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LCA Analysis of Campus Photovoltaic Power Generation System and Its Application Potential in Low Carbon Campus: Case Study of Shandong Jianzhu University

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Abstract:

Photovoltaic power generation system plays an important role in and serves as a major support in the construction of low-carbon campuses. Although many universities have already demonstrated the application of photovoltaic power generation systems, due to the limitations of installation scale, their power generation accounts for a relatively small proportion of campus energy, and due to insufficient maintenance and cleaning, their utilization rate is low. Therefore, the utilization of photovoltaic power generation systems still has great potential for development with the goal of building low-carbon campuses. Taking the 1MW campus photovoltaic system of Shandong Jianzhu University as an example, the carbon emissions and carbon emission recovery period of the photovoltaic power generation system in the whole life cycle were calculated, and the carbon reduction benefits of the existing photovoltaic power generation system of Shandong Jianzhu University on the campus were analyzed. The application potential brought by expanding the use scale, combining heat pump heating, residual power grid, and strengthening maintenance and cleaning measures were also discussed.

Keywords:

Low carbon campus
Photovoltaic power generation system
Full lifecycle
Carbon emissions
Carbon reduction analysis
Potential analysis

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1. Introduction

As of the end of 2021, the number of higher education institutions in China increased to 3,012, with campus areas expanding to 2.17 billion m², nearly 300 million m² more than in 2015. The student population reached 44.3 million, an increase of 7.83 million since 2015. With the growth of campus construction and student and staff numbers, resource consumption has risen, and energy usage has increased yearly [1]. Campus emissions are relatively intense and concentrated, making emission reduction efforts especially impactful [2]. As primary hubs for talent development, universities also play a crucial role in promoting and embodying green development concepts [3]. Thus, implementing green development on campuses holds significant educational and exemplary value for establishing a low-carbon campus.

Photovoltaic (PV) systems harness renewable energy, offering green, clean, environmentally friendly, and low-carbon energy production [4]. In line with China's goals for carbon neutrality, the state strongly promotes the use of solar and other renewable energies. Consequently, integrating PV technology into campus buildings is a necessary step to meet current developmental trends and is vital in constructing low-carbon campuses [5]. Today, PV power generation is already a component of most campus energy systems. Although many universities have installed PV systems to some extent, considerable potential remains to increase capacity, optimize PV utilization, and improve operation and maintenance.

However, PV product manufacturing is relatively energy-intensive, leading to doubts about its environmental benefits from a life cycle perspective [6]. Critics argue that the generated electricity does not offset the carbon emissions produced over the system's life cycle. Life Cycle Assessment (LCA) is widely considered the best method for evaluating low-carbon, green products and technologies. Therefore, this study uses the PV system at Shandong Jianzhu University as a case study. It begins by calculating the life cycle carbon emissions per unit area of PV systems on campus and analyzing the carbon payback period. The study then assesses the carbon emissions and reduction potential of a 1 MW PV system at Shandong Jianzhu University. Finally, it explores the potential of scaling up PV installation on campus, selling excess electricity to the grid, integrating PV with heat pumps for heating, and enhancing maintenance and cleaning.

2. Research methodology

Referring to the renewable energy systems section of GB/T 51366-2019 "Standard for Calculation of Building Carbon Emissions" [7], this study uses the PV module area as the measurement unit for the annual electricity output of PV systems. To facilitate carbon emission and reduction calculations for Shandong Jianzhu University's PV systems, each square meter of PV module, along with its share of mounting structures, inverters, and cables, is considered as a unit area of the PV system for analytical purposes. Subsequently, a carbon reduction and potential analysis of campus PV systems is conducted.

The system boundary for the life cycle study of PV systems includes the production, transportation, usage, and disposal stages. Following life cycle assessment methods and relevant carbon accounting standards, the carbon emission calculation model for PV systems is established as:

$$C_t = C_1 + C_2 + C_3 + C_4 = \sum_{i=1}^{n} M_i F_i + \sum_{i=1}^{n} M_i D_i T_i \quad (1)$$

where C_t represents the total life cycle carbon emissions of each PV system, in $kgCO_2$; C_1, C_2, C_3, and C_4 are the carbon emissions during the production, transportation, usage, and disposal stages, respectively, in $kgCO_2$; M_i is the consumption amount of the i^{th} production material; is the carbon emission factor of the i^{th} main material, in $kgCO_2$ per unit of material; is the average transportation distance of the i^{th} material, in km; and is the carbon emission factor for transporting the i^{th} material per unit weight and distance, in $kgCO_2/(t\cdot km)$.

3. Research content

3.1. Life cycle carbon emission analysis for PV system per unit area

3.1.1. Production stage

The carbon emissions during the production stage of a PV system mainly result from energy and resource consumption, as well as pollutant treatment. In this study, the eFootprint software is used to create a cradle-to-gate model to calculate the carbon emissions associated with the production stage of a single PV module and a set of mounting structures. eFootprint is an online tool for full life cycle process analysis, featuring databases from China, the EU, and Switzerland, and is already accessible to students and researchers in various universities. The carbon emission data for the production of inverters and PV cables come from the China Products Carbon Footprint Factors Database (CPCD).

(1) Photovoltaic modules

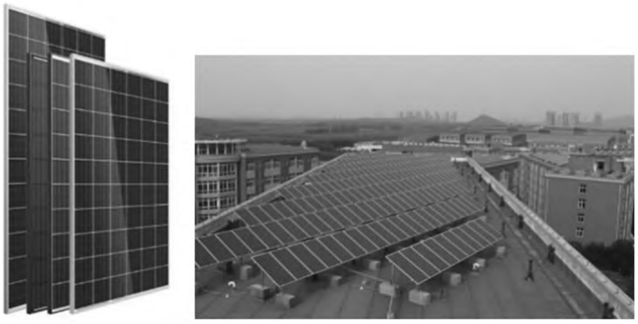

Figure 1. PV module diagram

The specifications of the PV modules used by Shandong Jianzhu University are shown in **Table 1**.

Table 1. Solar cell module specifications

Indicator	Unit
Model	Piece
Size and structure of solar cell module	mm
Weight of solar cell module	kg
Efficiency of solar cell module	%
Peak power	Wp
Open circuit voltage (Voc)	V
Short circuit current (Isc)	A
Operating voltage (Vmpp)	V
Operating current (Impp)	A
Power temperature coefficient	%/°C
Open circuit voltage temperature coefficient	%/°C
Short circuit current temperature coefficient	%/°C

The carbon emissions generated during the production of one PV module amount to 466.75 $kgCO_2$, which translates to 335.69 $kgCO_2$ per square meter of PV module area.

(2) Mounting structures

The mounting structures selected for this project are illustrated in **Figure 2**. The carbon emissions associated with producing one set of mounting structures are calculated at 1,165.15 $kgCO_2$. Since each set of mounting structures supports three PV modules, the production-stage carbon emissions attributed to the mounting structures per square meter of PV module area are 279.33 $kgCO_2$.

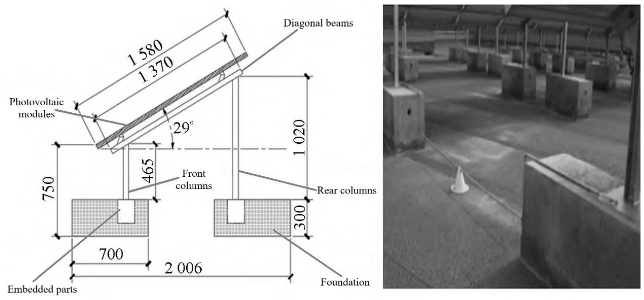

Figure 2. Mounting structure diagram (unit: mm)

(3) Inverters and cables

This project utilizes inverters with capacities of 5 kW, 10 kW, 30 kW, and 50 kW, totaling 1,075 kW across 52 units. The statistics and calculation results are shown in **Table 2**, with total production-stage carbon emissions for inverters amounting to 25,296.5 $kgCO_2$. The capacity ratio of inverters to PV modules is 1.07:1. Converting this to a per-square-meter basis, each square meter of PV module area requires 160 W of inverter capacity, corresponding to 3.77 $kgCO_2$ in carbon emissions during the production stage per square meter of PV module area.

Table 2. Inverter specifications

Power (kW)	Net weight (kg)	Quantity (units)	CO_2 emissions ($kgCO_2$)
5	13	5	1,012.5
10	18	32	10,400
30	39	5	3,900
50	72	10	9,984

The cross-sectional area of PV cables in this project is 4 mm^2, with a total length of approximately 19,000 meters. This corresponds to an allocation of 2.6 meters of PV cable per square meter of PV module area, with production-stage carbon emissions of approximately 1.98 $kgCO_2$.

Considering the PV modules, mounting structures, inverters, and cables together, the total carbon emissions during the production stage for each square meter of PV system area amount to 620.77 $kgCO_2$.

3.1.2. Transportation stage

The emissions during the transportation stage refer to those generated during the transport of production materials from the manufacturing facility to the power generation project site [8]. These emissions primarily arise from energy consumption during transportation. The carbon emissions produced during the transportation stage of the photovoltaic power generation system can be calculated using **Formula (2)**, and the calculation data is presented in **Table 3**.

$$C_2 = G_i H D R_i \tag{2}$$

where, C_2 represents the carbon emissions generated during the transportation stage of the photovoltaic power generation system, in $kgCO_2$; G_i represents the unit energy consumption for material transportation, in mL/(kg·km); H represents the mass of the material, in kg; D represents the transportation distance, in km; R_i represents the CO_2 emission factor of the fuel, in $kgCO_2/L$.

3.1.3. Usage phase

The usage phase of photovoltaic power generation systems belongs to renewable energy generation, which consumes almost no energy [9]. To facilitate cleaning and maintenance, photovoltaic cleaning robots can be used to regularly clean photovoltaic modules. The power of these robots is 300 W, and they can clean 9 to 10 m per minute. Assuming a maintenance cycle of 2 months, the power consumption for cleaning per square meter of photovoltaic modules is approximately 0.014 kWh, resulting in carbon emissions of approximately 0.0139 $kgCO_2$.

3.1.4. End-of-life phase

In photovoltaic power generation systems, carbon emissions during the end-of-life phase mainly come from waste disposal and transportation processes. Since the components of photovoltaic power generation systems are mostly recyclable materials such as glass, metal, and silicon wafers, the disposal plan adopts manual dismantling and thermal treatment methods. The carbon emission inventory for the end-of-life phase is shown in **Table 4**, with data mainly sourced from actual product parameters and literature data [10-13].

Transportation emissions can be calculated using **Formula (2)**. The calculation data is shown in **Table 5**.

In summary, the end-of-life phase reduces carbon emissions by 59.07 $kgCO_2$.

3.1.5. Full lifecycle carbon emissions

After calculation, the full lifecycle carbon emissions per square meter of photovoltaic power generation system are 561.73 $kgCO_2$. The carbon emissions at each stage of the full lifecycle are shown in **Figure 3**, with the production phase accounting for the largest proportion of carbon emissions.

Table 3. Transportation stage

	Value	Unit	Data source
Fuel consumption per 100 km of transportation vehicle	20	L	Provided by supplier
Loading capacity of transportation vehicle	20	t	Provided by supplier
Unit energy consumption for transportation of photovoltaic power generation system per square meter	0.01	mL/(kg·km)	Calculated value
Weight of photovoltaic power generation system per square meter	103.04	kg/m^2	Provided by manufacturer
Transportation distance	6.7	km	Provided by supplier
CO_2 emission factor of diesel	2.73	$kgCO_2/L$	Provided by IPCC
CO_2 emissions of photovoltaic power generation system per square meter	0.019	$kgCO_2$	Calculated value

Abbreviation: IPCC, Intergovernmental Panel on Climate Change.

Table 4. Carbon emission inventory for the end-of-life phase

Components	Dismantling/Thermal decomposition	Recycling	CO_2 emissions per square meter of photovoltaic modules ($kgCO_2/m^2$)
Photovoltaic modules	8.22 $kgCO_2/m^2$	61.78 $kgCO_2/m^2$	-53.56
Support frame		Direct recycling of steel per square meter of photovoltaic modules	-4.9
Inverter	Power consumption per square meter of photovoltaic modules 0.023 kWh/m^2	Recycling of aluminum per square meter of photovoltaic modules 0.66 $kgCO_2/m^2$	-0.64
Cables	Power consumption per square meter of photovoltaic modules 0.012 kWh/m^2	Recycling of copper per square meter of photovoltaic modules 0.067 $kgCO_2/m^2$	-0.05
Total			-59.1

Table 5. Carbon emissions from waste transportation

	Value	Unit	Data source
Fuel consumption per 100 km of transportation vehicle	20	L	Provided by supplier
Loading capacity of transportation vehicle	20	t	Provided by supplier
Unit energy consumption for transportation of photovoltaic power generation system per square meter	0.01	mL/(kg·km)	Calculated value
Weight of photovoltaic power generation system per square meter	103.04	kg/m^2	Provided by manufacturer
Transportation distance	10	km	Provided by supplier
CO_2 emission factor of diesel	2.73	$kgCO_2/L$	Provided by IPCC
CO_2 emissions of photovoltaic power generation system per square meter	0.028	$kgCO_2$	Calculated value

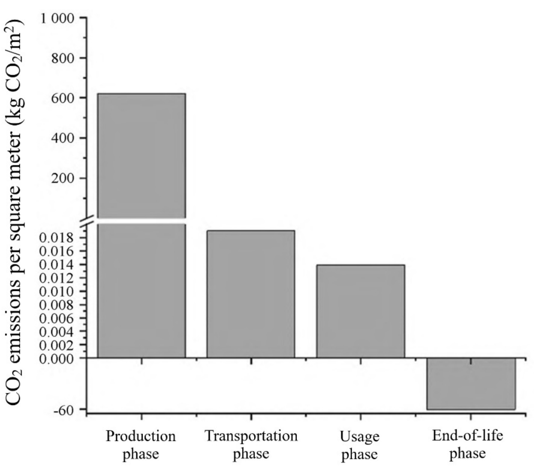

Figure 3. Carbon dioxide emissions at each stage of the lifecycle

3.2. Full lifecycle carbon reduction analysis of photovoltaic power generation system per unit area

3.2.1. Carbon reduction of photovoltaic power generation system per unit area

$$E_{PV} = I K_E (1-K_S) A_P \quad (3)$$

In this formula, E_{PV} is the annual power generation of the photovoltaic power generation system, in kW·h; I is the annual total solar radiation on the inclined array surface, in kW·h; K_E is the conversion efficiency of the photovoltaic cell, in %; K_S is the loss efficiency of the photovoltaic power generation system, in %, where K_S = 21.04%; A_P is the area of the photovoltaic modules in the photovoltaic power generation system, in m^2.

The estimated annual power generation per square meter of the photovoltaic power generation system is 162.54 kW·h.

Based on the segmented linear attenuation of the 25-year attenuation rate of photovoltaic cell modules, the cumulative annual power generation is calculated [13], as shown in **Table 6**.

Based on the emission factors for the baseline of China's regional power grids in the annual emission reduction projects released by the Ministry of Environmental Protection, this study uses the average data from 2013 to 2019 to calculate the emission factor for the power grid in Shandong as 0.9979 tCO_2/MWh. The cumulative CO_2 emission reductions for each year of the project's full lifecycle are shown in **Table 7**.

The carbon emissions generated during the full lifecycle of a photovoltaic power generation system per

Table 6. Cumulative annual power generation of photovoltaic power generation system per unit area

Year	Power generation (kW·h)	Year	Power generation (kW·h)
2012	159.29	2025	2,125.26
2013	317.38	2026	2,268.98
2014	474.29	2027	2,411.69
2015	630.03	2028	2,553.40
2016	784.59	2029	2,694.12
2017	937.99	2030	2,833.86
2018	1,090.25	2031	2,972.61
2019	1,241.36	2032	3,110.40
2020	1,391.34	2033	3,247.22
2021	1,540.19	2034	3,383.08
2022	1,688.01	2035	3,517.99
2023	1,834.78	2036	3,651.96
2024	1,980.53		

Table 7. Cumulative CO_2 emission reductions for photovoltaic power generation system per unit area year by year

Year	Cumulative CO_2 emission reductions year by year/kg	Year	Cumulative CO_2 emission reductions year by year/kg
2012	158.95	2025	2,120.80
2013	316.72	2026	2,264.21
2014	473.30	2027	2,406.63
2015	628.70	2028	2,548.04
2016	782.94	2029	2,688.46
2017	936.02	2030	2,827.91
2018	1,087.96	2031	2,966.37
2019	1,238.75	2032	3,103.87
2020	1,388.42	2033	3,240.40
2021	1,536.96	2034	3,375.98
2022	1,684.46	2035	3,510.61
2023	1,830.93	2036	3,644.29
2024	1,976.37		

square meter are 561.73 $kgCO_2$. Therefore, it reduces emissions by approximately 3,082.56 $kgCO_2$ over its full lifecycle, with an average annual emission reduction of approximately 123.3 $kgCO_2$.

3.2.2. Carbon emission recovery period of photovoltaic power generation system per unit area

By comparing the CO_2 emissions over the full lifecycle of a photovoltaic power generation system per square meter, we can determine its carbon emission recovery period. In the fourth year of operation, the system's CO_2 emission reductions begin to exceed the lifecycle CO_2 emissions, as shown in **Figure 4**. This indicates that the system's CO_2 recovery period is approximately 4 years, further validating that the emission reductions of the photovoltaic power generation system far exceed the carbon emissions it generates over its full lifecycle.

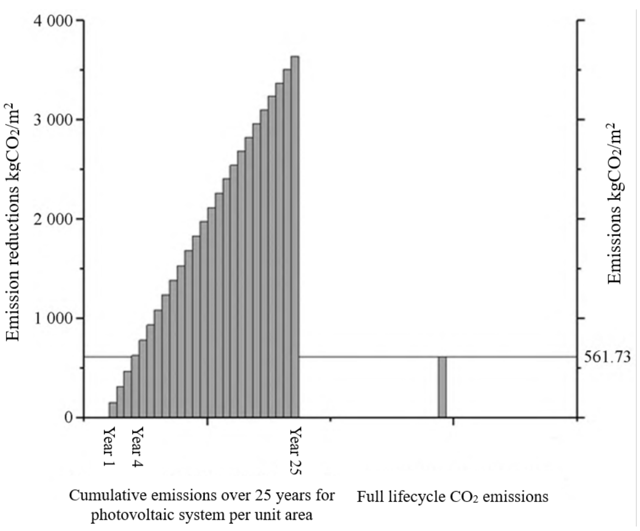

Figure 4. Comparison of full lifecycle emission reductions for photovoltaic power generation system per unit area

3.3. Carbon reduction analysis: taking Shandong Jianzhu University as an example

The photovoltaic power generation system project at Shandong Jianzhu University started construction in January 2012 and was put into use in August of that year. It was the first megawatt-scale solar photovoltaic building application project among domestic universities at that time [14]. The entire system's photovoltaic module array consists of 5,310 190Wp monocrystalline cell modules, covering an area of approximately 20,000 m^2 on the building's roof, with a total installed capacity of 1.0089 MWp. It adopts a user-side grid connection and is mainly used to meet daily electricity needs such as office work and lighting within the building. The roof photovoltaic modules are arranged in a vertical single-row layout, and the installation angle is determined to be 29° after comprehensive consideration of factors such as maximizing solar radiation exposure, wind resistance, and installation capacity. A few photovoltaic modules installed on the facade adopt a vertical installation format.

3.3.1. Full lifecycle carbon emissions of the photovoltaic power generation system at Shandong Jianzhu University

The current distribution of the campus photovoltaic power generation system is shown in **Table 8**. The system is currently installed on the roofs of 13 buildings, including 8 dormitory buildings, 3 teaching and office buildings, 1 canteen, and the library. The total area of photovoltaic modules is 7,383.64 m^2.

After calculation, the full lifecycle carbon emissions of the photovoltaic power generation system on the campus of Shandong Jianzhu University are 4,147.61 tCO_2.

3.3.2. Full lifecycle carbon reduction analysis of the photovoltaic power generation system at Shandong Jianzhu University

Based on the analysis of annual power generation and emission reductions per unit area of the photovoltaic power generation system, it can be inferred that the photovoltaic power generation system at Shandong Jianzhu University will generate approximately 26.96 million kWh of electricity over 25 years, reducing emissions by approximately 22,755.8 tCO_2, with an average annual emission reduction of approximately 910.23 tCO_2.

After calculation, the total annual carbon emissions of Shandong Jianzhu University are 22,345 tCO_2, and the photovoltaic power generation system can reduce the campus's carbon emissions by an average of 4% per year, as shown in **Figure 5**.

Table 8. Scale of photovoltaic power generation systems installed on the roofs of various buildings at Shandong Jianzhu University

Serial no.	Building	No. of modules	Module area (m^2)	Total capacity (kWp)
1	Meiyuan 1 Apartment	300	417.12	57
2	Songyuan 1 Apartment	360	500.544	68.4
3	Songyuan 2 Apartment	300	417.12	57
4	Songyuan 3 Apartment	360	500.544	68.4
5	Zhuyuan 1 Apartment	270	375.408	51.3
6	Zhuyuan 2 Apartment	330	458.832	62.7
7	Meiyuan 2 Apartment	330	458.832	62.7
8	Meiyuan 3 Apartment	330	458.832	62.7
9	Library	645	896.808	122.55
10	Office Building	195	271.128	37.05
11	Canteen 1	1,010	1,404.304	191.9
12	Jianyi Building	240	333.696	45.6
13	Science and Technology Building	640	889.856	121.6
Total		5,310	7383.64	1008.9

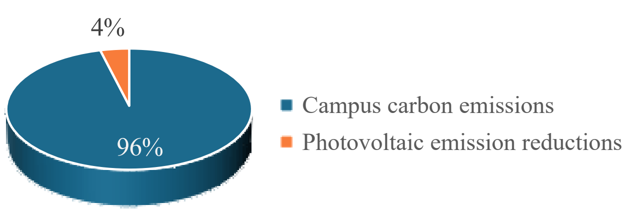

Figure 5. Annual average emission reduction ratio of the photovoltaic power generation system at Shandong Jianzhu University

3.4. Analysis of the application potential of the photovoltaic power generation system at Shandong Jianzhu University

Taking Shandong Jianzhu University as an example, there is still untapped potential in its photovoltaic power generation system. Firstly, the installation scale can be further expanded. Secondly, the electricity usage efficiency during school holidays is low. Thirdly, its utilization methods can be further expanded. Fourthly, the maintenance and cleaning level can be further improved.

3.4.1. Expanding the scale of use

Expanding the installation scale of the photovoltaic power generation system is an effective way to improve the campus's photovoltaic emission reduction benefits. Although Shandong Jianzhu University has installed a 1 MW photovoltaic power generation system at this stage, there are still many roofs and façades that can be utilized, as shown in **Figure 6**. Since building roofs receive the most solar radiation and have less obstruction, most campus photovoltaics are installed on building roofs, but there are still some roofs that are not utilized; building façades have less irradiance and are subject to obstruction compared to roofs, but installing photovoltaics on building façades can also improve campus carbon reduction benefits. Due to the low solar irradiance on the north façades of buildings in the Jinan area, it is not suitable to install the adopted photovoltaic power generation system. After comprehensive consideration, this study calculates the carbon reduction benefits of installing photovoltaic power generation systems on campus building roofs and south, east, and west façades.

The photovoltaic power generation system at Shandong Jianzhu University has been operating for more than ten years, and there have been significant improvements in the current level of photovoltaic technology development. Therefore, this project adopts monocrystalline silicon cell modules from leading brands for the newly installed photovoltaics, with parameters as shown in **Table 9**.

Installing photovoltaic modules on unused and available roofs and façades of Shandong Jianzhu University. Among them, the roof photovoltaics are installed in an optimal tilt arrangement, and the façade photovoltaics are installed vertically. The calculation results are shown in **Table 10**.

After calculation, the average annual power generation of roof photovoltaic is about 8,308,000 kW·h. Through the analysis of the irradiance in different orientations in Jinan City using Grasshopper (as shown in **Figure 7**), taking the best inclined plane of the roof as 100%, the power generation efficiency of each orientation is converted (as shown in **Figure 8**), and the average annual power generation of each facade is calculated (as shown in **Table 11**).

The photovoltaic modules experience a power attenuation of 1.5% in the first year and 0.4% per year from the 2nd to the 25th year. They were put into use in 2023. The cumulative power generation for each year over 25 years is calculated as shown in **Table 12**, with a total power generation of 62,347.94 kW·h over 25 years.

The cumulative emission reductions from 2012 to 2047 are shown in **Table 13**. Combining the newly installed photovoltaics with the existing ones, the total emission reductions from 2012 to 2047 are calculated to be 621,608.97 tons of CO_2, with an average annual emission reduction of 17,346.65 tons. The annual average carbon emission reduction on campus increased from 4% to 77.2%, greatly increasing the campus's carbon reduction, as shown in **Figure 9**.

Figure 6. Partial available roofs and façades of Shandong Jianzhu University

Table 9. Solar cell module parameters

Type of solar cell		Monocrystalline silicon
Indicator	Unit	
Size and structure of solar cell module	mm	2,278×1,134×35
Weight of solar cell module	kg	27.5
Efficiency of solar cell module	%	22.6
Peak power	Wp	585Wp
Open circuit voltage (Voc)	V	52.36
Short circuit current (Isc)	A	14.27
Operating voltage (Vmpp)	V	44.21
Operating current (Impp)	A	13.24
Power temperature coefficient	%/°C	-0.290%/°C
Open circuit voltage temperature coefficient	%/°C	-0.230%/°C
Short circuit current temperature coefficient	%/°C	0.050%/°C

Table 10. Information statistics of photovoltaic power generation systems installed on roofs and façades

	Roof	South façade	East façade	West façade	Total
Area (m^2)	89,638.00	47,351.50	34,856.80	34,949.00	206,795.30
Number of photovoltaic modules (pieces)	11,935.00	18,353.00	13,510.00	13,546.00	57,344.00
Module area (m^2)	16,594.42	25,518.01	18,784.30	18,834.36	79,731.09
Installed capacity (kWp)	6,982.40	10,736.50	7,903.40	7,924.40	33,546.70

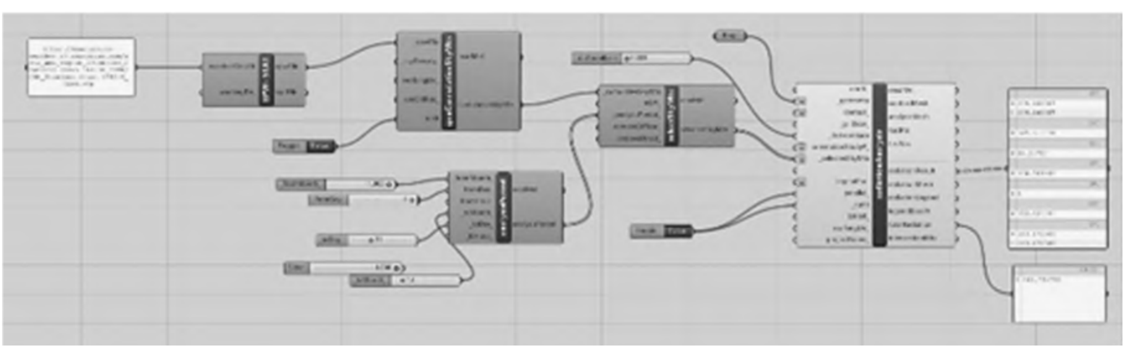

Figure 7. Schematic diagram of Grasshopper irradiance calculation for battery connection

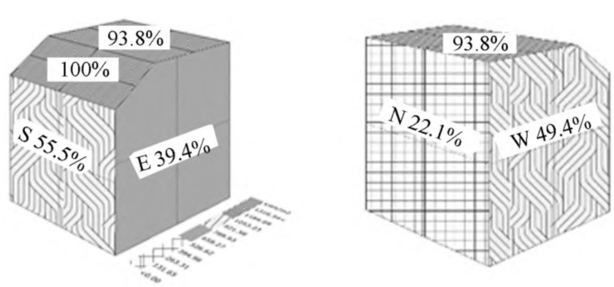

Figure 8. Power generation efficiency in different orientations

Table 11. Annual average power generation of newly installed photovoltaic power generation systems on roofs and facades

	Roof	South façade	East façade	West façade	Total
Annual average power generation (10,000 kW·h)	830.8	708.7	370.4	465.6	2,375.5

Table 12. Cumulative power generation of newly installed photovoltaic power generation system year by year

Year	Cumulative power generation year by year (10,000 kW·h)	Year	Cumulative power generation year by year (10,000 kW·h)
2023	2,339.87	2036	35,559.67
2024	4,957.14	2037	38,044.06
2025	7,563.95	2038	40,518.52
2026	10,160.33	2039	42,983.08
2027	12,746.32	2040	45,437.78
2028	15,321.97	2041	47,882.66
2029	17,887.31	2042	50,317.76
2030	20,442.39	2043	52,743.12
2031	22,987.25	2044	55,158.78
2032	25,521.93	2045	57,564.78
2033	28,046.47	2046	59,961.15
2034	30,560.92	2047	62,347.94
2035	33,065.30		

Table 13. Cumulative CO_2 emission reductions from all photovoltaic systems on campus year by year

Year	Cumulative CO_2 emission reductions year by year (kg)	Year	Cumulative CO_2 emission reductions year by year (kg)
2012	1,172.47	2030	224,669.44
2013	2,336.07	2031	251,063.01
2014	3,490.99	2032	277,347.92
2015	4,637.24	2033	303,524.56
2016	5,774.92	2034	329,593.63
2017	6,904.12	2035	355,555.30
2018	8,024.85	2036	381,410.20
2019	9,137.1	2037	379,299.28
2020	10,241.08	2038	403,969.64
2021	11,336.78	2039	428,541.31
2022	12,424.80	2040	453,014.67
2023	36,833.65	2041	477,390.12
2024	64,000.60	2042	501,668.07
2025	91,055.79	2043	525,848.91
2026	117,999.52	2044	549,933.04
2027	144,832.28	2045	573,920.86
2028	171,554.57	2046	597,812.67
2029	198,166.79	2047	621,608.97

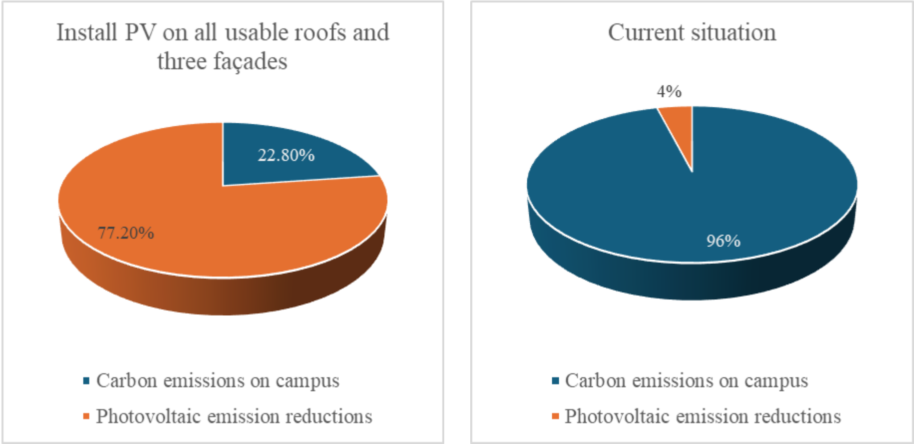

Figure 9. Comparison of carbon reduction before and after installation

3.4.2. Surplus electricity uploading

Due to the special operating hours of the campus, during the summer and winter vacations every year, the electricity consumption on campus is low (see **Figure 10**), and the electricity generated by the photovoltaic power generation system cannot be fully utilized. The surplus photovoltaic electricity can be uploaded to the power grid to participate in green electricity trading, providing green electricity to society and playing a certain role in relieving the power supply pressure of the local power grid. Currently, the policy of distributed photovoltaic power generation systems participating in green electricity trading has only been piloted in some cities. If implemented on a large scale, the campus can obtain green electricity certificates and revenue after uploading surplus electricity to the grid. This revenue can be used to purchase green electricity for other purposes and obtain green electricity consumption certificates, which can then be used to offset indirect carbon emissions on campus, bringing certain economic benefits and achieving a win-win situation for ecological and economic benefits.

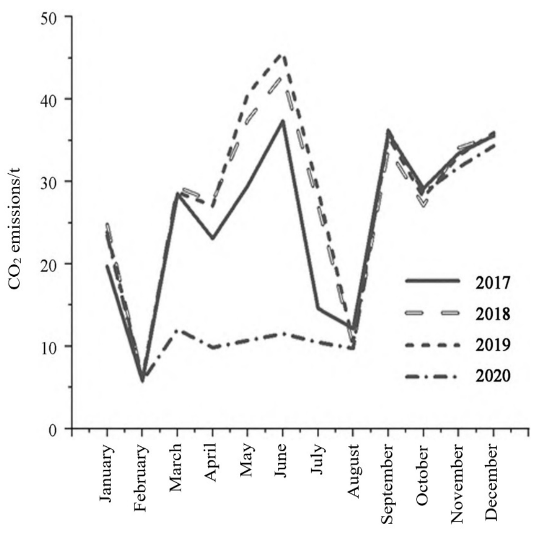

Figure 10. Monthly electricity carbon emissions of Bowen Building, Shandong Jianzhu University

3.4.3. Combining photovoltaic with heat pumps for heating to expand usage methods

For most universities in northern regions, carbon emissions from heating account for a significant proportion of campus carbon emissions. In recent years, with the implementation of the environmental protection policy of "coal to gas" conversion, many universities in northern regions have replaced coal-fired boilers with gas-fired boilers. This measure has indeed greatly reduced campus carbon emissions. However, carbon emissions from gas combustion still account for a large proportion of campus carbon emissions. Therefore, photovoltaics can be combined with air-source heat pumps and ground-source heat pumps for heating to replace coal and gas heating, thereby reducing the use of primary energy and reducing direct campus carbon emissions from coal and gas.

First, the carbon emissions of different heating forms on campus are calculated when external energy sources, i.e., not combined with the photovoltaic power generation system, are used. The heating area of Shandong Jianzhu University is approximately 700,000 m^2, and the annual heating time in Jinan City is 120 days. No heating is provided during the winter vacation (January 15–February 25), so the annual heating time is taken as 80 days. The campus was built earlier, and energy-saving design standards for buildings had not been developed, issued, or implemented at the time of design. Based on the heating index values and calculation methods for Jinan City statistics by Gao *et al.* [15] in 2008, the heat consumption index for the entire heating season for buildings in the eastern part of Jinan City during the same period was 28.46 W/m^2. The comprehensive heating index for the campus is calculated based on the average outdoor temperatures in Jinan City in late November, December, early to mid-January, late February, and early to mid-March, with values of 12.53 W/m^2, 31.33 W/m^2, 28.65 W/m^2, 23.28 W/m^2, and 7.16 W/m^2, respectively. The heating demand on campus is calculated as 1.077×10^5 GJ. The heating demand is converted into energy consumption for different heating methods, considering the primary energy utilization rates of different heating methods. For coal-fired boilers, the rate is taken as 55%, for gas-fired boilers it is 90%, and for air-source heat pumps, the coefficient of performance (COP) is taken as 2.5 in this study, resulting in a primary energy utilization rate of 80.94% [16]. For electrically driven ground-source heat pumps, the COP is taken as 3.5 in this study, resulting in a primary energy utilization rate of 113.31%. Then, based on the carbon dioxide emission factors of different energy sources, the carbon dioxide emissions of different heating methods are calculated. The calculation results show that the carbon dioxide emissions of the four different heating methods, from highest to lowest, are: coal-fired boilers, air-source heat pumps, gas-fired boilers, and ground-source heat pumps, as shown in **Table 14** and **Figure 11**.

Carbon dioxide emissions for different heating methods:

$$C_i = E_i EF_{ci} \tag{4}$$

where C_i is the carbon emission of the i^{th} heating method, in kgCO$_2$; E_i is the energy consumption of the i^{th} heating method; and EF_{ci} is the carbon dioxide emission factor of the energy source for the i^{th} heating method, in kgCO$_2$ per unit.

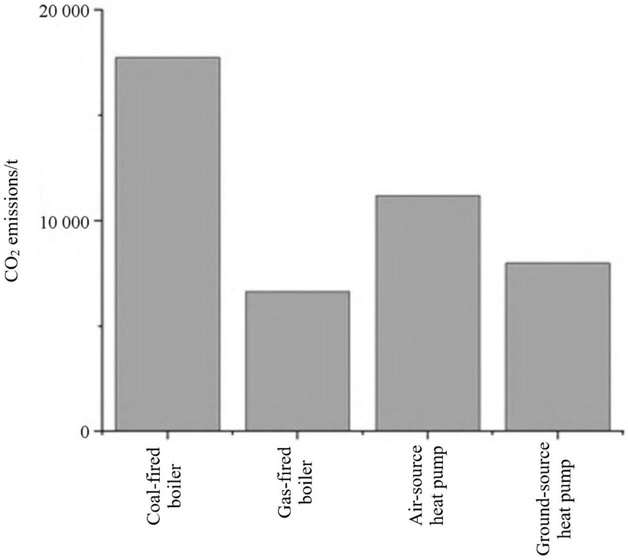

Figure 11. Annual CO_2 emissions from different heating methods

After combining the photovoltaic power generation system with heat pumps, calculations show that when the photovoltaic system is applied to all available roofs and facades on campus, it can provide approximately 297.76 million kW·h of electricity to the heat pumps during the annual heating season on campus. This portion of electricity does not generate carbon emissions, thus reducing carbon emissions by 2,971.32 t of CO_2. At this time, the combination of photovoltaic and air-source heat pumps and ground-source heat pumps still requires an external grid supply of 824.4 million kW·h and 503.8 million kW·h, respectively, resulting in indirect carbon emissions of 8,226.8 t of CO_2 and 5,027.7 t of CO_2, respectively.

Table 14. Annual carbon dioxide emissions for different heating methods

Heating method	Type of heating energy	Energy required for heating	Carbon dioxide emission coefficient	Carbon dioxide emissions
Coal-fired boiler	Raw coal	9,344.37 t	1.9003 kgCO$_2$/kg	17,757.12 t
Gas-fired boiler	Natural gas	3,065,649.81 m^3	2.1622 kgCO$_2$/m^3	6,628.55 t
Air-source heat pump	Electricity	11,221,700 kW·h	0.9979 kgCO$_2$/kW·h	11,198.17 t
Ground-source heat pump		8,015,900 kW·h		7,999.09 t

During the winter and summer vacations, the campus photovoltaic power generation system uploads surplus electricity to the grid to participate in green electricity trading. This means using the revenue from selling surplus electricity during vacations to purchase green electricity for heating. Assuming a 1:1 ratio between green electricity revenue and the cost of purchasing green electricity, calculations show that the electricity generation during vacations is approximately 466.42 million kW·h. Therefore, the total electricity provided by the photovoltaic power generation system during the heating season and the grid-connected green electricity during vacations is 764.18 million kW·h, reducing emissions by 7,625.75 t of CO_2. After combining the campus photovoltaic power generation system with heat pumps, the carbon emissions from the four heating methods are shown in **Figure 12**.

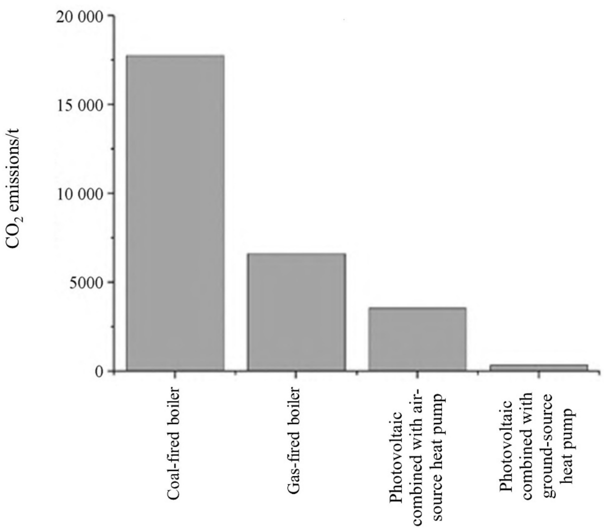

Figure 12. Annual carbon dioxide emissions from different heating methods after combining photovoltaic with heat pumps

It can be seen that the actual annual carbon emissions from the heating method combining photovoltaic with air-source heat pumps at Shandong Jianzhu University are 3,572.42 t. This represents a reduction of 79.9% in carbon dioxide emissions compared to coal-fired boilers and a reduction of 46.1% compared to gas-fired boilers. When combining photovoltaic with ground-source heat pumps, the actual annual carbon emissions are 373.34 t, which is a 97.9% reduction compared to coal-fired boilers and a 94.4% reduction compared to gas-fired boilers. The scheme of combining photovoltaics with heat pumps for heating and fully utilizing green electricity policies can greatly improve the emission reduction benefits on campuses in northern heating areas.

3.4.4. Strengthening maintenance and cleaning

The efficiency of photovoltaic power generation systems decays with use. Apart from uncontrollable factors such as the natural environment, regular maintenance and cleaning can reduce the decay rate. If the photovoltaic power generation system has been in operation for a long time, dust accumulation usually occurs on the surface of the photovoltaic arrays due to the action of fine particles in the air, especially during certain seasons in northern regions. Additionally, partial blockages by debris can cause light spots, severely reducing the efficiency of photovoltaic power generation. Therefore, regular maintenance and cleaning of the photovoltaic power generation system are necessary to ensure its power generation efficiency [17]. Based on years of industry monitoring, annual photovoltaic power station maintenance, with a cleaning cycle of 2 months, can increase power generation by an average of approximately 5.5% [18]. Given that the total power generation of the photovoltaic power generation system at Shandong Jianzhu University, without regular maintenance, is 26.96 million kW·h over 25 years, calculations based on the annual average increase in power generation show that regular maintenance and cleaning of the photovoltaic power generation system would increase power generation by approximately 1.4829 million kW·h over 25 years, as shown in **Figure 13**.

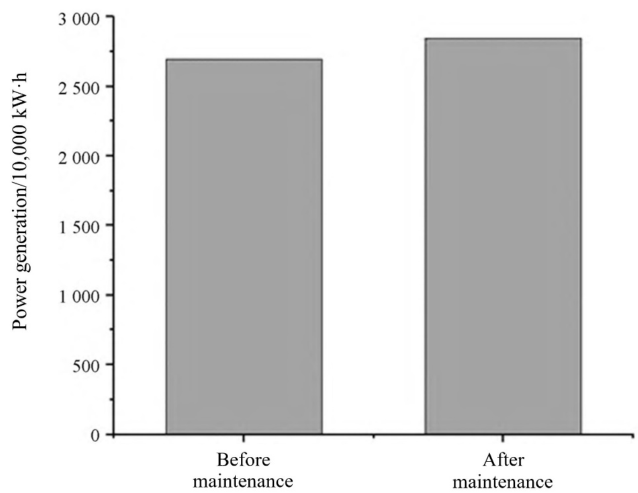

Figure 13. Comparison of photovoltaic power generation before and after regular maintenance

4. Conclusion

This study first analyzed the carbon emission reduction benefits and carbon emission recovery period of photovoltaic power generation systems by calculating the carbon emissions and power generation at various stages of their full life cycle per unit area. Taking Shandong Jianzhu University as an example, a carbon emission reduction analysis was conducted on the existing photovoltaic power generation system on campus. The potential for applying photovoltaic power generation systems on campus was analyzed by expanding the scale of photovoltaic use, connecting excess electricity to the grid, expanding usage methods, and strengthening maintenance and cleaning.

(1) The study investigated the full life cycle carbon emissions of campus photovoltaic power generation systems. The full life cycle carbon emissions of photovoltaic power generation systems per unit area were 561.73 $kgCO_2/m^2$, with the production stage contributing the most emissions. Over its full life cycle, the photovoltaic power generation system per unit area reduced CO_2 emissions by 3,082.56 kg/m^2, with an average annual reduction of approximately 123.3 kg/m^2. The carbon emission recovery period was 4 years, indicating significant carbon emission reduction benefits.

(2) Taking the photovoltaic power generation system on the campus of Shandong Jianzhu University as an example, the study analyzed its carbon emission reduction benefits. The results showed that the emission reductions from the photovoltaic power generation system accounted for 4% of the campus's total carbon emissions, indicating a certain level of carbon emission reduction. However, there is still significant potential for further reductions. Measures such as expanding the installation scale of photovoltaic power generation systems, expanding utilization methods, connecting excess electricity to the grid, and strengthening maintenance and cleaning can enhance emission reduction benefits and broaden the application of photovoltaics in low-carbon campus construction.

(a) By applying photovoltaics to all available roofs and facades on campus, emission reductions increased from 4% to 77.2%.

(b) Uploading excess photovoltaic electricity, especially the large amount generated during summer and winter vacations, to the grid and participating in green electricity trading can alleviate local grid supply pressure and offset indirect campus carbon emissions.

(c) Combining photovoltaics with air-source heat pumps for heating can reduce carbon dioxide emissions by 79.9% compared to coal-fired boilers and by 46.1% compared to gas-fired boilers. When combined with ground-source heat pumps, photovoltaics can reduce carbon dioxide emissions by 97.9% compared to coal-fired boilers and by 94.4% compared to gas-fired boilers.

(d) Regular maintenance and cleaning of the photovoltaic power generation system every 2 months over 25 years can increase power generation by approximately 1.4829 million kWh.

(3) This study concluded that photovoltaic power generation systems have significant environmental benefits over their full life cycle. Furthermore, photovoltaic power generation systems still have considerable potential for low-carbon campus construction. It is recommended to improve the relevant technical guidelines and procedures for photovoltaic utilization on campus, closely integrate them with campus characteristics, accelerate the participation of university photovoltaic systems in green electricity trading, and fully leverage the leading role of photovoltaic power generation technology in low-carbon campus development.

Disclosure statement

The authors declare no conflict of interest.

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