Comprehensive Economic Benefits Evaluation Model of Greenhouse Photovoltaic

Zhonghui Wei, Xueqian Fu*, Feifei Yang and Shaoqian Fan

College of Information and Electrical Engineering, China Agricultural University, Beijing 100083, China

Abstract: Photovoltaic integrated greenhouse has become an important form of deep coupling between new energy power generation and facility agriculture. Greenhouse photovoltaic power generation will affect the light environment, thermal environment, and water environment of facility agriculture. The precise coupling modeling method of greenhouse photovoltaics and loads is to carry out the basis for the calculation of comprehensive economic benefits of greenhouse photovoltaics. This paper studies the deep coupling modeling method of greenhouse photovoltaic and greenhouse load, and accurately calculates the changes in the light environment, thermal environment, and water environment regulation load of facility agriculture caused by the laying of greenhouse photovoltaics. Firstly, the greenhouse photovoltaic power generation model and the environmental regulation load model of facility agriculture are established; secondly, the coupling relationship between greenhouse photovoltaic power generation and facility agricultural load is described, and on this basis, the comprehensive economic benefits evaluation model of photovoltaic power generation is proposed. The 10kV medium-voltage distribution network and facility agricultural greenhouse that exist in the northern region are used as the research objects. It verifies the validity of the photovoltaic comprehensive economic benefits evaluation model proposed in this paper.

Keywords: Photovoltaic, Greenhouse, Photovoltaic power, Facility agriculture load, Coupling modeling, Comprehensive benefits evaluation.

1. INTRODUCTION

In the current energy consumption structure of the world, traditional fossil energy still occupies the vast majority of the energy market [1]. In recent years, with the continuous strengthening of the world's awareness of environmental protection, various new energy sources have been widely developed, and the construction of a power system with renewable energy as the main body has become a key direction for future power systems development. Due to the dual characteristics of environmental protection and renewable energy of solar energy, the progress of photovoltaic power generation technology provides the possibility for renewable energy to meet the energy demand of society [2]. For example, the government of Bangladesh has set a target of producing 6000MW of electricity through solar photovoltaics to ensure sufficient electricity supply in each region by 2041 [3].

A Photovoltaic integrated greenhouse is an important form of existence that combines solar power generation technology with greenhouse agricultural production. It not only has power generation capacity but also provides a suitable growth environment for crops. At the same time, photovoltaic integrated greenhouse technology solves the problem of photovoltaic installation land and agricultural production. The contradiction between land use has developed a new model of "agricultural and solar complementary" energy production and agricultural production. Greenhouses are the most energy-intensive sector of agricultural production. There are various facility agricultural loads in greenhouses. These facility agricultural loads maintain the climate of the greenhouse in a stable range and provide a suitable microclimate for the growth of greenhouse crops. The agricultural loads such as the supplementary light, heat pump, and water pump in the greenhouse can control the light environment, thermal environment, and water environment of facility agriculture [4].

Modern photovoltaic agriculture has shown good development prospects. In addition to supplying electricity for agricultural production in the greenhouse itself, photovoltaic integrated greenhouses can also sell the excess electricity generated to the grid system to generate direct economic benefits [5]. Carbon emission reduction in the power industry is under enormous pressure. Since photovoltaic power generation can replace traditional fossil energy to achieve carbon emission reduction, it can generate low-carbon benefits. At the same time, a large number of distributed photovoltaics connected to the distribution network will have an impact on the economic operation of the distribution network [6].

*Address correspondence to this author at the College of Information and Electrical Engineering, China Agricultural University, Beijing, China;
Tel: +8618813103877; E-mail: fuxueqian@cau.edu.cn

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There have been many studies on photovoltaic greenhouses today. Hassanien *et al*. considered the impact of photovoltaic shading on pepper growth from the perspective of agricultural systems but did not involve photovoltaics and the energy situation of the greenhouse [7]. Ezzaeri *et al*. studied the impact of photovoltaics on the greenhouse climate, but did not involve the energy consumption analysis of the agricultural load inside the greenhouse [8]. Fern *et al*. analyzed the impact of greenhouse photovoltaics on the light environment of facility agriculture but did not involve the light environment regulation load of facility agriculture and the impact on other agricultural loads [9]. Llna *et al*. studied the greenhouse application of hybrid photovoltaics and organic photovoltaics, but did not study the operation mode and economics of photovoltaics [10]. Zhang *et al*. took the photovoltaic integrated greenhouse as the research object, carried out economic optimization and scheduling of greenhouse agricultural production activities and energy consumption, but did not describe the coupling relationship between facility agricultural load and greenhouse photovoltaics in detail [11]. To sum up, most of the current research on photovoltaic integrated greenhouses is concentrated in the respective fields of agriculture and energy, without accurate modeling of the coupling relationship between photovoltaic systems and agricultural systems, and the economic benefits of greenhouse photovoltaics. The study did not consider the impact of photovoltaic systems on the economics of distribution grids and the impact of energy consumption characteristics of greenhouse loads on the economics of greenhouse photovoltaics.

The main contributions of this paper are mainly reflected in the following aspects: (1) Considering multiple meteorological and environmental factors, facility agricultural loads inside the greenhouse are accurately modeled; (2) The coupling link between greenhouse photovoltaics and greenhouse loads is established, and the impact of greenhouse roof photovoltaic on the facility agricultural loads inside the greenhouse is detailed; (3) Based on the accurate modeling of greenhouse photovoltaics and greenhouse loads, an evaluation model of the comprehensive benefits of greenhouse photovoltaic is established for practical projects.

2. PHOTOVOLTAIC POWER GENERATION MODEL

The greenhouse photovoltaic power generation model is related to many factors such as light, temperature, wind speed, and photovoltaic layout area. The photovoltaic active power on the greenhouse roof is calculated in formula (1) [12]:

$$P_{\mathrm{PV}}=d_{\mathrm{PV}}\times P_{\mathrm{rated}}\times\frac{E_{\mathrm{PV}}}{E_{\mathrm{STC}}}\times\left[1+\alpha_{\mathrm{p}}\left(T_s-T_{\mathrm{stc}}\right)\right] \tag{1}$$

where P_{PV} represents the active power of the photovoltaic panel. E_{PV} represents the solar radiation intensity on the surface of photovoltaic panels. P_{rated} represents the rated power of photovoltaic power generation. T_{s} represents the surface temperature of photovoltaic panels under current conditions. E_{STC} represents the solar radiation intensity on the surface of the photovoltaic panel under standard conditions = 1 kW/m^2.

The rated power of photovoltaic power generation is calculated in formula (2) [11]:

$$P_{\mathrm{rated}}=\eta_{\mathrm{STC}}\times E_{\mathrm{STC}}\times A\times s_{\mathrm{r}} \tag{2}$$

where η_{STC} represents the photoelectric conversion efficiency per unit area of photovoltaic panels under standard conditions, which is 6%, 14%, and 13% for amorphous, monocrystalline, and polycrystalline silicon photovoltaic panels, respectively. A represents the area of the top of the greenhouse facing the sun. s_{r} represents the shading rate on top of the greenhouse.

The surface temperature of the photovoltaic panel is calculated in formula (3) [11]:

$$\begin{aligned}T_s = T_{\mathrm{outdoor}} + 0.138\left(1+0.031T_{\mathrm{outdoor}}\right)\times \\ \left(1-0.042v_{\mathrm{PV}}\right)\times E_{\mathrm{PV}}\end{aligned} \tag{3}$$

where v_{PV} represents the wind speed. T_{outdoor} represents the outdoor temperature.

3. GREENHOUSE AGRICULTURAL LOAD MODEL

Establishing an accurate facility agricultural load model is the key to calculating the energy consumption of greenhouse agricultural production. The necessity of modeling is that only by accurately calculating the energy consumption of the facility agricultural load can the economic benefits of the photovoltaic integrated greenhouse be accurately calculated.

3.1. Supplementary Light Load Model

The maximum photosynthetic rate of crops is calculated in formula (4):

$$R_m = R_m\left(T_{opt}\right)\times\left[\left(\frac{T_{upper}-T}{T_{upper}-T_{opt}}\right)\times\left(\frac{T-T_{base}}{T_{opt}-T_{base}}\right)^{\frac{T_{opt}-T_{base}}{T_{upper}-T_{opt}}}\right]^{\frac{T_{opt}}{T}} \quad (4)$$

where $R_m(T_{opt})$ represents the maximum photosynthetic rate of crops at optimum temperature, μmol/(m^2•s). T_{opt}, T_{upper}, and T_{base} represent the optimum temperature, maximum temperature, and minimum temperature for crop growth, respectively.

The light intensity of the crop surface should be maintained between the light compensation point and the light saturation point of the crop. The crop light compensation point is calculated in formula (5) [4]:

$$I_{LCP} = \frac{R_m}{\alpha_0}\times\ln\left(\frac{R_m}{R_m - R_d}\right) \quad (5)$$

where I_{LCP} represents the light compensation point. α_0 represents the apparent quantum efficiency. R_d represents the dark respiratory rate, μmol/(m^2•s).

The crop light saturation point is calculated in formula (6) [4]:

$$I_{LSP} = \frac{R_m\times\ln(100)}{\alpha_0} \quad (6)$$

where I_{LSP} represents the light saturation point.

The net irradiance on the crop surface should be limited between the light compensation point and the light saturation point, as shown in formula (7):

$$I_{LCP} \le R_n \le I_{LSP} \quad (7)$$

where R_n represents the net radiation at the crop level.

The solar radiation intensity in the greenhouse is calculated in formula (8):

$$I_{solar} = \alpha_1\left(1 - s_r\right)I_{outsolar} \quad (8)$$

where I_{solar} represents the solar radiation intensity in the greenhouse. $I_{outsolar}$ represents the solar radiation intensity outside the greenhouse, W/m^2.

For metal halide lamps, the conversion relationship between the two light intensity units is shown in formula (9) [4]:

$$I_E = \frac{-48}{10^4}\left(\frac{I_t}{11.57}\right)^2 + 7\left(\frac{I_t}{11.57}\right) - 0.41 \quad (9)$$

where the unit of I_E and I_t are W/m^2 and μmol/(m^2•s) respectively.

The net radiation on the crop surface is calculated in formula (10):

$$R_n = 0.86\left(1 - e^{-0.7LAI}\right)\left(I_{solar} + P_E\right) \quad (10)$$

where LAI represents the leaf area index. P_E represents the light intensity of the light supplement lamp, W/m^2.

The light intensity of the light supplement lamp is calculated in formula (11) [13]:

$$P_E = \frac{\omega\cdot N\cdot U\cdot M}{L\cdot W_d} \quad (11)$$

where ω represents the luminous flux of the light supplement lamp. N represents the number of light supplement lamps. U is the utilization coefficient of supplementary light in the greenhouse, which needs to be obtained by looking up the table according to the room index of the greenhouse. M represents the maintenance factor of the light supplement lamp. L represents the length of the greenhouse. W_d represents the width of the greenhouse.

The room index of the greenhouse is calculated in formula (12) [13]:

$$K = \frac{L\cdot W_d}{H\cdot\left(L + W_d\right)} \quad (12)$$

where K represents the room index of the greenhouse. H represents the height of the light supplement lamp from the illuminated surface.

After the number of the light supplement lamp is determined by the above formula (11), the total power required for supplementary light for greenhouse crops is calculated in formula (13):

$$P_{light} = N\cdot P_{sing} \quad (13)$$

where P_{light} represents the total power of the light supplement lamp. P_{sing} represents the power of a single light supplement lamp.

3.2. Thermal Load Model

The thermal demand of the glass greenhouse considers the heat transfer loss of the envelope structure and the heat loss of the indoor and outdoor air exchange. The thermal demand of the glass greenhouse is shown in formula (14) [14]:

$$Q = C_{\mathrm{ht}} A_{\mathrm{cover}} \left(T_{\mathrm{indoor}} - T_{\mathrm{outdoor}}\right) + \rho_{\mathrm{i}} N_{\mathrm{c}} V \left[c_{\mathrm{p}} \left(T_{\mathrm{indoor}} - T_{\mathrm{outdoor}}\right) + h_{\mathrm{va}} \left(W_{\mathrm{i}} - W_{\mathrm{o}}\right)\right] \quad (14)$$

where Q represents the original heat demand power of the greenhouse. C_{ht} represents the heat transfer coefficient of glass. A_{cover} represents the glass-covered area of the greenhouse. T_{indoor} and T_{outdoor} represent the indoor and outdoor temperature, respectively. N_{c} represents the number of air changes per second in the greenhouse. V represents the volume of the greenhouse. c_{p} represents the specific heat at a constant pressure of indoor air. h_{va} represents the latent heat of vaporization of water. W_{i} represents the moisture content of indoor air. W_{o} represents the moisture content of outdoor air.

The thermal demand power of the greenhouse is calculated in formula (15):

$$Q_{\mathrm{H}}\left(t\right) = Q - Q_{\mathrm{lamp}} - Q_{\mathrm{sun}} \quad (15)$$

where Q_{sun} represents the thermal power generated by indoor solar radiation. Q_{lamp} represents the thermal power generated by the light supplement lamp. The calculation formulas of Q_{sun} and Q_{lamp} are shown in formulas (16) and (17), respectively:

$$Q_{\mathrm{sun}} = A I_{\mathrm{solar}} \quad (16)$$

$$Q_{\mathrm{lamp}} = \eta A P_{\mathrm{E}} \quad (17)$$

where η represents the conversion coefficient of lamp power into thermal power.

The air source heat pump can realize the conversion of electrical energy to thermal energy, and the relationship between the output thermal power and the consumed electrical power is shown in formula (18):

$$P_{\mathrm{H}} = Q_{\mathrm{H}} / C_{\mathrm{H}} \quad (18)$$

where Q_{H} represents the output thermal power of the air source heat pump. C_{H} represents the heating coefficient of the air source heat pump. P_{H} represents the electric power consumed by the air source heat pump.

3.3. Irrigation Load Model

In this paper, using the greenhouse water demand model proposed in the paper [15-17], a calculation method of energy consumption for precise irrigation in the greenhouse is given, and the specific process is given below.

The differential equation describing the dynamic change of greenhouse soil water content is shown in formula (19):

$$\frac{\mathrm{d}S_{\mathrm{W}}}{\mathrm{d}t} = W_0 - ET_{\mathrm{C}} \quad (19)$$

where S_{W} represents the soil water content of the greenhouse. W_0 represents the water demand for irrigation, mm/d. ET_{C} represents the crop evapotranspiration, mm/d.

In much research, the basis for controlling the greenhouse irrigation load is to control the soil water content unchanged, so the first derivative of S_{W} concerning time is equal to zero, and W_0 is calculated in formula (20):

$$W_0 = ET_{\mathrm{C}} = ET_0 \cdot K_{\mathrm{C}} \quad (20)$$

where ET_0 represents the reference evapotranspiration, mm/d. K_{C} represents the crop coefficient.

The reference evapotranspiration of the greenhouse is calculated by the modified Panman-Monteith equation, and the calculation formula is shown in formula (21):

$$ET_0 = \frac{0.408\Delta\left(R_{\mathrm{n}} - G\right) + \lambda \frac{1713}{T_{\mathrm{air}} + 273}\left(e_{\mathrm{s}} - e_{\mathrm{a}}\right)}{\Delta + 1.64\lambda} \quad (21)$$

where G represents the soil heat density, λ is the psychometric constant, 0.008. T_{air} represents the temperature of the air in the greenhouse. e_{s} represents the saturation vapour pressure. e_{a} represents the average saturation vapour pressure. Δ represents the slope of the vapor pressure curve.

e_{s} is calculated in formula (22):

$$e_s = 0.6108 \times \exp\left(\frac{17.27 \times T_{\mathrm{air}}}{T_{\mathrm{air}} + 273.3}\right) \quad (22)$$

Δ is calculated in formula (23):

$$\Delta = \frac{4098 \times e_s}{\left(T_{\mathrm{air}} + 237.3\right)^2} \quad (23)$$

e_{a} is calculated in formula (24):

$$e_a = e_s \times RH_{\mathrm{air}} \quad (24)$$

where RH_{air} represents the relative humidity of greenhouse air.

RH_{air} is calculated in formula (25):

$$RH_{air}=H_{air} / H_{air,sat} \tag{25}$$

where $H_{air,\ sat}$ represents the saturated vapour concentration. H_{air} represents the vapour concentration of the greenhouse air.

$H_{air,\ sat}$ is calculated in formula (26):

$$H_{air,sat} = 5.5638e^{0.0572T_{air}} \tag{26}$$

H_{air} can be calculated from the differential equation shown in formula (27):

$$\frac{dH_{air}}{dt} = \frac{1}{h_0}\left(H_{trans} - H_{cov} - H_{vent}\right) \tag{27}$$

where H_{trans} represents the vapour produced by plant transpiration, H_{cov} represents the vapour condensation to the cover, and H_{vent} represents the vapour flux caused by ventilation. h_0 represents the height of the greenhouse.

In this paper, the real-time drip irrigation is used for irrigation, and the irrigation power is shown in formula (28) [18]:

$$P_{ir} = W_n \times Z_{ir} \times \left(\frac{\rho g}{3600}\right) \times \left(\frac{100}{\eta_{ir}}\right) \tag{28}$$

where P_{ir} represents the irrigation power, W_n represents the volume of water consumed by the drip irrigation system per hour, m^3/h. ρ is the density of irrigation water, kg/m^3. g is the acceleration of gravity, m/s^2. Zir represents the pumping head of water, m.

The total load of the greenhouse is calculated in formula (29):

$$P_{load} = P_{light} + P_H + P_{ir} \tag{29}$$

4. THE COUPLING RELATIONSHIP BETWEEN GREENHOUSE PHOTOVOLTAIC, AGRICULTURAL LOAD, ENERGY SYSTEM

The shading rate of the photovoltaic system on the top of the greenhouse can affect the amount of sunlight entering the greenhouse, which in turn affects the supplementary light load of the greenhouse. The solar radiation in the greenhouse can generate heat, and the light supplement lamp can also generate heat, so the heat required by the greenhouse also be affected by these two factors. The greenhouse irrigation load is affected by the greenhouse temperature and the light intensity, so the solar light intensity, the supplementary light intensity, and the thermal power of the greenhouse can also bring about changes in the greenhouse irrigation load. Both photovoltaic power generation and greenhouse load are sensitive to meteorological factors. Fluctuations in meteorological conditions can bring changes in some index of distribution network such as distribution network losses, affecting the economics of distribution network operation. Through the above analysis, the solar radiation intensity and the ambient temperature outside the greenhouse are pivotal variables that affect the output of photovoltaic power generation, the change of greenhouse load, and the operation of the energy system. The coupling relationship between the above models is shown in formula (30). The coupling schematic diagram of the photovoltaic, load, and energy systems in the greenhouse is shown in Figure **1**.

$$\begin{cases} P_{PV}=f_1\left(s_r, I_{outsolar}, T_{outdoor}\right) \\ P_{light} = f_2\left(s_r, I_{outsolar}\right) \\ P_H = f_3\left(s_r, I_{outsolar}, T_{outdoor}, T_{indoor}, P_{light}\right) \\ P_{ir} = f_4\left(s_r, I_{outsolar}, T_{indoor}, P_{light}\right) \end{cases} \tag{30}$$

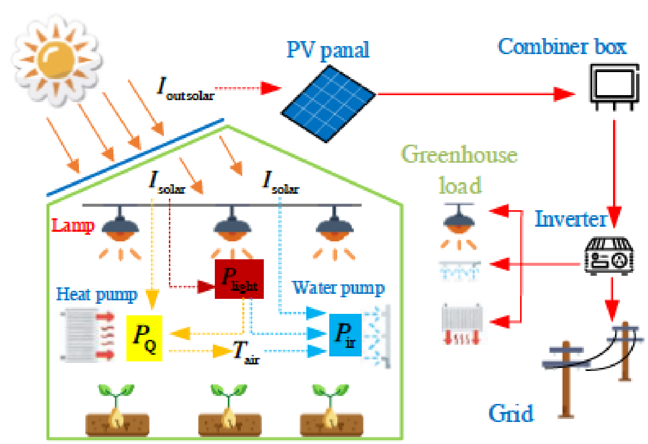

Figure 1: Schematic diagram of coupling of photovoltaic, load, and energy systems in the greenhouse.

5. COMPREHENSIVE ECONOMIC BENEFIT EVALUATION OF GREENHOUSE PHOTOVOLTAIC

The comprehensive economic benefits considered in this paper mainly include two aspects: economic benefits, including the economic benefits of greenhouse photovoltaic power generation, and the economic benefits of network loss improvement.

Environmental benefits include the carbon emission reduction benefits of photovoltaic power generation and the carbon emission reduction benefits brought by the improvement of system network loss.

5.1. Economic Benefits of Photovoltaic Power Generation

This paper adopts the photovoltaic power generation system operation mode of "self-generated and self-used, surplus power on-grid". Due to the difference between the selling price of photovoltaic power generation and the electricity purchase price from the grid, the economic value of the photovoltaic power generation system in operation in each period is different. The income is affected by the relationship between the active power of photovoltaic power generation and the energy consumption of the greenhouse. The photovoltaic power generation in one year can be calculated by the typical daily method, and the photovoltaic power generation income in one year is calculated in formula (31)-(33):

$$M_1 = \sum_{s\in\Omega}\sum_{j=1}^{m_s}\sum_{i=1}^{n_{m1}}\int_{t_{s,j,i}} f_{\text{buy},t_{s,j,i}} P_{\text{PV},t_{s,j,i}}\,\mathrm{d}t \tag{31}$$

$$M_2 = \sum_{s\in\Omega}\sum_{j=1}^{m_s}\sum_{i=1}^{n_{m2}}\int_{t_{s,j,i}} f_{\text{sell},t_{s,j,i}}\left(P_{\text{PV},t_{s,j,i}} - P_{\text{load},t_{s,j,i}}\right)\mathrm{d}t + \sum_{s\in\Omega}\sum_{j=1}^{m_s}\sum_{i=1}^{n_{m2}}\int_{t_{s,j,i}} f_{\text{buy},t_{s,j,i}} P_{\text{load},t_{s,j,i}}\,\mathrm{d}t \tag{32}$$

$$M_3 = M_1 + M_2 \tag{33}$$

where M_3 represents the annual revenue of photovoltaic power generation. Ω is the collection of seasons. m_s is the number of days included in a season. n_{m1} represents the number of periods during the day when the greenhouse load is greater than the active power of photovoltaic power generation in a certain season. n_{m2} represents the number of periods during the day when the greenhouse load is less than the active power of photovoltaic power generation in a certain season. f_{buy} represents the time-of-use price of electricity purchased from the local grid; f_{sell} represents the electricity sales price of local photovoltaic power generation.

The carbon emission reduction brought about by replacing traditional fossil energy power generation with photovoltaic power generation is calculated in formula (34):

$$C_1 = m_{\text{r}}\sum_{s\in\Omega}\sum_{j=1}^{m_s}\sum_{i=1}^{n_m}\int_{t_{s,j,i}} P_{\text{PV},t_{s,j,i}}\,\mathrm{d}t \tag{34}$$

where C_1 is the carbon emission reduction.

The carbon emission reduction benefit of photovoltaic power generation is calculated in formula (35):

$$M_4 = m_{\text{r}} C_1 \tag{35}$$

where M_4 represents the carbon emission reduction benefit. m_r is the local carbon trading price.

5.2. System Network Loss Improves Economic Benefits

Assume that the grid power loss of the system when not connected to photovoltaic and when connected to photovoltaic is P_3 and P_4, respectively. The carbon emission reduction brought by the improvement of network loss within one year is calculated in formula (36)-(37) [19]:

$$\Delta P = P_3 - P_4 \tag{36}$$

$$C_2 = m_{\text{c}}\sum_{s\in\Omega}\sum_{j=1}^{m_s}\sum_{i=1}^{n_m}\int_{t_{s,j,i}} \Delta P_{t_{s,j,i}}\,\mathrm{d}t \tag{37}$$

where ΔP represents the network loss improvement power. m_c is the CO_2 emission index on the centralized power generation side.

The carbon emission reduction benefits brought by the improvement of system network loss are shown in formula (38):

$$M_5 = m_{\text{r}} C_2 \tag{38}$$

where m_r is the local carbon trading price.

The economic benefit brought by the improvement of network loss within one year is calculated in formula (39) [19]:

$$M_6 = f_{\text{sell}}\sum_{s\in\Omega}\sum_{j=1}^{m_s}\sum_{i=1}^{n_m}\int_{t_{s,j,i}} \Delta P_{t_{s,j,i}}\,\mathrm{d}t \tag{39}$$

6. CASE ANALYSIS

The simulation platform of this paper is MATLAB2014b, the modeling and simulation of greenhouse photovoltaic and load are realized through programming. Taking an actual 48-node 10kV medium-voltage distribution network (118.17°E, 40.77°N) and an actual photovoltaic greenhouse in a rural area in northern China as the research objects. The total active load of residential electricity in this distribution network is 2.566 MW, and the total reactive load is 1.278 MVar. The time-of-use electricity price is shown in Table **1**. There is a facility agricultural greenhouse (112m×32m×2.5m) connected to the No. 10 node of the distribution network. The electrification level of this greenhouse is high, and there are agricultural loads such as supplementary light, temperature control, and irrigation inside the greenhouse. The parameters of the greenhouse are shown in Table **2**. Some constant power loads of the greenhouse are shown in Table **3**.

The crop grown in the greenhouse is cucumber. According to the physiological characteristics of cucumber, the supplementary light strategy adopted in this paper is: when the net radiation intensity of the crop surface in the greenhouse is less than 200 μmol/(m^2·s), the light supplement lamp is turned on to supplement the light for the cucumber; and when the net radiation intensity of the crop surface is greater than 200μmol/(m^2·s), the light supplement lamp is turned off [4]. The heating season of the greenhouse is winter and spring and the indoor temperature is set at 28.

The photovoltaic panels are laid on the sunny side of the greenhouse, the shading rate of photovoltaic panels is 75%, and the angle between the photovoltaic panels and the ground is 35°. The manufacturer of the photovoltaic panels is Ningbo Ulica Solar Science & Technology Co., Ltd. (China). The parameters of the photovoltaic panels are shown in Table **4** [20].

The schematic diagram of the photovoltaic integrated greenhouse connected to the distribution network is shown in Figure **2**.

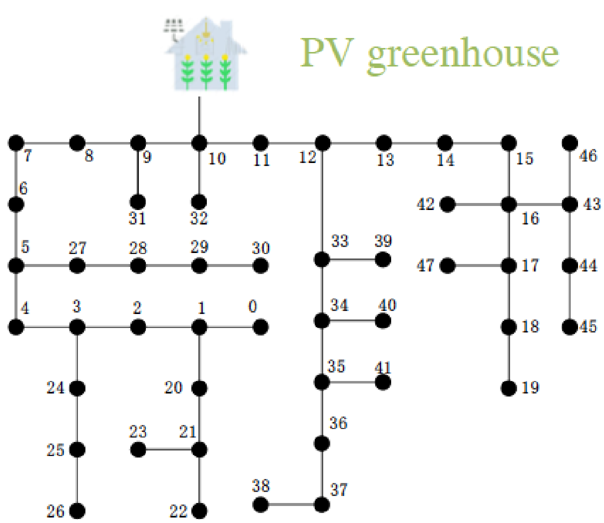

Figure 2: Schematic diagram of photovoltaic integrated greenhouse connected to the distribution network.

Table 1: Time-of-use Electricity Price

Period		Price/yuan
12:00-13:00	23:00-7:00	0.2349
8:00-11:00	4:00-21:00	0.9203
Other Period		0.6226

Table 2: Greenhouse Parameters

Parameter	Value	Parameter	Value
C_{ht}/(W/(m^2•℃))	6.2	T_{base}(℃)	10
ρ_i/(kg/m^3)	1.225	T_{upper}(℃)	40
c_{pi}/(KJ/(kg·K))	1.01	M	0.83
N_c	1/3600	L(m)	112
W_i(g/kg)	8.485	W_d(m)	32
W_o(g/kg)	0.66	P_{sing}(kW)	1
h_{fg}(J/kg)	67.22	K_c	0.7
R_m(T_{opt})	16.19	C_H	3.7
T_{opt}(℃)	32	H(m)	2
α_1	0.7	η	0.75
s_r	0.75	LAI	2.6
η_{ir}	0.75	ρ(kg/m^3)	1000
g(m/s^2)	9.8	Z_{ir}(m)	7

Table 3: Some Constant Power Loads in the Greenhouse

Greenhouse load	Power	Working priod
Plasma nitrogen fixation	0.5kW	8:00-18:00
Physical insecticide	0.125kW	0:00-24:00
Sonic boost	0.3kW	8:00-18:00

Table 4: Technical Data of Photovoltaic Modules

Parameter	Specification
Model No.	UL-315P-72
PV type	P-Si
Panel dimension (H/W/D)	1956×992×46mm
Weight	22.5kg
Maximum Power at STC	315Wp
Temperature coefficient of power	-0.40%/℃
Derating factor	0.80
Nominal operating cell temperature	47℃
Efficiency at standard test conditions	16.23%
Lifetime	25 years

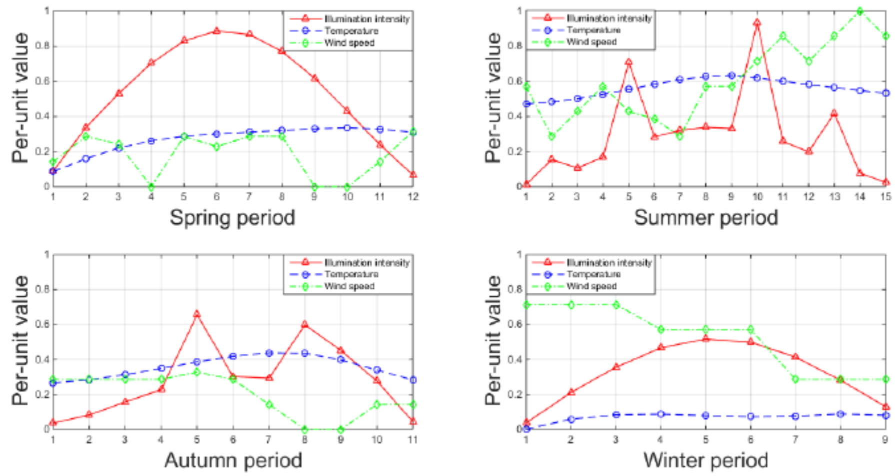

Figure 3: Variations of typical sunlight and temperature in four seasons.

6.1. Photovoltaic Output and Greenhouse Energy Consumption Analysis

The changes in outdoor boundary light intensity and temperature on typical days in the four seasons are shown in Figure **3**. In this paper, the per-unit value is used. The basic value of light intensity is 1000W/m^2, and the basic value of temperature is 50°C, The basic value of wind speed is 7m/s.

Accurate calculation of photovoltaic output and greenhouse energy consumption combined with meteorological data is the basis for evaluating the comprehensive economic benefits of greenhouse photovoltaics. The variation of typical daily greenhouse photovoltaic output and greenhouse load in four seasons is shown in Figure **4**. It shows that the photovoltaic output is mainly affected by the solar radiation intensity outside the greenhouse, and its trend is consistent with the solar radiation intensity.

In the vicinity of noon in the day, due to the large indoor solar light intensity, the supplementary light load of the greenhouse is small. When the indoor solar radiation illumination is greater than the light intensity required by the crops, the supplementary light load is zero. There is no need for heating in summer and autumn, so the heat load in summer and autumn is zero. Due to the temperature outside the greenhouse changing little during the day, the temperature and room temperature control load are relatively stable. Due to the real-time irrigation method based on soil water balance, the irrigation load in each period is very small. Taking the spring typical day in this paper as an example, the average hourly power consumption of greenhouse irrigation is only 0.1457kW·h, and the average water consumption per hour is only 2.4979 m^3.

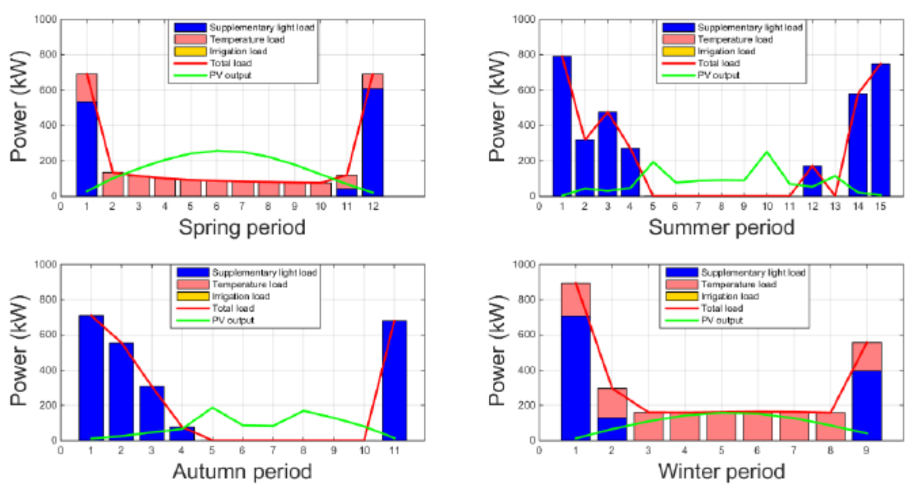

Figure 4: Greenhouse load and photovoltaic output under typical days in four seasons.

Through the above analysis, in summer and autumn, the energy consumption of the greenhouse is mainly generated by the supplementary light load. In the autumn and winter, the energy consumption of the greenhouse is mainly generated by the supplementary light and the temperature control load, and the greenhouse irrigation load accounts for a small proportion of the total greenhouse load.

6.2. Photovoltaic Comprehensive Economic Benefit Assessment

The economic benefits brought by the installation of greenhouse photovoltaics are analyzed from the user side and the grid side respectively.

6.2.1. Calculation of Photovoltaic Power Generation Income

The traditional photovoltaic consumption strategy of the facility agricultural greenhouse generally adopts the operation mode of "self-use, surplus power grid". When the total greenhouse load is greater than the photovoltaic power generation, the photovoltaic power generation is completely absorbed by the greenhouse load, and the electricity generated by the photovoltaic uses the electricity purchase price to calculate the economic benefit. When the total load of the greenhouse is less than the photovoltaic power generation, a part of the photovoltaic power generation is consumed. The power consumption is implemented at the electricity purchase price, and the electricity transmitted to the grid is at the photovoltaic power sales price.

Therefore, the relationship between agricultural load and photovoltaic power generation in each period directly affects the economic benefits of photovoltaic power generation under this operating mode.

The photovoltaic power generation revenue under the typical days of the four seasons is shown in Figure **5**. The annual revenue of photovoltaic power generation on the user side is 178158 yuan. The carbon trading price is 107.5 yuan/t. The annual carbon emission reduction of greenhouse photovoltaic power generation is 328.42 tons, and the annual carbon emission reduction income is 35305 yuan.

6.2.2. Network Loss Improvement Benefits

To analyze the distribution network loss improvement benefits of the system, this section first analyzes the relationship between network loss, greenhouse load, and greenhouse photovoltaic output for the photovoltaic integrated greenhouse connected to the distribution network. The relationship between the network loss, the greenhouse load and the greenhouse photovoltaic output under each typical day in the four seasons is shown in Figure **6**.

Both the greenhouse load and photovoltaic output are sensitive to meteorological factors. As shown in Figure **6**, the connection of photovoltaic power generation to the distribution network can reduce network loss. When the photovoltaic output of the greenhouse is small and the greenhouse electricity load is large, the system network loss is large. When the greenhouse photovoltaic output is large and the greenhouse load is small, the system network loss is small. Therefore, the connection of the photovoltaic system to the distribution network will reduce the network loss of the system, thereby bringing certain economic benefits.

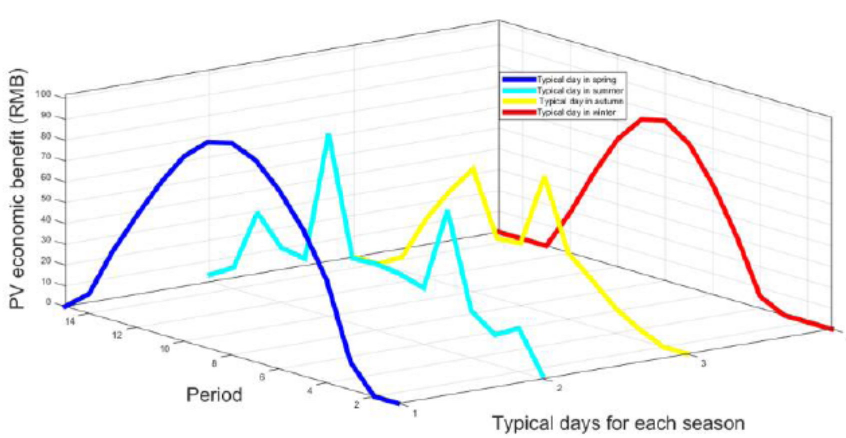

Figure 5: PV power generation income under typical days in four seasons.

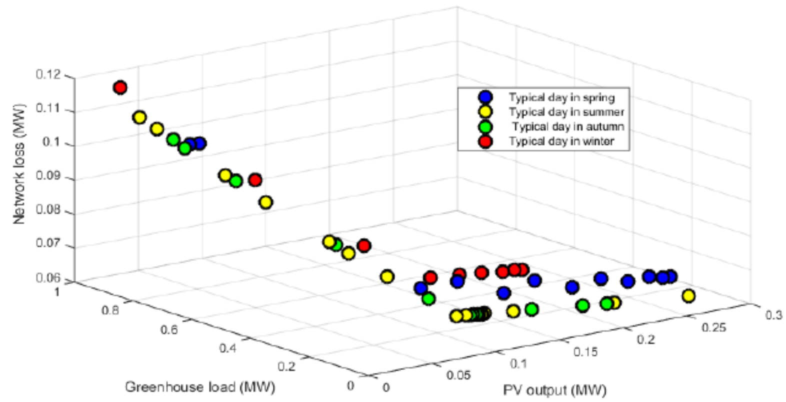

Figure 6: Relationship between grid loss, greenhouse load, and photovoltaic output.

Through the refined modeling of greenhouse photovoltaic and greenhouse load, concerning meteorological data, greenhouse data, and distribution network data, photovoltaic output, and greenhouse load energy consumption can be accurately calculated. Then, through the power flow calculation of the power system, the improvement of the network loss in each season can be calculated.

Table **5** shows the change of network loss in each period after PV is connected to the typical sun in winter. Table **6** shows that the annual network loss improvement of the system calculated by the typical daily method is 19.305 MW, so the annual economic benefit of the network loss improvement is 11003 yuan. The carbon emission reduction brought by the improvement of network loss is 14.671 t, and the annual carbon emission reduction income generated by the network loss improvement is 1557 yuan.

Table 5: Improvement of Network Loss in one Day on Typical Winter Days

Period	Greenhouse load /MW	PV not connected /MW	PV connected /MW	Network loss improvement /MW
1	0.8945	0.1202	0.1195	0.00067
2	0.2955	0.0866	0.0856	0.0030
3	0.1593	0.0824	0.0777	0.0047
4	0.1582	0.0823	0.0762	0.0061
5	0.1606	0.0824	0.0757	0.0068
6	0.1630	0.0825	0.0760	0.0065
7	0.1618	0.0825	0.0770	0.0055
8	0.1578	0.0823	0.0786	0.0037
9	0.5571	0.1015	0.0995	0.0021
Total		0.8048	0.7657	0.0390

Table 6: Network Loss Improvement in Four-Season

Season	Network loss improvement（MW•h）
Spring	7.146
Summer	4.941
Autumn	3.708
Winter	3.510
Total	19.305

This paper pays great attention to the practical engineering application of the proposed photovoltaic comprehensive benefits evaluation model. Therefore, the distribution network used in this paper is a 10kV medium-voltage distribution network in a rural area in northern China, the greenhouse used is an actual greenhouse, and the photovoltaic panel data used are the actual photovoltaic panel data produced by a company in Ningbo, China, the meteorological data used are locally measured data, which enhances the practicability of this paper. Once the crop types, greenhouse parameters, actual distribution network data, and local actual meteorological data are determined, the model can be used to accurately evaluate the comprehensive economic benefits of greenhouse photovoltaics.

CONCLUSIONS

This paper takes the photovoltaic integrated greenhouse as the research object, analyzes the coupling relationship between greenhouse photovoltaics and greenhouse loads, and establishes the comprehensive benefits evaluation model of greenhouse photovoltaics based on this relationship. The main conclusions are as follows: (1) The refined greenhouse photovoltaic and greenhouse load construction model can accurately calculate the energy consumption of photovoltaic power generation and greenhouse, and then can accurately calculate the comprehensive income of greenhouse photovoltaics according to the difference of electricity purchase and sales price; (2) The PV comprehensive benefits evaluation model can be oriented to practical engineering applications. Once the actual data of weather, PV, greenhouse, and distribution network are obtained, the accurate comprehensive economic benefits of greenhouse PV can be obtained.

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