the temporal dependency of the pool change coefficient; F_{LU} is the factor of change in the carbon pool for the land use system or subsystem in a given land use; F_{MG} is the pool change factor for the management system; F_I is the pool change factor for organic matter inputs; A is the land area.

3.2.3. Carbon emission reduction accounting model

Carbon emission reductions mainly refer to the decrease in carbon emissions from photovoltaic power generation. Photovoltaic power generation belongs to new energy generation, and photovoltaic power generation in agricultural parks does not produce carbon emissions, but can indirectly reduce carbon emissions because it can provide power for energy-using equipment in greenhouses and thus reduce the purchase of power from the grid. The carbon emission reduction model of photovoltaic power generation can be obtained:

$$E_{\mathrm{CO_2}} = P_{pv} \cdot EF \tag{17}$$

$$EF = \rho_{OM} \cdot EF_{OM} + \rho_{BM} \cdot EF_{BM} \tag{18}$$

where $E_{\mathrm{CO_2}}$ is the carbon emissions reduced by photovoltaic power generation; P_{pv} is the generation of electricity of the photovoltaic power plant; EF is the grid baseline emission factor; EF_{OM} is the marginal emission factor related to power; EF_{BM} is the marginal emission factor related to capacity; ρ_{OM} is the weight of EF_{OM}; ρ_{BM} is the weight of EF_{BM}.

4. Demand Analysis and Platform Design of Carbon Monitoring System for AEI

Section 4 provides a detailed analysis of the requirements for the carbon monitoring system and designs its overall architecture and functional modules. The system is based on a five-layer architecture model, including the user layer, application layer, transmission layer, data layer, and infrastructure layer. It aims to accurately display carbon emissions in agricultural parks through real-time monitoring and dynamic calculations. Based on this architecture, the system can offer comprehensive functionalities such as data collection, parameter management, emission accounting, emission reduction accounting, emission analysis, and report generation, thereby enabling precise monitoring and management of carbon emissions.

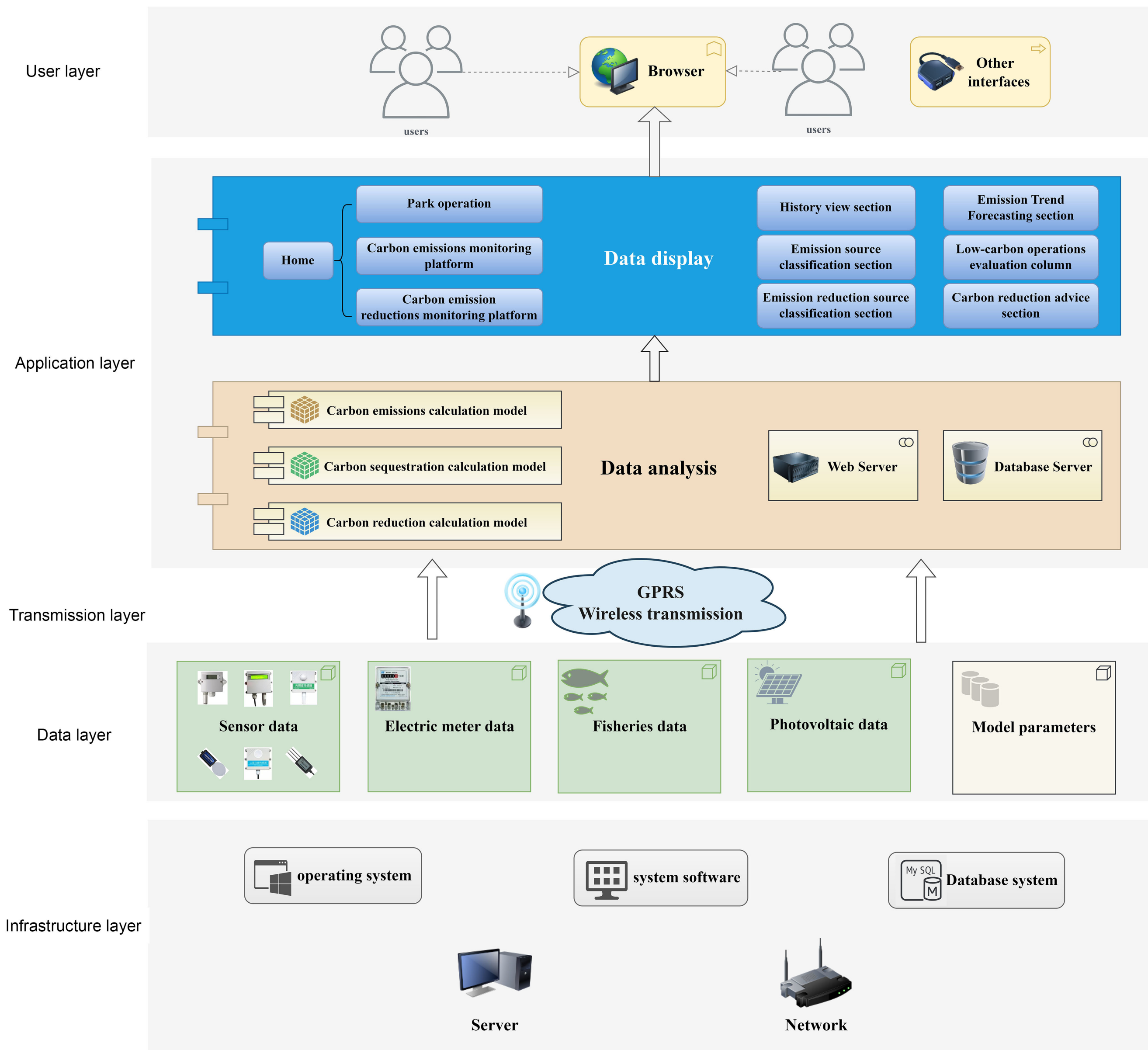
4.1. System demand analysis

The carbon emission situation in agricultural parks is dynamic and changing, and the traditional static statistical methods cannot meet the requirements of real time and accuracy. Therefore, there is a need to develop a system that can dynamically calculate carbon emissions through real-time monitoring data to provide an accurate display of carbon emissions. The carbon monitoring system platform of AEI can accurately calculate the carbon emission and carbon absorption of the agricultural park, dynamically calculate the carbon emission of the park by monitoring the data of the agricultural park, and realize the accurate, real-time, and intelligent display of the carbon emission of the park, promote the transformation of agriculture to the direction of low-carbon development, and promote the sustainable development of agriculture.

4.2. System architecture

After analyzing and summarizing the system requirements, the overall system architecture diagram is obtained as shown in Figure 3 according to the five-layer composition of user layer, application layer, transmission layer, data layer, and infrastructure layer. In the system framework, the user layer and application layer mainly complete the interaction between the user and the system, the user can send a request to the system through the browser interface, and the system will call the corresponding data analysis module to perform specific functions to respond to the user's needs, complete the processing of the data and feedback the results to the user, the platform will be a real time through the browser to show the user the carbon emissions of the agricultural park. The transmission layer is responsible for depositing the data collected in the data layer into the database and adopts GPRS wireless transmission technology to ensure the real-time integrity of the data. The data layer serves as the foundational data source for the system, responsible for collecting and storing the data of the park and providing data support for the upper layer. The infrastructure layer forms the foundation of the system, including hardware resources such as servers and networks, and software resources such as operating systems and database systems, to provide a stable operating environment and required services for the system.

Figure 3
System architecture diagram



4.3. System function design

The carbon monitoring system platform has six core functional modules: data collection, parameter management, emission accounting, emission reduction calculation, emission analysis, and report generation, as shown in Figure 4. The system can help users comprehensively understand the carbon emissions of agricultural parks, assess the effect of emission reduction, and achieve comprehensive support for carbon monitoring management and optimization.

4.3.1. Data collection

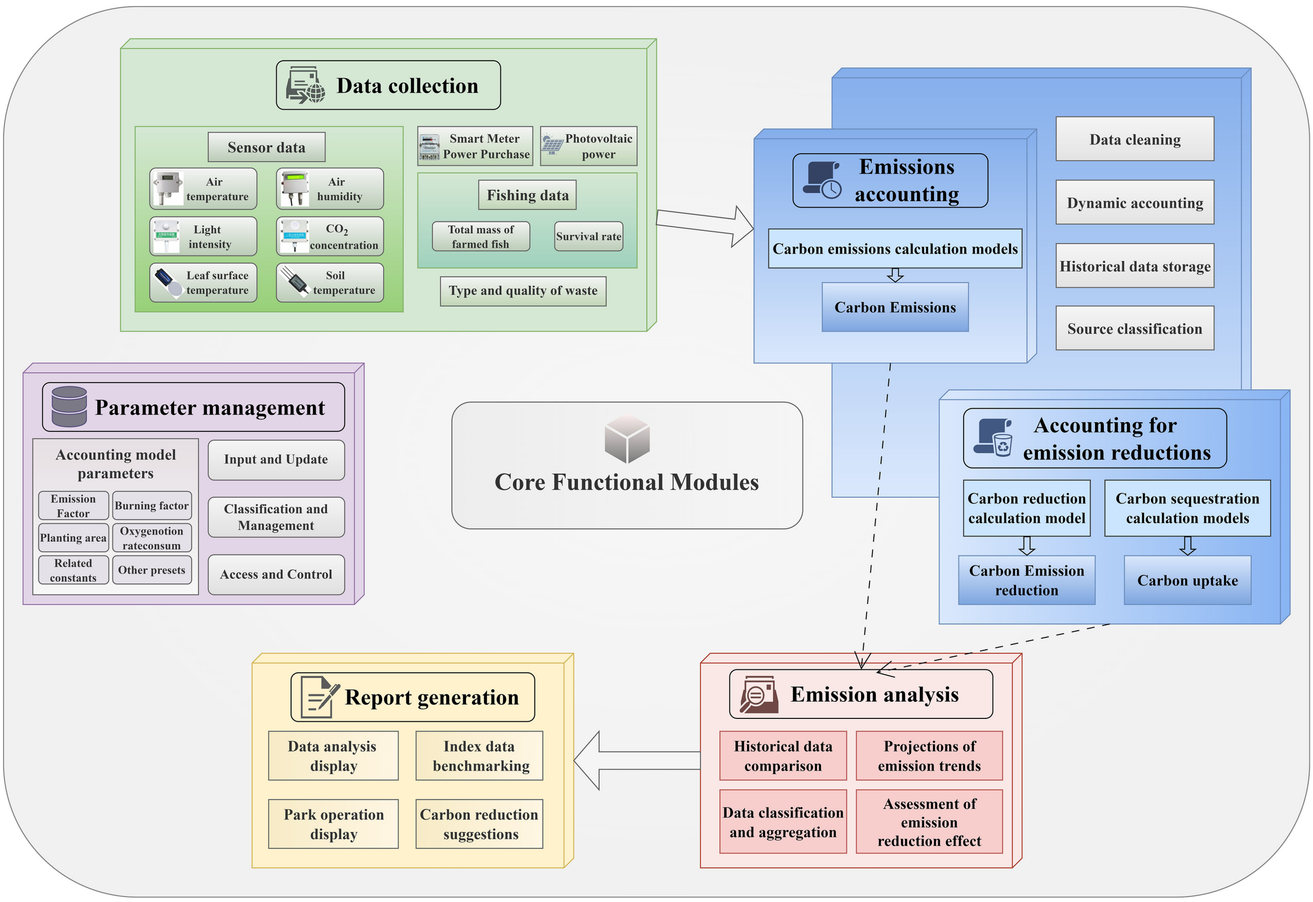
The data collection module is tasked with the real-time collection, processing, and storage of various data pertinent to carbon emissions and carbon absorption to guarantee the precision, completeness, and real-time nature of the data, and to provide basic data support for the subsequent emission accounting and emission reduction calculation.

a. *Sensor data:* The system uses high-precision sensors for real-time surveillance of the greenhouse environment, and the collected data are not only used for real-time display but also processed cleaned and stored in the back-end database for subsequent analysis and calculation. The soil temperature sensor is used to continuously monitor the temperature of the soil to calculate the carbon emission from soil respiration, and the leaf temperature sensor and carbon dioxide concentration sensor are used to monitor the temperature of the plant leaves and the carbon dioxide concentration in the greenhouse in real time to calculate the carbon sink of the plant.
b. *Purchased power data:* Real-time monitoring of greenhouse power consumption using high-precision electricity meters, which record and upload power consumption during each period, providing a key database for carbon emission accounting.
c. *Fisheries data:* data on the total mass of farmed fish, survival rates, etc., are recorded based on actual conditions in greenhouses and are used to calculate carbon emissions from fish respiration.
d. *Photovoltaic power generation data:* Used for real-time collection of photovoltaic power generation in the greenhouse to calculate the carbon emission reduction.

4.3.2. Parameter management

The parameter management module plays a key role in the carbon monitoring system of the AEI. This module is responsible for managing all kinds of parameters in the carbon accounting model, which will be selected and adjusted according to the actual situation of the greenhouse to ensure the accuracy and scientificity of the carbon accounting model. At the same time, the parameter management module will provide the carbon accounting module

Figure 4
Functional module diagram



with the parameters needed for calculation, and in the implementation of carbon accounting, the accounting module will directly obtain the required parameters from the parameter management module, and substitute them into the corresponding formula for the calculation of carbon emissions.

4.3.3. Emission accounting

The emission accounting module dynamically calculates the carbon emissions and sequestration of the park based on the collected data and the parameters of the monitoring model, obtains the latest emission situation at any time, and provides the function of storing historical data. The module calculates carbon emissions from consumption data such as purchased electricity, fish respiration, and carbon emissions from waste treatment according to the carbon emission calculation model and formula and then classifies and summarizes the data according to different emission sources.

4.3.4. Emission reduction accounting

The emission reduction accounting module mainly calculates the carbon emission reduction based on the photovoltaic power generation and then calculates the carbon sink of the park according to the carbon sequestration calculation model and formulae based on the data of vegetation area and vegetation type and at the same time classifies and stores the data to assess the effect of carbon emission reduction.

4.3.5. Emission analysis

The emission analysis module will analyze and process the results of emission accounting and emission reduction calculations, including carbon emission trends, emission source types, and emission reduction effects. It compares the current data with the data of the same period in history and analyzes the emission trend and influencing factors. It is also able to classify and summarize data according to different time and emission sources. The results of the analysis will be used to assess the low-carbon operation level of the park, explore the potential for emission reduction, and provide a foundation for devising strategies and measures geared towards low-carbon development.

4.3.6. Report generation

The report generation module provides users with intuitive data display and analysis results, presenting the results of emission accounting and emission reduction calculations to users in a visual and easy-to-understand form. The module will display the operation of the park and the results of data analysis in real time through the carbon monitoring and accounting platform of the agricultural park, evaluate the operation efficiency of the park according to ISO standards, put forward feasible low-carbon evaluation plans for the agricultural park, and provide users with strategies and suggestions to reduce carbon emissions drawing on the outcomes of the analysis and generate a report on the carbon emissions of the park according to the needs of the users.

4.4. System security

In designing and implementing the carbon monitoring system for the AEI, the security of the system is particularly critical, and the following are the main security measures taken by the system.

4.4.1. Data encryption and integrity check

In the carbon monitoring system for the AEI, data security during transmission is of utmost importance. We plan to implement SSL/TLS protocols for data encryption to protect the integrity and confidentiality of data as it travels between sensors, servers, and user interfaces. This encryption will prevent unauthorized interception and tampering of data. After transmission, we will employ data integrity checks using checksum and hashing techniques. These methods will ensure that the data received is exactly what was sent, without any alterations. By performing these checks, we can detect and mitigate any corruption or unauthorized changes to the data, thereby maintaining the reliability of our monitoring system.

4.4.2. Access control and authentication

We will establish a robust access control mechanism to safeguard the carbon monitoring system. This mechanism will ensure that only authorized personnel can access sensitive modules and data within the system. Each user must authenticate their identity through multi-factor authentication (MFA), which will add an additional layer of security beyond simple password protection. MFA requires users to provide two or more verification factors, reducing the likelihood of unauthorized access. By implementing strict access controls and robust authentication processes, we protect sensitive data and system functionalities from potential security breaches.

4.4.3. Logging and monitoring tools

To maintain continuous oversight of the system's security status, we plan to integrate comprehensive logging and monitoring tools. These tools will record all significant system activities and data access events, providing a detailed audit trail. Real-time monitoring allows for the immediate detection of any abnormal or suspicious activities, which can trigger alerts to system administrators. This approach minimizes the risk of data leakage and system compromise, thus promoting continuous improvement in system security.

5. Realization of a Carbon Monitoring System for the AEI

Section 5 describes the implementation of the carbon monitoring system for the AEI, firstly describing the operating environment of the system and the technologies used, and then describing in detail the workflow of the system and the interface display part. The system collects data through sensors, electricity meters, and other devices and displays the calculated results to users in real time based on the carbon accounting model.

5.1. System operating environment

This system is based on B/S architecture, using architecture models for development featuring separation between front-end and back-end, where the front-end is constructed using the Vue.js framework, and the back-end is developed utilizing the Spring Boot framework, with MyBatis employed for database access.

Spring Boot is a widely used Java framework known for its simple configuration and robust ecosystem. It offers built-in servers and a range of pre-configured features, simplifying the development process and accelerating application deployment. Additionally, Spring Boot's modular design makes it easy to extend and maintain, which is particularly suitable for complex enterprise applications. MyBatis is an excellent persistence layer framework that simplifies database operations and provides efficient SQL mapping capabilities. Compared to other ORM frameworks, MyBatis offers greater flexibility, allowing developers to write SQL queries directly to meet complex business requirements. Its seamless integration with Spring Boot further enhances the overall performance and data access efficiency of the system.

Therefore, when designing the carbon monitoring system platform, we chose Spring Boot and MyBatis as the back-end and database frameworks, mainly based on their significant advantages in scalability, flexibility, and integration with other systems, as well as their suitability for long-term expansion and optimization of our system.

5.2. Implementation of the carbon monitoring system

This system is capable of achieving real-time data collection by the sensor and displays the results calculated according to the carbon accounting model to the user in real time, and its workflow diagram is shown in Figure 5.

The user interface of the system will provide a detailed presentation of the carbon accounting results and its data sources, respectively, and has been optimized and designed for specific needs and functions to provide a clear, intuitive, and user-friendly presentation of information to support decision-making in greenhouse management. The main interface of the system is subdivided into several modules, each of which provides specific data and functions to meet the user's monitoring and management needs.

The interface diagram of the carbon accounting results is shown in Figure 6, which provides an intuitive, real-time data display of the accounting results according to the power side and the load side respectively, while Figure 7 provides a further display of the carbon accounting results of the load side, which enables the user to clearly and intuitively understand the latest situation of the carbon emissions generated by each module through the interface diagram. In addition, the carbon monitoring system can view the historical emission records by days, months, and years and provide a data comparison function, which is convenient for users to have a more comprehensive understanding of the operation of the greenhouse.

The main interface diagram of data sources is shown in Figure 8, which collects, processes, and stores data related to carbon emissions and carbon sequestration in real time, while also presenting the data sources for each module of carbon accounting in real time. For the power side, the system will record the purchased electricity and photovoltaic power of the greenhouse in real time and make statistics of power generation according to days, months, and years; for the load side, the system will monitor the greenhouse in real time according to the fishery module, planting module and waste module respectively.

Clicking on each module will enter the corresponding module's data and operation display, as shown in Figures 9, 10, and 11, respectively. The power side data can show the power generation status of the greenhouse and the proportion of PV power generation in each period; the fishery module shows the operation of each fish pond and the health status of farmed fish in a comprehensive and detailed manner, and the planting module monitors the environmental conditions of each location according to the type of planting and shows the health status of the plants in real time.

Figure 5
Workflow chart of the carbon monitoring system

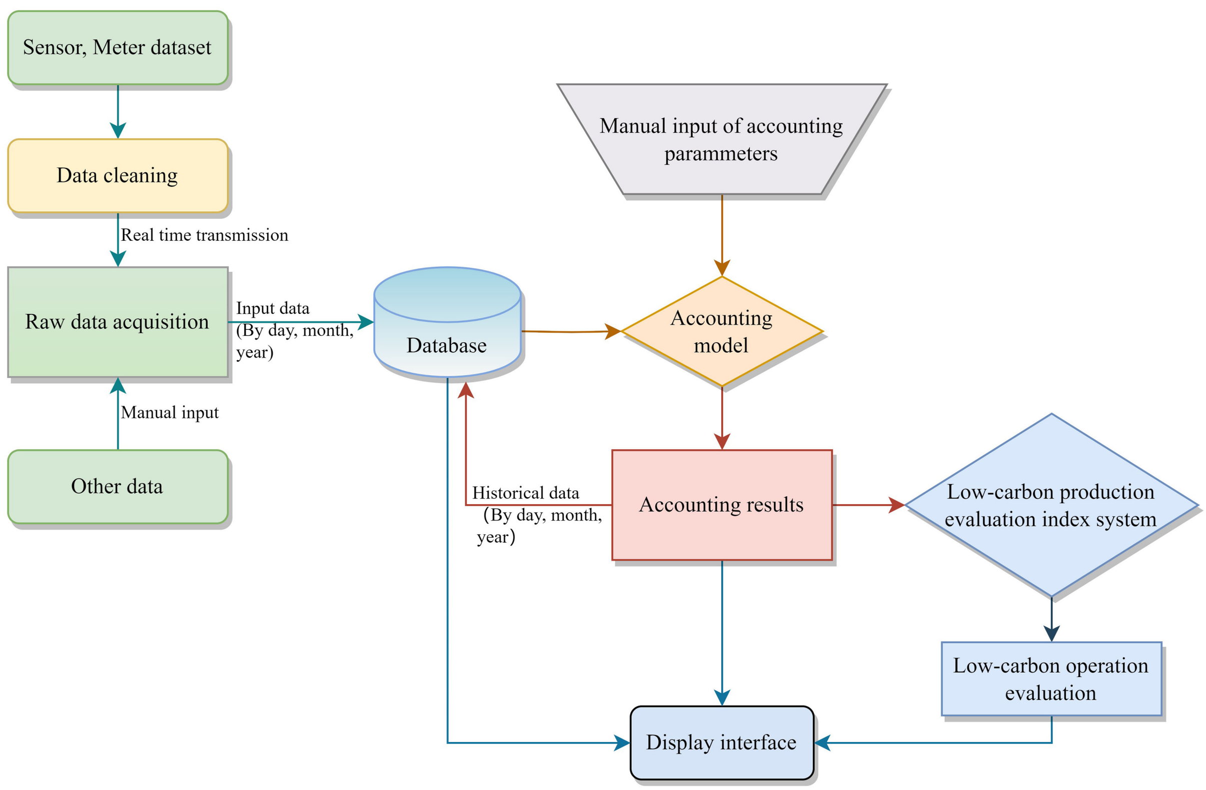


Figure 6
Carbon accounting results interface diagram

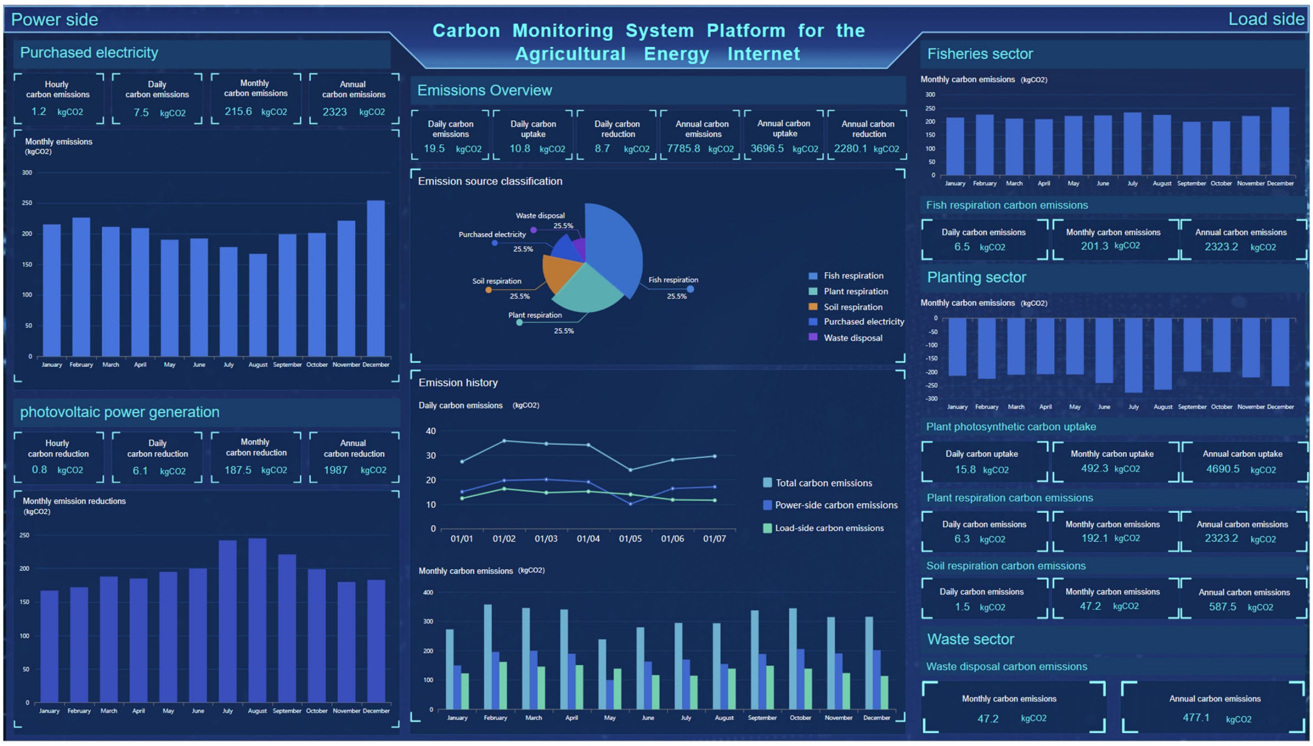


Figure 7
Carbon accounting results load side interface diagram

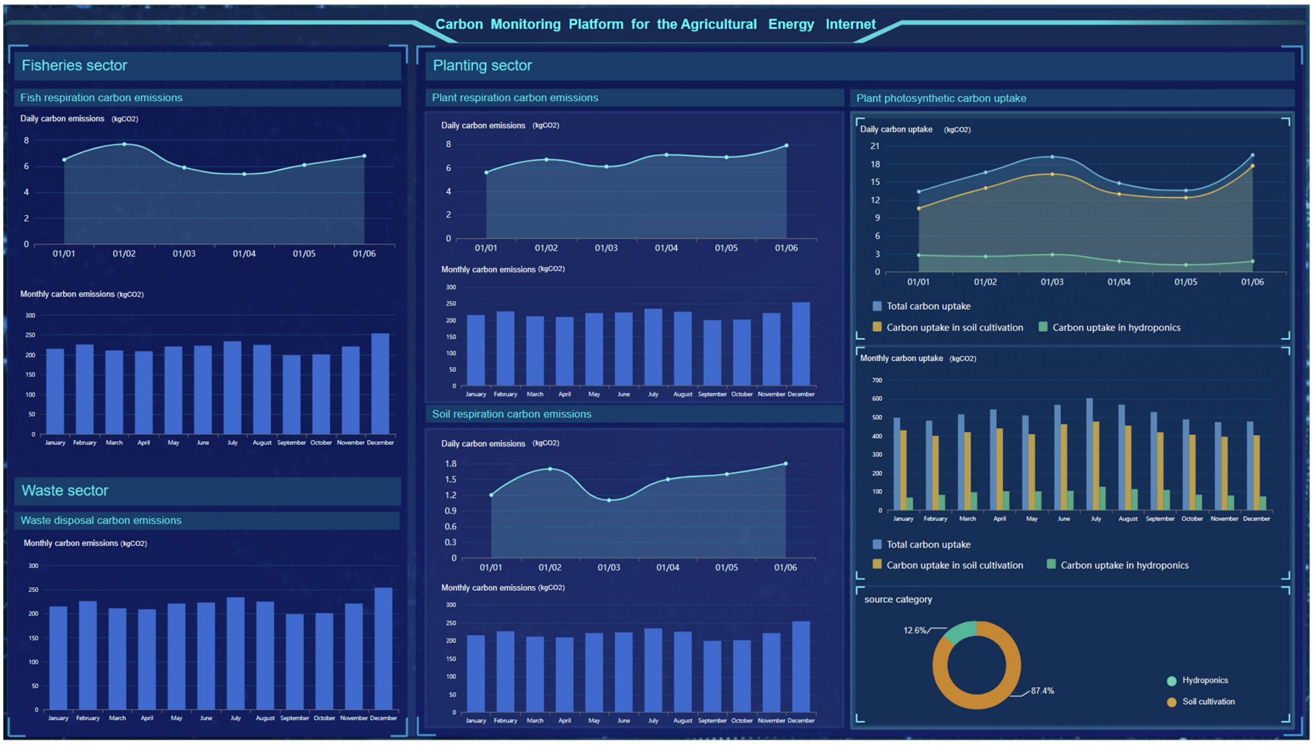


Figure 8
Data source interface diagram

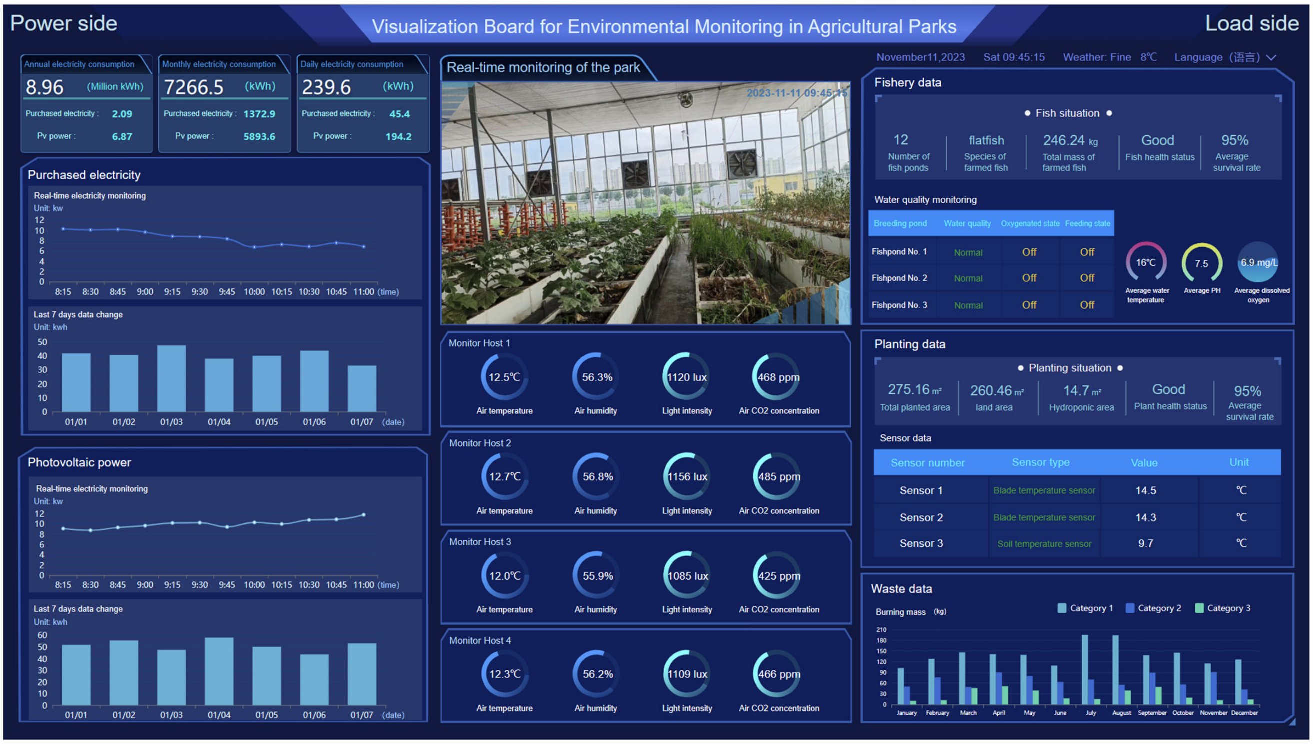


Figure 9
Power generation data interface diagram

Figure 10
Fisheries data interface diagram

Figure 11
Plantation data interface diagram

6. Conclusion

This paper presents a design proposal for a carbon monitoring system platform within the AEI, offering a novel carbon accounting and monitoring solution for the unique environment of aquaponics greenhouses. The system is capable of real-time and accurate monitoring and evaluation of carbon emissions, absorption, and reduction in agricultural parks. Utilizing the IoT environmental monitoring technology and detailed functional module design enables precise carbon accounting in agricultural parks. We have not only expanded the theoretical model of carbon accounting in the AEI but also provided a powerful tool for low-carbon management in practical applications. This design can assist managers in gaining a deeper insight and assessment of the energy efficiency and carbon footprint of greenhouses, leading to the development of more effective emission reduction strategies. However, there are still some potential limitations of this system. A major limitation is the reliance on real-time data from various sensors, which may be affected by hardware failures or environmental factors, leading to inaccuracies. In addition, the current model focuses on specific greenhouse environments and may need to be adapted to different types of agricultural setups.

In future research, we aim to extend this design to a broader range of agricultural production systems to further validate and optimize the model. In addition, reliable fault-tolerant mechanisms and adaptive models should be explored for the limitations of this system to enhance its reliability and applicability. Finally, we hope that future research focuses on integrating artificial intelligence (AI) with the IoT-based system to enhance its functionality. AI algorithms can be employed to predict carbon emissions based on historical data and real-time inputs, enabling proactive management and optimization. Exploring AI-driven data analytics and decision support systems can further empower agricultural managers, thus advancing the overall efficiency and sustainability of agricultural energy systems.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

Xueqian Fu is an Editorial Board Member for the *Journal of Data Science and Intelligent Systems* and was not involved in the editorial review or the decision to publish this article. The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Ruihan Liu: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Xueqian Fu:** Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Xiangrong Zeng:** Writing – original draft.

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