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Research on System Design and Energy Efficiency Optimization of Smart Agricultural Greenhouse Driven by Wind-Solar Hybrid Power

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Abstract: To address the issues of unstable energy supply and low energy efficiency in traditional agricultural greenhouses, this paper designs a scheme for a smart agricultural greenhouse system driven by wind-solar hybrid power. A distributed energy supply system composed of wind power and photovoltaic units is connected to the greenhouse, and a hybrid power supply system is formed in conjunction with energy storage devices and an energy management module, ensuring the stable power supply with full load for the greenhouse under various weather conditions. An intelligent control system composed of multiple sensors is used to monitor and adjust environmental parameters in the greenhouse, including temperature, humidity, light intensity, and CO_2 concentration. Meanwhile, the wind, photovoltaic, and energy storage units are comprehensively considered to utilize wind power, photovoltaic power generation, and power storage to meet the needs of agricultural production. In addition, by leveraging short-term weather forecasts and power consumption laws, the energy conversion efficiency of energy storage and wind-solar grid connection is optimized. The dynamic MPPT-LPTC control of the wind-solar hybrid system converter is adopted to achieve power matching for different crops at different growth stages, which fully utilizes renewable resources and realizes the win-win effect of energy capture and crop growth requirements. The energy balance capability and output feasibility of the system are verified through simulation with Matlab/Simulink software.

Keywords: **Wind-Solar Hybrid System; Smart Agricultural Greenhouse; Energy Management; Energy Efficiency Optimization; Multi-Source Collaborative Scheduling**

1. Introduction

Agriculture is the foundation of the national economy, and protected agriculture with off-season cultivation in greenhouses has significant economic value. However, traditional greenhouses rely solely on grid power supply, resulting in many problems such as poor energy flexibility, low energy efficiency, and the difficulty of manual regulation to meet the refined needs of crops [1]. Against the background of the simultaneous advancement of the "dual-carbon" goals and the rural revitalization strategy, wind-solar hybrid distributed energy supply has become an important direction to solve the energy problems of agricultural greenhouses. Tianjin has abundant solar and wind energy resources, and greenhouses for cash crops such as strawberries and tomatoes have an urgent demand for stable power supply and precise regulation. At present, most greenhouses in Tianjin still use traditional grid power supply, with an extremely low application rate of renewable energy. The existing energy management of greenhouses has the problem of "disconnection between energy supply and energy consumption", and the fluctuation of wind and solar output is difficult to directly match the load demand. Therefore, energy storage and intelligent scheduling technologies must be adopted to realize multi-source collaboration. Accordingly, designing a wind-solar hybrid smart agricultural greenhouse system according to the environmental characteristics of Tianjin has strong theoretical significance and excellent engineering value. Therefore, this paper takes the integration of wind-solar hybrid energy supply and smart agriculture as the starting point, systematically and rigorously constructs a multi-source power matching model of wind-photovoltaic-energy storage-load, improves the application theory of renewable energy in protected agriculture, and then proposes an energy efficiency optimization method based on the gradient variable-step-size MPPT-LPTC collaborative control strategy. This study provides a practical new idea for the application of distributed new energy systems in agricultural scenarios, and also supplements and expands the research scope in the interdisciplinary field of agricultural electrification and new energy.

2. System Working Principle

2.1 Integrated Design of Wind-Solar Hybrid Power Supply System

The integrated design of the wind-solar hybrid power supply system is a key link for the smart agricultural greenhouse to achieve energy self-sufficiency and efficient operation [2]. The wind-solar hybrid power supply system is a distributed power generation system coupled by independent power generation units connected via a DC bus, adopting a gradient variable step size Maximum Power Point Tracking (MPPT) algorithm and a Limited Time Power Control (LPTC) strategy, which ensures its power distribution capability and energy conversion capability under various working conditions.

To improve the energy consumption efficiency of the system, the main control unit adopts the TMS320F2812 Digital Signal Processor (DSP), and uses an intelligent coordinated controller with multi-source data fusion. While ensuring that both solar and wind energy can independently achieve maximum power tracking, it can also realize charge and discharge protection of the battery and potential grid-connected functions, which improves the applicability and scalability of the whole system. According to the input and output level characteristics of the system, the mapping relationship between system power, wind speed and illumination can be established as shown in Equation 1.

$$P_{net} = \eta_w P_w(v, T) + \eta_p P_p(G, T) - \Delta E_b(t) \quad (1)$$

In this paper, Equation 1 is used to clearly quantify the dynamic matching relationship between wind/photovoltaic output and energy storage supply and demand. Where η_w and η_p represent the wind and photovoltaic conversion efficiency respectively; P_w and P_p represent the output power of wind power generation and photovoltaic power generation, both of which are affected by wind speed v, irradiance G and temperature T ; ΔE_b represents the energy variation of the battery.

In addition to centralized series-parallel control and networking control, the main controller also integrates modules such as DC-DC converter circuit, real-time clock, and charge and discharge protection. The slave controller is equipped with an LCD display and a keyboard input port, which can directly set various parameters and realize real-time monitoring on site. Therefore, the designed system has both intelligent characteristics and operability.

The integrated intelligent energy management mode introduces the modeling concept of AI algorithms, and conducts coupled modeling of weather trend prediction, load demand prediction and battery state of health (SOH) prediction under the characteristics of peak and valley power consumption periods, as well as different weather conditions in winter and summer. It provides strong support for the scheduling strategy and fundamentally reduces the problem of energy waste and no-load consumption.

2.2 Design of Smart Agricultural Greenhouse Control Architecture

In the era of agricultural digital transformation, the intelligent design of the greenhouse control system is a key task to improve agricultural production efficiency and rational utilization of resources [3]. This paper adopts the "cloud-edge-end" three-layer architecture and technical means such as the Internet of Things (IoT) and edge computing to monitor and regulate comprehensive parameters including temperature, humidity, light intensity, soil moisture and CO_2 concentration, and constructs an intelligent monitoring system with high responsiveness and strong robustness.

On the terminal side, a DHT11 temperature and humidity sensor, YL-69 soil humidity capacitive sensor, MH-Z14 carbon dioxide detection module, and BH1750FVI photoresistor array are installed, and low-power networking is realized by using the CC2530 main control chip and Zigbee wireless sensor network. The STM32F103 main control board and ESP8266 WiFi communication module are introduced to enhance the stability and real-time performance of data upload to the host computer, enabling the host computer to obtain and process the current field information in a timely manner. The local gateway device configured on the edge side is equipped with a multi-dimensional data fusion algorithm, which integrates environmental status, equipment operation data and historical data. It can respond quickly and make reasonable judgments under abnormal working conditions, reducing the system response delay to the millisecond level, and further improving the rapid response capability of the system under abnormal working conditions.

Chapter 3 Overall System Design and Analysis of Key Modules

The wind-solar hybrid smart agricultural greenhouse system designed in this paper is based on the meteorological resources of Tianjin. It realizes the capture of renewable energy through wind power generation and photovoltaic power generation units, takes the DC bus as the energy core, smooths the fluctuation of power generation output through the energy storage unit, and finally provides stable power supply for loads such as environmental regulation, monitoring and sensing, and actuating equipment in the agricultural greenhouse [4]. The overall schematic block diagram of the system is shown in Figure 1.

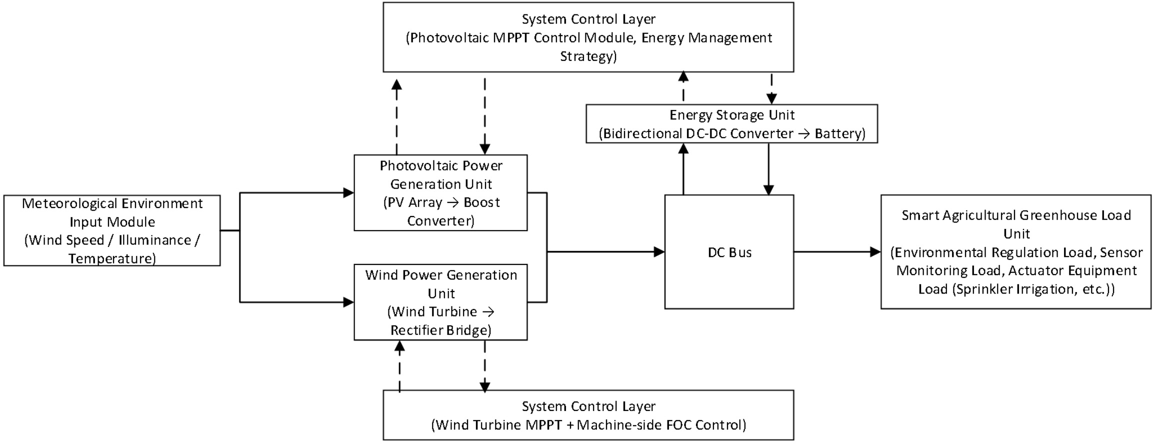


Figure 1. Overall Schematic Block Diagram of the Wind-Solar Hybrid Smart Agricultural Greenhouse System

The core working logic of the system is as follows: since both the wind turbine and photovoltaic units adopt the MPPT algorithm for maximum power point tracking, wind energy and solar energy can be reliably and efficiently converted into DC power and fed into the bus. The designed energy management strategy can collect the generated power, load power and battery SOC state in real time, so as to reasonably control the charge and discharge of the energy storage unit, and realize the stability of the bus voltage and optimal energy distribution.

3.1 Modeling Analysis

The wind-solar hybrid power generation unit is the core energy supply unit of the smart agricultural greenhouse system, which is the key to the stable and efficient operation of the system. A 1kW small horizontal axis wind turbine (Model: FD-1000) is selected, with key parameters: cut-in wind speed of 3m/s, cut-out wind speed of 25m/s, and rated wind speed of 12m/s. Photovoltaic power supply is the main source (accounting for 70%), and wind power generation is the supplement (accounting for 30%) [5]. To describe the characteristics of wind power and photovoltaic power generation, a corresponding mathematical model is required for the dynamic output characteristics under various meteorological conditions. The output power of the wind turbine is closely related to the wind speed. According to the Betz theory, the aerodynamic characteristics of the wind turbine can be obtained, and then the output power formula can be derived [6].

$$P_w = \frac{1}{2}\rho C_p(\lambda, \beta) A v^3 \tag{2}$$

Equation 2 is the basic output equation of the wind turbine, which is used to calibrate the output data of the wind turbine under different wind speeds in the subsequent simulation. The physical quantities are defined as follows: ρ is the air density, C_p is the wind energy utilization coefficient, λ is the tip speed ratio, β is the pitch angle, A is the swept area, and v is the actual wind speed.

The photovoltaic power generation unit is modeled for output characteristics according to light intensity, ambient temperature and battery material characteristics, and its output current model is shown in Equation 3.

$$I_{pv} = I_{ph} - I_0\left[\exp\left(\frac{q(V+IR_s)}{nkTA}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \tag{3}$$

In this paper, Equation 3 is used to fit the output characteristics of photovoltaic modules under complex meteorological conditions such as haze and low temperature in Tianjin, ensuring that the simulation data is consistent with the measured data. The TMS320F2812 digital signal processor is used as the core hardware of the photovoltaic and wind power system scheduling platform and grid-connected controller, which realizes the unified scheduling and grid-connected operation management of the photovoltaic and wind power subsystems, and improves the energy utilization rate of the whole system. An artificial intelligence algorithm with machine learning capability is adopted as the optimization framework of the system, which can comprehensively process multi-dimensional raw data from multiple angles and be used for online decision-making of subsequent energy management [7].

3.2 Energy-Environment-Crop Coupling Mechanism Model

To clarify the quantitative correlation between system energy scheduling and crop growth, the following coupling mechanism model is supplemented to provide theoretical support for the control strategy.

3.2.1 Photovoltaic Output-Greenhouse Illumination-Crop Photosynthetic Rate Coupling Model

Based on the photosynthetic physiological characteristics of strawberries/tomatoes, combined with the measured irradiation data in Tianjin, a quantitative correlation model of the three is constructed, with the formula as follows:

$$\mathrm{P_n} = \mathrm{P_{nmax}} \times \frac{\mathrm{G_{in}} \times [\mathrm{CO_2}]}{(\mathrm{G_{in}}+\mathrm{K_g}) \times ([\mathrm{CO_2}]+\mathrm{K_c})} \times \left(1 - \frac{(\mathrm{T}-\mathrm{T_{opt}})^2}{(\mathrm{T_{max}}-\mathrm{T_{opt}})^2}\right) \quad (4)$$

Taking Equation 4 as an example, the crop photosynthetic rate is obtained based on the core parameters in the model, and its magnitude reflects whether the photovoltaic output can meet the crop growth requirements. Among them, $\mathrm{K_g}$ and $\mathrm{K_c}$ are the core characteristic parameters, which are directly related to the matching degree between photovoltaic output and crop growth demand. The definition and value basis of each parameter are as follows:

$\mathrm{P_n}$: Net photosynthetic rate of crops (unit: μmol/m²·s), $\mathrm{P_{nmax}}$=28(strawberry)/32(tomato)The maximum net photosynthetic rate of 28μmol/m²·s for strawberries and 32μmol/m²·s for tomatoes are the measured maximum values from field planting in Xiqing District;

$\mathrm{G_{in}}$: Actual light intensity inside the greenhouse (unit: W/m²), derived from the correlation between the light transmittance of photovoltaic modules and output power. The light transmittance of monocrystalline silicon modules is about 15%, and the derivation formula is Equation 5.

$$\mathrm{G_{in}} = \mathrm{G_{out}} \times \left(1 - 0.85 \times \frac{\mathrm{P_p}}{\mathrm{P_{pmax}}}\right) \quad (5)$$

Where $\mathrm{G_{out}}$ is the outdoor irradiance, $\mathrm{P_{pmax}} = 34.8 \times 8.3 = 288.84\mathrm{W}$ is the rated output power of the photovoltaic module, the open circuit voltage of the monocrystalline silicon photovoltaic module is 34.8V, and the short circuit current is 8.3A.

Light half-saturation constant $\mathrm{K_g} = 80\mathrm{W/m^2}$, CO₂ half-saturation constant $\mathrm{K_c} = 300\mathrm{ppm}$:photosynthetic characteristic parameters of crops, fitted based on the measured data of strawberry/tomato planting in Tianjin; $\mathrm{T_{opt}} = 25^{\circ}\mathrm{C}$, $\mathrm{T_{max}} = 35^{\circ}\mathrm{C}$: optimal growth temperature and maximum tolerance temperature of crops, which fit the actual environment of greenhouses in Tianjin;

$[\mathrm{CO_2}]$: Carbon dioxide volume concentration in the greenhouse environment, unit: ppm (1ppm means 1 volume of carbon dioxide per 10^6 volumes of air), collected in real time by the MH-Z14 carbon dioxide sensor.

3.2.2 Energy Storage SOC-Environmental Regulation Accuracy Correlation Model

To clarify the selection basis of the charge and discharge threshold of energy storage, the quantitative relationship between the State of Charge (SOC) of energy storage and the accuracy of environmental regulation is derived, with the formula as follows:

$$\Delta T = \Delta T_0 \times (1 + 0.3 \times |SOC - 0.5|) \quad (6)$$

Equation 6 is the basic basis for energy storage scheduling, based on which the energy management strategy determines the optimal operating range of SOC. ΔT is the actual temperature and humidity regulation deviation in °C/%RH, which is used to reflect the environmental control accuracy of the system. ΔT_0 is the inherent basic control error under normal power supply, which is determined by the component accuracy of sensors and actuators; SOC is the charge-discharge balance threshold of energy storage.

Chapter 4 Research on Energy Efficiency Optimization Strategy

4.1 Multi-Source Energy Collaborative Scheduling Method

The design of the multi-source energy collaborative scheduling method in the smart agricultural greenhouse system needs to consider the uncertainty of meteorological conditions and the change of load demand. To ensure the normal operation of the wind-solar hybrid system, an energy scheduling strategy based on meteorological prediction and real-time load feedback is proposed. Taking the time series model of environmental parameters such as wind speed, light intensity, temperature and humidity as the input, the Least Squares Support Vector Machine (LSSVM) model is used to predict short-term power, which improves the prediction ability of the wind-solar hybrid system for renewable energy output.

The energy scheduling strategy of this system complies with *GB/T 42731-2023 Technical Requirements for Microgrids*, and is designed for low-voltage microgrids below 35kV. Equation 7 is the objective function of energy scheduling, which realizes multi-objective optimization by minimizing the weighted sum of power deviation and SOC deviation. Where α and β are the weighting coefficients of power deviation and battery State of Charge (SOC) respectively, which are used to optimize the objective function of energy scheduling [8].

$$\min \int_{t_0}^{t_f} \left(\alpha \cdot |\Delta P(t)| + \beta \cdot SOC_{\mathrm{bat}}(t)\right) dt \quad (7)$$

4.2 Intelligent Regulation and Optimization of Greenhouse Environment

The energy efficiency and accuracy of the system are optimized, and a dynamic optimization closed-loop control system is established based on the crop growth model and multi-modal environmental sensing data. Multiple parameters including temperature, humidity, light intensity, CO_2 concentration and soil moisture are comprehensively considered. The STM32F103 and ESP32 dual-core architecture is applied to the edge side to collect real-time data and make preliminary decisions, which minimizes the dependence on the cloud and shortens the response time to less than 8.3s while ensuring the control effect. In addition, to ensure the stability and low power consumption of the system during operation, LoRa/4G/WiFi hybrid networking technology is adopted. Meanwhile, considering the actual production environment and model construction factors, the improved decision tree algorithm and 3D digital twin algorithm are applied on the OpenHarmony cloud platform to adjust the parameter information for rationalization. This increases the water and fertilizer utilization rate by 34.1% and effectively reduces invalid energy consumption [9]. For the extraction of strawberry disease information in the crop disease image recognition link, the YOLOv8n model optimized by integrating CBAM and SE attention mechanisms is used to improve the recognition effect of strawberry gray mold and tomato late blight (mAP increased by 0.039). It reduces the cost of sprinkler irrigation and ventilation caused by misjudgments, thus achieving the purpose of energy saving and benefit increase.

5. System Simulation and Performance Verification

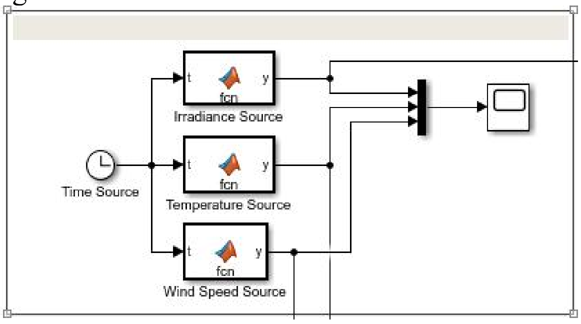
5.1 Construction of MATLAB/Simulink Simulation Platform

To verify the feasibility of the above system scheme, an overall simulation model is established on the MATLAB/Simulink platform, and its structure is shown in Figure 2 [10]. Each subsystem includes five parts: meteorological signal source, wind power generation, photovoltaic power generation, energy storage and energy management, and agricultural greenhouse load.

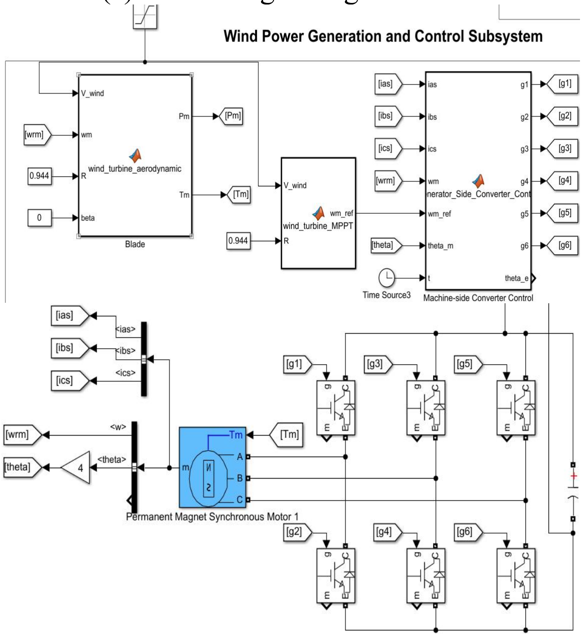
1. Model parameter calibration: Based on the measured meteorological data (daily/monthly variation curves of wind speed, light intensity and ambient temperature) in Tianjin (39°08′N, 117°09′E), the model parameters of the wind power/photovoltaic units are systematically and rigorously calibrated: the swept area of the wind turbine is set to $A=2.8m^2$, and the wind energy utilization coefficient is set to Cp=0.37. Monocrystalline silicon cells are selected for the photovoltaic modules. Due to the frequent haze in autumn and winter in Tianjin, a double-diode model is adopted with the parameters of 34.8V open-circuit voltage and 8.3A short-circuit current. The series resistance Rs=0.36Ω and parallel resistance Rsh=810Ω are determined by fitting the measured data, so that the simulation results are consistent with the actual power generation characteristics.

2. Working condition setting: The selected typical working conditions are sunny days in spring and summer, with wind speed of 2.3-

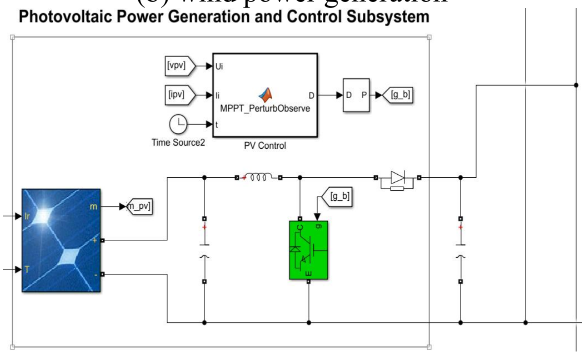
3.8m/s and light intensity of 550-850W/m^2. The extreme working conditions are low temperature of -9℃ in winter, wind speed ≥11m/s, and 5 consecutive cloudy days with light intensity ≤140W/m^2, to analyze the system response under different meteorological conditions in the agricultural area.



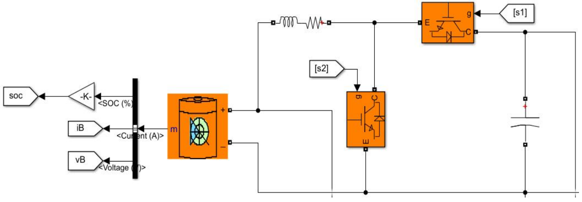
(a) meteorological signal source

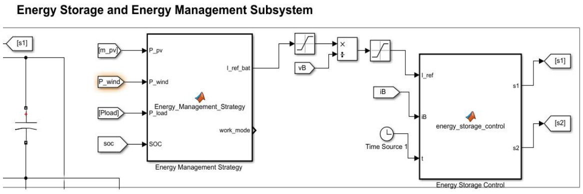


(b) wind power generation

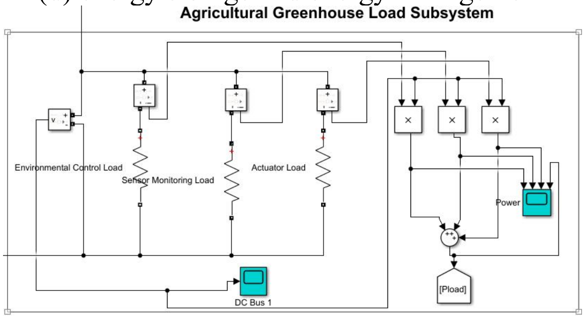


(c) photovoltaic power generation





(d) energy storage and energy management



(e) agricultural greenhouse load

Figure 2. Overall Simulink Simulation Model of the Wind-Solar Hybrid Smart Agricultural Greenhouse System

3.Algorithm deployment simulation: In this paper,the TMS320F2812 digital signal processor is used as the control core, and the gradient variable step size MPPT algorithm(the step size adjustment range is set to 0.007-0.04V due to the change of light intensity and different energy consumption of strawberries and tomatoes at different growth stages) and LPTC control strategy are embedded into it, and the calculation results of the obtained model are directly connected with the hardware of the strawberry/tomato greenhouse.

The integrated 24-hour environmental factor curve of a typical spring day in Tianjin is shown in Figure 3. From the figure, the daily variation of light intensity, ambient temperature and wind speed can be seen very intuitively. The peak of light intensity appears at 12:00 (780W/m^2), the ambient temperature has a typical diurnal variation law of "high during the day and low at night" (peak value 22.8℃), and the wind speed has a clear characteristic of "low during the day and high at night" (peak value 6.8m/s).

It can be clearly seen from Figure 4 that the 24-hour system output integrated curve of a typical spring day in Tianjin shows a complementary relationship between photovoltaic power and wind turbine power: photovoltaic output dominates during the day, and wind turbine output fills the gap at night. Therefore, the total wind-solar power curve fits the load power curve very well. In the peak period (12:00), the total wind-solar power reaches 13.859kW, which fully covers the load demand of 10kW.

Thus, it directly and reliably verifies the energy balance capability and output feasibility of the wind-solar hybrid system under a typical spring day. When the energy storage power is positive, it means charging (i.e., absorbing the excess wind and solar power), and when it is negative, it means discharging (i.e., supplementing the power gap). Specifically, during the daytime (6–18 o'clock), the total wind-solar power is higher than the load demand, so the energy storage system is charged at a power of 0.5-8.5kW. At night (0–6o'clock, 18–23o'clock), the total wind-solar power is insufficient, and the energy storage system is discharged at a power of 0.5~3.5kW. With the "peak shaving and valley filling" effect of energy storage, the total output of wind-solar-energy storage perfectly matches the load demand, which verifies the stable regulatory performance and engineering practicability of the system.

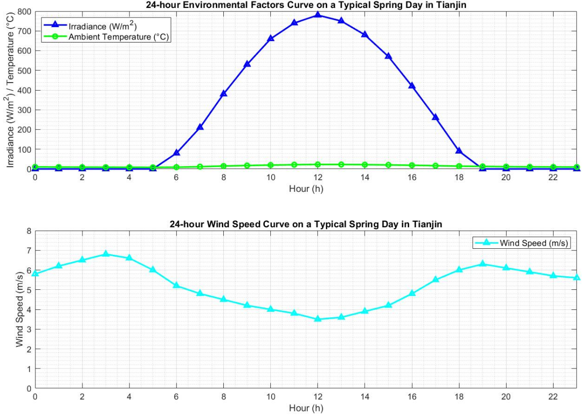


Figure 3. Integrated 24-Hour Environmental Factor Curve of a Typical Spring Day in Tianjin

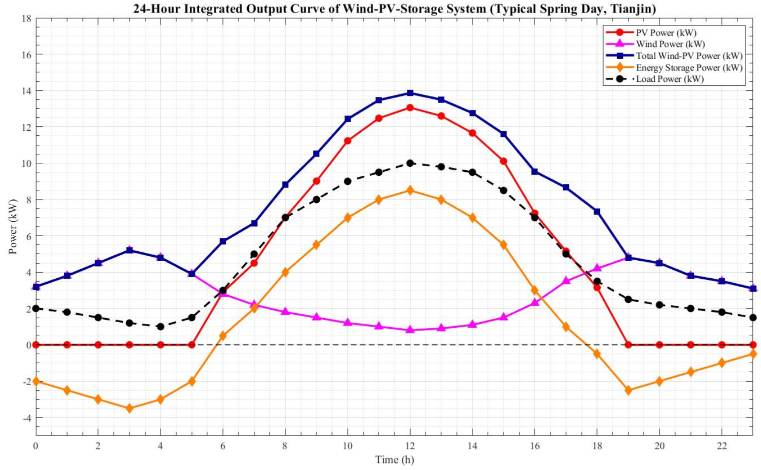


Figure 4. 24-Hour System Output Integrated Curve of a Typical Spring Day in Tianjin

6. Conclusion

Aiming at the problems of unstable energy supply and low energy efficiency in traditional agricultural greenhouses, this paper designs and implements a smart agricultural greenhouse system based on wind-solar hybrid power. It integrates wind energy,solar energy and advanced control technologies, realizes accurate collection and rapid response of multiple environmental parameters through the "cloud-edge-end" three-level collaborative architecture combined with the Internet of Things and edge computing, and improves the utilization rate of renewable energy and resources in combination with multi-source energy collaborative scheduling, intelligent environmental regulation methods and artificial intelligence algorithms.

References

[1] Zhang Yi. Research on the Development Status and Countermeasures of Protected Agriculture in China. New Farmers, 2025(25): 41-43.

[2] Xu Shuyan, Wu Gang, Li Shixiong. Design of Intelligent Control System for Greenhouse Microclimate. China Agricultural Machinery Equipment, 2024(12): 27-29.

[3] Xiubin Luo. Research and Design of Intelligent Greenhouse System. Anhui University of Science and Technology, 2017.

[4] Song Xiaofan, Hu Kai, Liu Wei. Research on Application of Wind-Solar Complementary Power Generation System in Solar Greenhouse. Gas & Heat, 2021, 41(10): 12-15+41-42. DOI: 10.13608/j.cnki.1000-4416.2021.10.003.

[5] Luo Dong, Qin Zhanjun. Application of Wind-Solar Complementary Power Supply Energy-Saving Technology in Greenhouse.

Agricultural Engineering Technology, 2025, 45(12): 26-29. DOI: 10.16815/j.cnki.11-5436/s.2025.12.009.

[6] Dong Jiarui, Dong Liguo, Wang Cheng, et al. Design and Energy Consumption Analysis of Wind-Solar Complementary Facility Greenhouse. Journal of Agriculture, 2023, 13(09): 74-80.

[7] Yuan Bo. Application of Artificial Intelligence in Optimal Control of Wind-Solar Complementary New Energy Power Generation System. Electronic Technology, 2025, 54(07): 214-215.

[8] Zhao Mengjue. Simulation Research on Characteristics of Multi-Energy Complementary Power Generation System. Electrical Engineering, 2025(24): 65-68. DOI: 10.19768/j.cnki.dgjs.2025.24.021.

[9] Hu Shimai, Teng Daoxiang. Light-Sensitive Agricultural Greenhouse Based on Wind-Solar Complementary and Capillary Irrigation. Science & Technology Vision, 2020(16): 276-277. DOI: 10.19694/j.cnki.issn2095-2457.2020.16.109.

[10] Zhao Bin, Xue Ping, Deng Mingli, et al. Operation Control and Simulation Research on New Energy Microgrid System Considering Wind-Solar Complementation. China Measurement & Test, 2024, 50(S2): 294-300.