J Ther Eng, Vol. 11, No. 5, pp. 1–12, September, 2025

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000000

Case Report

Enhancing carbon neutrality through renewable energy and demand-side management: A case study

Yeqing ZHU[1], Yu WANG[1], Shen HOU[1], Yanjun CHEN[2], Luzheng ZHANG[2,*]

[1]*State Power Environmental Protection Research Institute, Nanjing, Jiangsu, 210018 China*
[2]*Jiangsu Skytech Industrial Internet CO., LTD, Nanjing,Jiangsu, 211899, China*

ARTICLE INFO

Article history
Received: 22 April 2025
Revised: 18 May 2025
Accepted: 20 May 2025

Keywords:
Carbon Reduction; Integrated Renewable Energy Systems; Carbon Dioxide Flux; Research and Office Parks

ABSTRACT

In the context of China's dual carbon goals—carbon peaking and carbon neutrality—the implementation of high-efficiency carbon reduction and control technologies is of paramount importance. This study evaluates the impact of renewable energy integration and energy management strategies on carbon emissions in a research and office institute park located in Nanjing, China. A 1.162 MW photovoltaic system was deployed to supply on-site electricity demand. The system exhibited substantial performance, achieving electricity self-sufficiency rates exceeding 100% on 50 days and surpassing 50% on 58.8% of the monitored days over the study period. To enhance energy efficiency on the demand side, the air conditioning temperature set point was raised from 25 °C to 27 °C. This adjustment led to a 15.1% reduction in air conditioning energy consumption and increased the average summer photovoltaic self-sufficiency rate from 51.27% to 56.85%.

In addition, a carbon flux tower was installed to facilitate continuous monitoring of carbon flux and atmospheric CO_2 concentrations. The measured data indicated consistently low carbon dioxide concentrations and negative carbon flux values, with average concentrations of 464.87 ppm and mean CO_2 flux of –0.0087 mg/m²·s, respectively. These results underscore the effectiveness of integrated renewable energy systems and active demand-side management in reducing operational carbon emissions in urban building clusters.

Cite this article as: Zhu Y, Wang Y, Hou S, Chen Y, Zhang L Enhancing carbon neutrality through renewable energy and demand-side management: A case study. J Ther Eng 2025;11(5):1–12.

INTRODUCTION

The modern world is facing serious environmental challenges, with climate change and global warming emerging as critical concerns. These issues are largely driven by carbon emissions originating from industrial activities, transportation systems, and fossil fuel-based power generation[1].

The development of low-carbon office and research parks has emerged as a critical strategy in addressing climate change and contemporary energy challenges.

***Corresponding author.**
*E-mail address: zhangluzheng@skynj.com

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

Research in this domain encompasses a wide range of topics, including sustainable architectural design, advanced energy management systems, carbon emissions assessment methodologies, and user behavior interventions. Current studies underscore an increasing demand for sustainable and energy-efficient work environments, as organizations strive to align their infrastructure with long-term carbon reduction targets—particularly those set for 2030 and 2060. Modern low-carbon parks emphasize not only the attainment of green building certifications but also the continuous optimization of building performance, enhancement of energy efficiency, electrification of energy systems, and large-scale integration of renewable energy technologies.

Sustainable design plays a pivotal role in reducing carbon emissions in office and research park developments. Low-carbon architectural strategies prioritize passive design approaches, including natural ventilation, daylight utilization, and the incorporation of energy-efficient building materials. Additionally, the integration of green infrastructure—such as rainwater harvesting systems, vegetative landscaping, and water recycling technologies—further supports the achievement of long-term sustainability objectives. For instance, Jiang et al. proposed a planning framework for agricultural rural industrial parks that emphasizes modernization and sustainability, leveraging the "negative carbon" potential of biochar and advanced agricultural facilities. Their approach utilizes a two-stage distributionally robust optimization model with a box-shaped uncertainty set to minimize total system costs, while simultaneously accounting for carbon emission reductions via carbon trading mechanisms [2]. Huang et al. [3] analyzed the low-carbon practices of an industrial park, focusing on measures like optimizing energy structure and transforming infrastructure. The findings suggested that optimizing energy structure and infrastructure transformation are vital for energy savings in industrial parks [3]. Wu et al. [4] delved into the multi-parameter optimization design approach for energy systems within low-carbon parks, revealing that energy storage devices play a significant role in elevating renewable energy utilization and promoting energy conservation and emission reduction [4]. Li et al. [5] discussed the performance and photovoltaic (PV) benefits analysis of multi-source renewable energy systems applied to various buildings on a university campus. It highlights the potential of utilizing renewable energy, specifically photovoltaic-assisted Heating, Ventilation, and Air Conditioning (PV-HVAC) systems, to reduce energy consumption on campus [5]. Aghamolaei et al.'s research showed that adopting renewable energy, optimizing energy systems, enhancing building envelope structures, and implementing intelligent technologies can make significant contributions to reducing carbon emissions and achieving a net zero carbon campus [6]. Hiltunen et al.[7] investigated the potential of reducing carbon emissions and enhancing energy efficiency on a university campus by connecting its heating system to the district heating network of the city. The key findings revealed that both connections lead to substantial CO_2 emission reductions compared to the existing natural gas boiler system of the campus [7]. The research on the University of Palerm campus as small-scale models of cities demonstrated that initiatives such as installing photovoltaic plants, green roofs, LED street lighting, and promoting sustainable mobility through mobile apps have significantly reduced energy consumption and CO_2 emissions, and university campuses have the potential to act as models for sustainable urban development [8].

Intelligent energy management systems are widely applied in low-carbon parks, optimizing energy use through IoT (Internet of Things) technologies and data analytics. Distributed energy resources such as micro grids and energy storage further enhance energy efficiency by balancing supply and demand, particularly during peak usage times. These systems help to manage energy loads efficiently, reducing peak energy demand and improving energy reliability within the park. Li et al.[9] optimized CO_2 utilization in a chemical industrial park in China using a carbon allocation network, guided by the Automated Carbon Tracking Algorithm (ACTA). Four scenarios are analyzed and achieved over a 50% reduction in carbon emissions at the park [9]. Zhao et al. established a comprehensive assessment framework with a multi-objective optimization model for reducing both carbon and air pollutant emissions in industrial parks. Five different scenarios were designed to quantify the reduction potential of greenhouse gases and air pollutants and evaluate the co-emission reduction control effects under four measures, including the industrial structure adjustment, the energy structure adjustment, the energy efficiency improvement, and the industrial synergy [10]. Qian et al. [11] proposed a low-carbon optimization scheduling method for energy-intensive industrial parks, integrating a parameter-adaptive demand response incentive mechanism. A three-layer optimization model focusing on energy supply, load-side optimization, and demand response parameter optimization was established [11]. Lyu et al. [12] addressed uncertainty in the integrated energy systems (IES) by proposing a low-carbon, robust economic dispatch model based on price. It incorporates vehicle-to-grid technology, a price-based integrated heat and electricity demand response model, and a carbon trading model [12]. Ho et al. [13] presented a multi-objective planning model to support energy conservation and renewable energy in low-carbon campuses. Using multi-objective linear programming (MOLP) and a fuzzy two-stage algorithm, it aims to reduce CO_2 emissions by considering electricity and heat from solar panels and water heaters, along with energy efficiency improvements from rooftop gardens [13]. A demand response (DR) model for heat and electricity, incorporating prices and a vehicle-to-grid (V2G) system, was put forward by Li et al. It employed the Monte Carlo method to analyze uncertainties in emission reduction technologies and economic development. The results indicate that the model effectively maintains system security and acceptable carbon emissions, serving as a roadmap for low-carbon industrial park development [14]. Hu et al. [15] adopted a multi-objective bi-level optimization approach, utilizing the non-dominated sorting genetic algorithm II (NSGA-II) in an optimal planning model for electric-heating integrated energy systems (EH-IES) in low-carbon parks. The upper-level model optimizes district heating network (DHN) equipment configuration based on economic costs and thermal energy satisfaction. The lower-level model then optimizes the hybrid energy storage system and accesses locations in the distribution network (DN), aiming to reduce net load fluctuation and voltage deviation [15]. Huo et al. [16] developed a dual-layer optimization strategy for a photovoltaic storage-hydrogen system in coal chemical industry parks. It proposed an energy management scheme that maximizes daily income based on time-of-use electricity prices, renewable energy generation, and load demands, providing a strategic roadmap for sustainable energy transitions in coal chemical industries [16].

Besides, assessing the carbon footprint of parks is essential for formulating strategies to reduce emissions. Life-cycle assessments (LCA) and carbon footprint calculations enable the precise evaluation of emissions from building construction, transportation, energy use, and waste management. These assessments inform carbon neutrality strategies, such as carbon capture, carbon sinks (e.g., afforestation), and participation in carbon trading schemes. Zheng et al. analyzed the sustainability of Huazhong University of Science and Technology (HUST) in China based on ecological footprint evaluation and machine learning [17]. Wang et al. [17] investigated the synergistic effect between pollution reduction and carbon emissions in an industrial park through LCA. Results showed a positive synergistic relationship between pollutants and carbon emissions, with strong synergy observed for SO_2, NO_x, and $PM_{2.5}$ due to their close link with energy consumption [18]. Wang et al. [18] assessed the carbon footprint of a medium-sized university campus in eastern China through an innovative hybrid methodology combining the Long-range Energy Alternatives Planning System (LEAP) and LCA. To reduce the carbon footprint, seven mitigation strategies are proposed, including electricity decarbonization, waste recycling, greening, HVAC control system optimization, installation of solar PV panels, lighting control, and control of appliances [19].

User behavior is another critical factor influencing energy consumption in low-carbon parks. Research shows that energy-saving behaviors can be encouraged through interventions such as energy-use feedback, behavioral nudges, and energy-saving incentives. Moreover, the implementation of shared economy models, such as shared workspaces and transportation, significantly reduces energy use. Reference [17] also gathered the students' daily carbon emissions related to clothing, food, housing, consumption, and transportation. The study underscores the importance of individual behavior changes, especially in energy-intensive activities like air conditioning use and food consumption.

Case studies from China's Yangtze River Delta, Pakistan, and ten Asian countries are analyzed using methods such as the Low Emissions Analysis Platform (LEAP) model, Autoregressive Distributed Lag (ARDL) model, and complex network evolutionary game model, exploring the impacts of renewable energy integration, demand-side management, and carbon trading policies on carbon neutrality.

Zhou et al.[20] focused on the China's Yangtze River Delta region, constructing a LEAP model to simulate five scenarios (64 sub-scenarios). They found that only 22 sub-scenarios could achieve carbon neutrality by 2060. A scenario with a 6% annual reduction in energy intensity achieved peak emissions ahead of schedule, while mixed policies (energy efficiency improvement, structural reform, and technological innovation) significantly reduced emissions, requiring an electrification rate of 64.19% in end-use sectors. The Analytic Hierarchy Process (AHP) validated that mixed policies enhance system reliability and cost-effectiveness.

Raza et al. [21] analyzed Pakistan's energy transition, comparing the Fossilized Energy System (FES) and Defossilized Energy System (DES). The DES scenario, with a 59.1% renewable energy share, reduced carbon emissions by 56,152.74 million tons but required an annual investment of $13.1 trillion. Economic indicators showed stabilization in inflation and unemployment after 2045, demonstrating the long-term economic benefits of renewable transitions.

Zhang et al. [22] examined carbon emissions from China's tourism sector using the ARDL model, revealing positive correlations between tourist numbers, fossil fuel consumption, and emissions, and a negative correlation with renewable energy use.

Wei et al. [23] studied demand-side flexible resources in China's power system, including demand response, electric vehicle charging, and power-to-hydrogen. Demand-side flexible resources reduced transition costs by 20%, decreasing investments in energy storage and flexible generation. Electric vehicle and power-to-hydrogen loads played pivotal roles in regional power balancing, reducing gas generation demand by 42% by 2060 and enhancing renewable energy integration.

Shafiei et al. [24] proposed a multi-objective optimization model integrating wind, photovoltaic (PV), energy storage, and demand response, using the Gravity Search Algorithm (GSA). Case simulations showed that wind power reduced generation by 6.61%, energy storage by 9.4%, and PV by 10.8%, while demand response reduced daily peak load by 45%.

Lu et al. [25] constructed a complex network evolutionary game model to analyze interactions between energy supply and demand sides under carbon trading policies.

They found that carbon price trends influence strategic choices.

Chau et al. [26] focused on ten Asian countries, exploring how natural resources and eco-financing impact renewable energy production. It highlighted that rational resource utilization and financial instruments can accelerate low-carbon transitions and enhance the feasibility of carbon neutrality pathways.

The current study investigates the energy load characteristics of a research and office institute park in Nanjing, China, with a focus on the distinct demands of office and research facilities. A renewable energy system centered on photovoltaic (PV) generation was implemented, achieving an average overall power self-sufficiency rate of 69.75%. To enhance energy utilization efficiency, a demand-side regulation strategy was applied by adjusting the indoor air conditioning set point. Notably, this study introduces the integration of a carbon flux tower within an urban office park environment to enable real-time monitoring of carbon emissions and sequestration. This combination of renewable energy deployment, active demand-side management, and direct carbon flux measurement provides a novel, data-driven approach to evaluating the carbon reduction performance of low-carbon campus systems.

SYSTEM DESCRIPTION

Park Profile

The research and office institute park is located at Nanjing Jiangbei New Area. As a state-level development zone, Jiangbei New Area focuses on promoting green energy and environmental protection industries.

The total building area of the park is 25,180 square meters, with a well-planned layout and distinct functional zones. As listed in Table 1, the main building types in the park consist of research laboratories, office buildings, apartments and canteen.

Energy Load Characteristics in The Park

The energy load patterns are influenced by the type of building, functional use, equipment characteristics, and usage time.

(1) Office Buildings

The energy load of office buildings is primarily driven by air conditioning, lighting, and office equipment. During summer and winter, the air conditioning load peaks, particularly during working hours. In summer, as external temperatures rise, the air conditioning systems operate to maintain indoor comfort, resulting in two distinct peaks in energy consumption: one in the morning (9 AM to 11 AM) and another in the afternoon (1 PM to 3 PM). Lighting loads are mainly concentrated during office hours from 8:00 AM to 18:00 PM, with significantly lower consumption during weekends and evenings. The energy consumption of office equipment, such as computers and printers, is relatively stable and correlates with working hours.

(2) Laboratories

The energy load in laboratories is mainly attributed to experimental equipment, ventilation systems, and air conditioning. Additionally, the laboratories often need to maintain specific temperature and humidity conditions, which increases the air conditioning load. Moreover, to ensure safety and compliance with environmental standards, efficient ventilation systems are necessary, further increasing energy consumption. Laboratories experience energy load peaks during working hours, and due to longer experiment cycles, energy consumption may present a more stable pattern throughout weekdays.

(3) Researchers Apartments

Energy consumption in researchers' apartments is primarily concentrated in lighting, hot water supply, household appliances, and air conditioning. As residential spaces, the energy load in apartments is relatively dispersed, with higher consumption during evenings and weekends. In winter and summer, the heating and cooling demands lead to increased energy consumption, especially during colder or hotter weather. The energy consumption patterns in apartments typically exhibit diurnal fluctuations, but overall remain stable, primarily influenced by the living habits of occupants and external climate conditions.

(4) Canteens

The energy load of canteens is closely linked to food service operations, including cooking equipment, lighting, and ventilation systems. Unlike other types of buildings, canteens also utilize gas energy for cooking processes, which adds another layer to their energy consumption profile. Peak energy consumption occurs during breakfast and lunch periods, particularly during the lunch rush, when both electrical and gas demands significantly increase. Canteens require substantial hot water and ventilation, contributing to the overall energy consumption. The operational hours of canteens usually align with weekdays, leading to distinct energy load patterns, with notably lower consumption during weekends.

To sum up, the energy load characteristics of different buildings exhibit significant temporal and spatial patterns in the park. During weekdays, the combined peak energy loads from office buildings and laboratories can result in high overall campus energy consumption. Conversely, during weekends, the energy consumption patterns of researcher apartments and cafeterias remain stable, while the energy consumption of office buildings and laboratories declines

Table 1. The main buildings in the park

Building type	Number	Total area (m^2)
Office building	2	11200
Laboratory	3	6300
Apartment	4	10400
Canteen	1	1180

Table 2. Layout area and power of solar photovoltaic panel in the park

Building	Roof area (m^2)	Number of photovoltaic modules	Power capacity (kWh)
Office building	1280	110	59.95
Laboratories	4975	1190	648.55
Electric bicycle carports	1496	576	313.9
Ground	800	256	139.5

significantly. To optimize the energy management within the park, the following strategies can be implemented:

Smart Control Systems: Introduce intelligent control systems to dynamically adjust the operation of air conditioning, lighting, and equipment to balance energy loads across various buildings.

Demand-Side Management: Implement demand-side management strategies during peak consumption periods, encouraging users to operate high-energy-consuming equipment during off-peak times.

Utilization of Renewable Energy: Promote the use of renewable energy sources, such as solar and wind, to reduce overall park energy costs and environmental impact.

Energy Monitoring and Analysis: Regularly energy consumption monitoring and analysis to identify high-energy-consuming equipment and optimize or retrofit them accordingly.

Renewable Energy Application Measures

Solar photovoltaic panels

To reduce the CO_2 emission in the park, the utilization of renewable energy is necessary. Nanjing Jiangbei New Area is in a subtropical monsoon climate zone, with an average annual sunshine duration exceeding 2,000 hours, which provides favorable natural conditions for solar photovoltaic (PV) power generation. Comparatively, wind energy resources in Nanjing Jiangbei New Area are relatively limited, primarily due to topographical and climatic factors. The geothermal energy resources in Nanjing Jiangbei New Area are relatively abundant, particularly in terms of geothermal water and shallow geothermal energy. But it is more suitable for applications such as air conditioning systems and hot water supply, and not suitable for electricity generation due to its low grade.

Therefore, within the Nanjing Jiangbei New Area, utilizing solar energy resources for power generation is the most feasible method for renewable energy utilization in the park. The abundant solar radiation and the ongoing promotion of photovoltaic projects make solar energy the primary renewable resource for meeting the park's electricity demands.

In the park, monocrystalline silicon solar photovoltaic panels have been installed on the roofs of laboratory buildings, office buildings, and electric bicycle carports, with a photoelectric conversion efficiency of 21.3% and a peak power of 545Wp. Additionally, solar photovoltaic panels have also been placed in certain ground spaces within the park, resulting in a total generation area of 8551 m^2. The specific distribution of these panels across various building spaces is detailed in Table 2. The park currently hosts a 1.162 MW smart photovoltaic capacity, equipped with a 60 kW/60 kWh energy storage system and two 60 kW DC (Direct Current) charging stations. The average daily electricity generation is over 3,000 kWh, operating under the model of "self-consumption with excess electricity fed back to the grid," which essentially covers the electricity load during office hours on the campus.

Control regulation and energy storage

Additionally, the park features a micro grid energy cloud management system and a demonstration platform for integrated resource optimization and control of the source-grid-load-storage (SGLS) system. The micro grid energy cloud management system is built on the park's photovoltaic systems, energy storage, and charging stations, incorporating elements such as photovoltaic generation, energy storage, meteorological monitoring, network communication, direct/alternating current load applications, energy management, and centralized information control. This system enables functions including data collection and processing, sequential control, power control, generation forecasting, load forecasting, and optimized operation. The integrated resource optimization and control platform aggregates resources from both the generation side and the load side within the park. It enhances energy consumption monitoring and facilitates the collection and analysis of data from photovoltaic systems and energy storage, thereby improving the utilization rate of energy assets and the absorption rate of photovoltaic generation.

The supply of solar PV resources exhibits instability, as light intensity is influenced by weather conditions (such as cloudy or rainy days) and seasonal variations, leading to fluctuations in power generation under different times and conditions. This instability makes it challenging for solar power to match stable electricity demand, increasing the complexity of grid management. Therefore, it is necessary to integrate energy storage technologies and flexible scheduling to balance supply and demand, enhancing the reliability and adaptability of the system. Based on this, within the park, photovoltaic energy storage will be facilitated

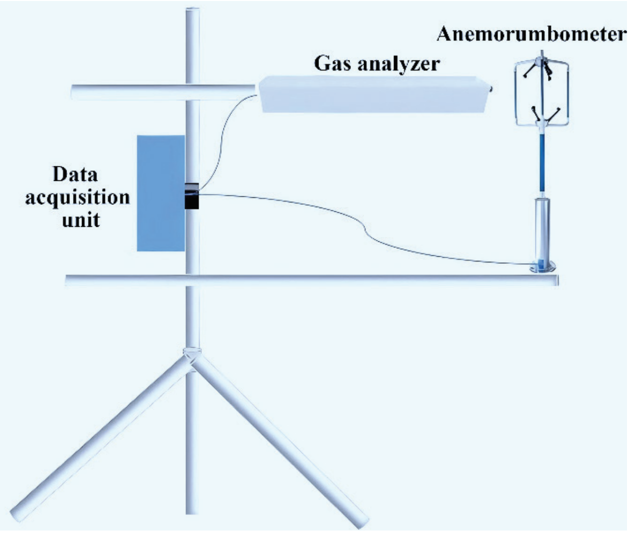

Figure 1. Schematic diagram of carbon flux tower.

through charging stations located in the electric bicycle carports, achieving a total charging power of 34.56 kW.

Carbon flux tower

Accurate monitoring and evaluation of carbon flux and carbon sequestration capacity are crucial for assessing the actual carbon reduction effects within the park and represent significant tasks in ecological research and management. Therefore, a carbon flux tower has been established within the park, as shown in Figure 1. The carbon flux tower is an important device for real-time dynamic monitoring, which measures gas concentrations and airflow movements at high frequencies, enabling precise capture of the carbon uptake and release processes by plants, soils, and other ecosystems.

The main components of the carbon flux tower include CO_2 flux analyzer (see Figure 2), anemorumbometer, and data acquisition unit. The CO_2 flux gas analyzer employs Tunable Diode Laser Absorption Spectroscopy (TDLAS) technology and its main components include a light source, a beam splitting system, a sampling system, a detector, and a data processing system. The near-infrared DFB diode laser with wavelength of 2004 nm is adopted to achieve online measurement of CO_2 concentration. The measurement range is 0-2000 ppm, with a measurement accuracy of 1% of the reading. The operating temperature ranges from -10°C to 50°C, which can meet the application requirements for carbon flux measurement in practical processes. The carbon flux tower is installed on the roof of the office building, with parameters designed to obtain the most accurate carbon flux data. This data is crucial for evaluating the carbon sequestration capacity within the park and for understanding the responsiveness of renewable energy and its regulation mechanisms to climate change, thereby providing data support for the management and protection of ecosystems.

RESULTS AND DISCUSSION

In this section, we present the outcomes of renewable energy systems and carbon flux monitoring at the research and office institute park. The deployment of solar photovoltaic power generation, demand-side regulation, real-time carbon flux monitoring has proven effective in reducing the park's carbon emissions, enhancing energy efficiency, and optimizing renewable energy utilization.

Energy Generation and Utilization

The park's energy generation capacity is centered around its 1.162 MW solar PV system, which serves as the primary renewable energy source. The system's performance is monitored by an integrated micro grid energy

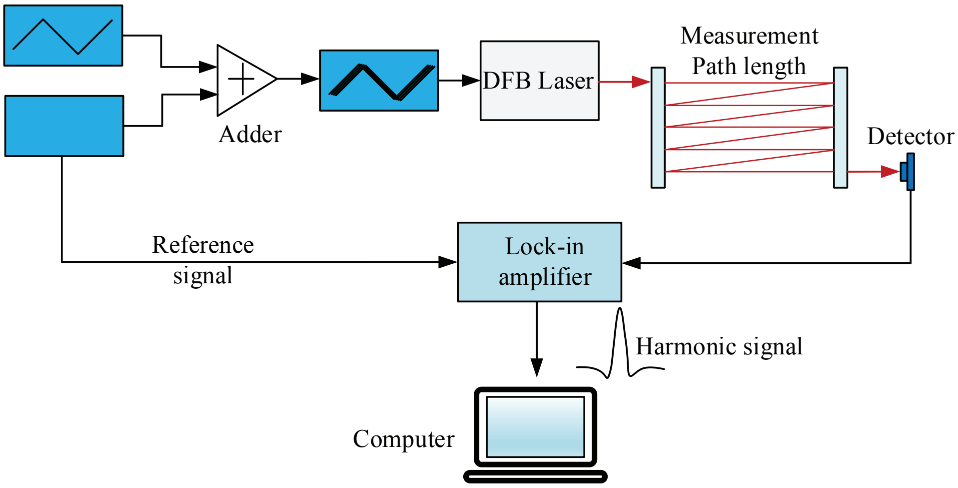

Figure 2. Schematic diagram of the CO_2 flux analyzer.

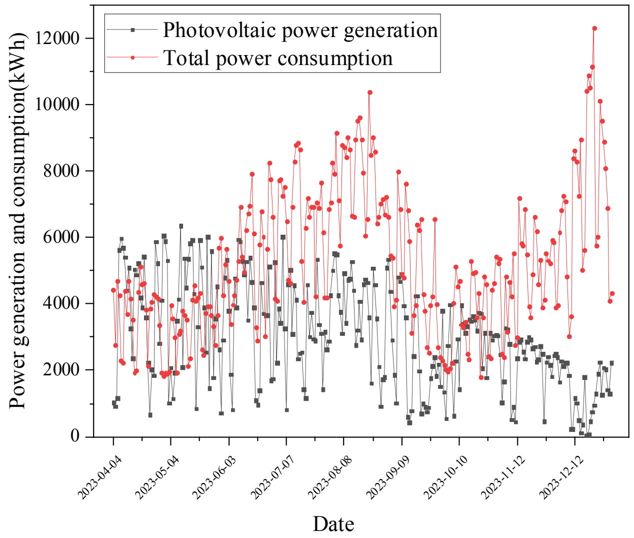

Figure 3. Energy production and consumption curve in the park from April to December.

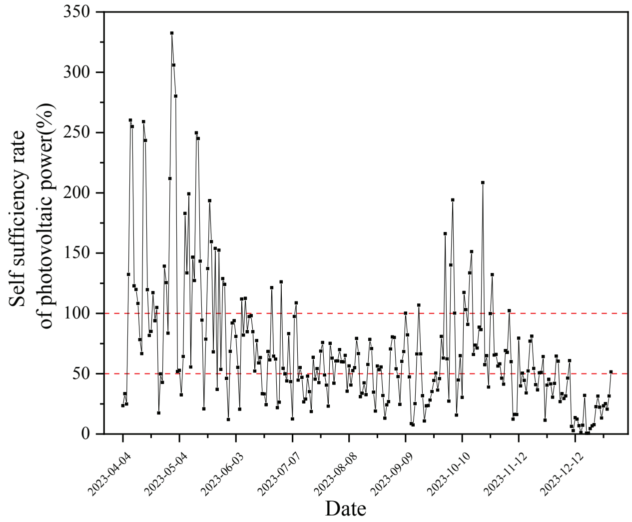

Figure 4. Daily self-sufficiency rate of solar photovoltaic power generation.

cloud management system, which ensures that electricity is distributed efficiently across the park.

Figure 3 illustrates the daily variation in electricity generation of the PV power system within the park from April to December, after its deployment in practical operation. As observed in the figure, the average daily power generation from April to June—during the spring and early summer period—reached 3779.86 kWh. This higher output can be attributed to the favorable air quality and enhanced atmospheric ventilation in Nanjing during this season, which resulted in stronger solar radiation intensity. In contrast, the average daily power generation decreased to 3215.96 kWh from July to September, during the summer months. This reduction is primarily due to the frequent rainfall and high humidity in Nanjing during summer, where the presence of abundant water vapor attenuated solar radiation intensity. From October onwards, in the autumn and winter months, the average daily power generation declined further, reaching only 2146.18 kWh. This reduction is attributed to the lower solar altitude angle relative to the ground in winter, which results in reduced solar radiation intensity in the Nanjing region.

Furthermore, Figure 3 reveals the comparative relationship between the PV power generation and the total electricity consumption of the park. From April to June, the PV power generation generally exceeds the park's total daily electricity consumption, indicating that the PV system is capable of achieving self-sufficiency in meeting the park's electricity demand during this period. However, in most days after July, the reduction in solar radiation intensity results in the park's total electricity consumption surpassing the PV power generation.

Figure 4 further illustrates the daily self-sufficiency rate of solar PV power generation from April to December. The self-sufficiency rate is defined as the ratio of PV power generation to total electricity consumption. Clearly, a higher self-sufficiency rate, especially values reaching or exceeding 1, is desirable, as it indicates that the renewable energy generated by the PV system is sufficient to meet the park's electricity demands. According to the data in Figure 3, out of the 260 days from April to December, the self-sufficiency rate exceeded 100% on 50 days. Among these, 35 days occurred from April to June, 4 days from July to September, and 11 days from October to December. Additionally, 33 days were recorded from April to June, 39 days from July to September, and 31 days from October to December

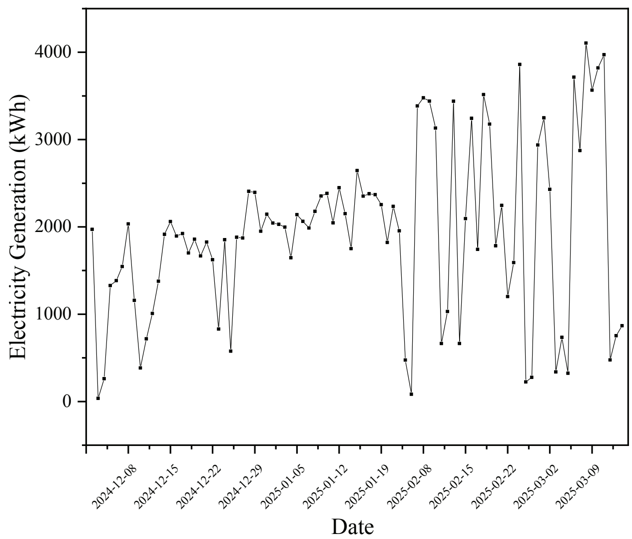

Figure 5. Energy production in the park from December to March.

where the self-sufficiency rate was between 50% and 100%. According to this, the PV power generation surpassed 50% of the park's electricity demand on 58.8% of the days, demonstrating how significant renewable energy is to the park's power supply.

Figure 5 presents the photovoltaic power generation data from December 2024 to March 2025. The corresponding monthly average power generation values are 1519.62 kWh, 1790.58 kWh, 1991.33 kWh, 2244.12 kWh and 2230.74 kWh, respectively. The reasons for the changes are analyzed as follows: In the Northern Hemisphere, November, December, and January belong to winter, while February and March gradually transition to spring. During winter, the solar altitude angle is relatively low, and the sunshine duration is short, which reduces the amount of solar radiation reaching the photovoltaic panels, resulting in relatively low photovoltaic power generation. The December average of 1519.62 kWh is the lowest value. As time progresses to February and March, the solar altitude angle gradually increases, the sunshine duration lengthens, and the solar radiation intensity increases, leading to an increase in photovoltaic power generation. The February average reaches 2244.12 kWh, and the March average is 2230.74 kWh. Overall, the trend of photovoltaic power generation is closely related to the changes in solar radiation brought about by seasonal changes.

Based on the actual operational data, it is estimated that the PV system can generate an annual average of 1.062 MWh of electricity for the park. In comparison, the total electricity consumption of the park for the year 2023 was 1.689 MWh. According to the latest electricity carbon emission factor for Jiangsu Province, officially released by the Ministry of Ecology and Environment of China (0.6451 kg CO_2/kWh), the PV system is expected to reduce carbon dioxide (CO_2) emissions by approximately 685.44 tons annually.

Regulation and Demand Management

As shown in Figures 3 and 4, the self-sufficiency rate of PV power generation is relatively low in both summer and winter. In winter, this is primarily due to the inherently low levels of solar radiation. In summer, however, the increased load and energy consumption from air conditioning systems represent another significant contributing factor. To enhance the proportion of renewable energy in the power supply (i.e., the self-sufficiency rate mentioned above), improvements can be achieved through measures such as regulation and demand-side management.

The total building area of the entire park is 25,180 m^2. In the Nanjing region, the summer climate is hot and humid, resulting in significant air conditioning loads and energy consumption. To address this issue, this study employs a simulation approach using EnergyPlus software to model the change in energy consumption within the park when the indoor air conditioning temperature set

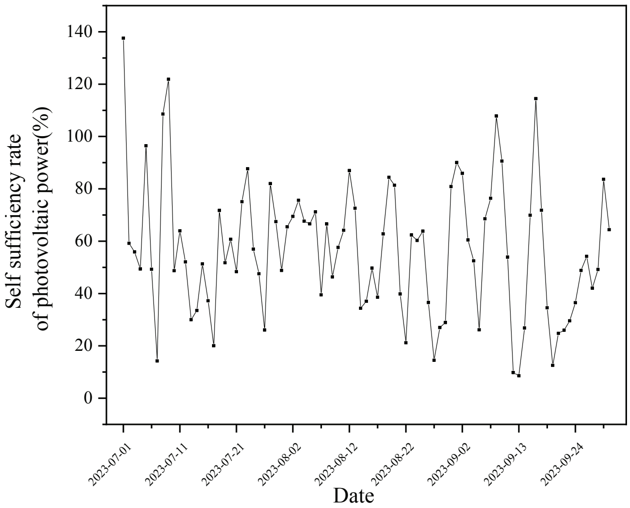

Figure 6. Electricity self-sufficiency rate after implementation of demand-side management adjustments.

point is adjusted from 25°C to 27°C. Overall, this adjustment led to a 15.1% reduction in the electrical energy consumption of the air conditioning system, thereby decreasing the total electricity consumption of the park and improving the self-sufficiency rate of the PV power generation system.

By implementing this demand-side management measure of adjusting the air conditioning system's set temperature, as shown in Figure 6, the average self-sufficiency rate of PV power generation from July to September increased from 51.27% to 56.85%, as compared to the data in Figure 3. The number of days with a self-sufficiency rate exceeding 50% increased from 43 days to 52 days, with the number of days within the range of 50% to 100% rising from 39 to 47 days. This significantly enhanced the proportion of renewable energy in the power supply, thereby reducing carbon emissions from traditional non-renewable electricity sources.

Carbon Flux Monitoring

One of the key objectives of this study was to evaluate the impact of renewable energy deployment on the park's carbon footprint. To achieve this, a carbon flux tower using was set up to monitor the dynamic changes in carbon flux and sequestration in real-time.

Figure 7 presents the daily average CO_2 concentrations recorded by the CO_2 flux tower during the period from October 1 to November 25, 2024. The data revealed that the CO_2 concentration remains at a relatively low level from 428~492 PPM, with an average value of 464.87 PPM. This suggests that the use of renewable energy for power generation has effectively suppressed CO_2 emissions within the park.

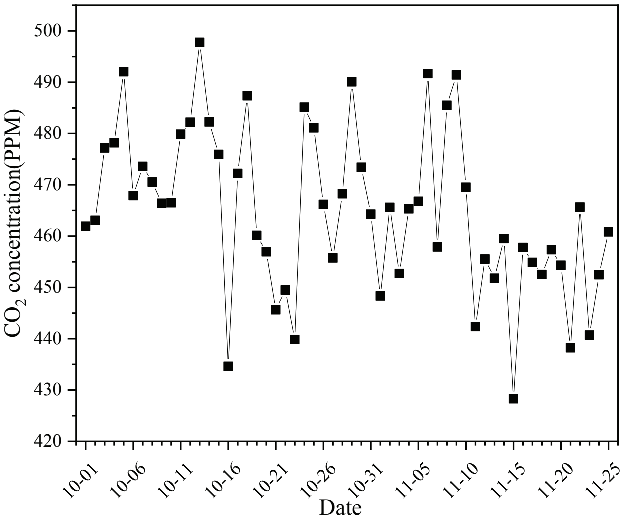

Figure 7. Daily average carbon dioxide concentration monitored by carbon flux tower.

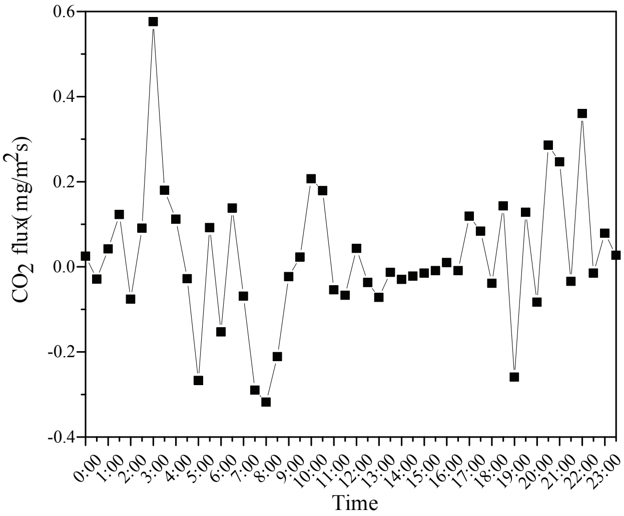

Figure 9. Hourly variation of carbon dioxide flux in a working day

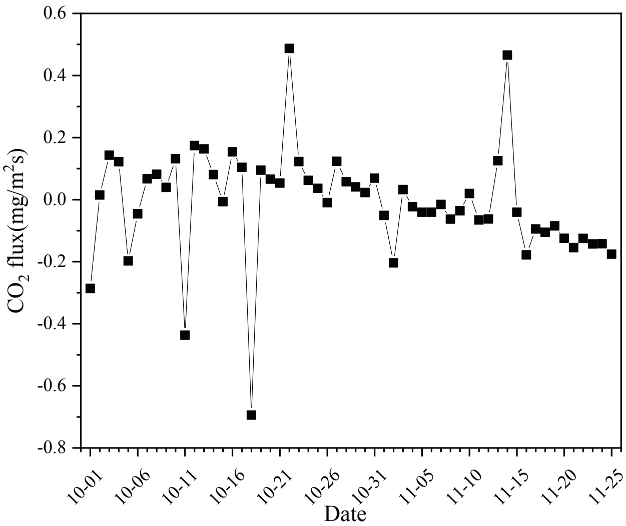

Figure 8. Daily average CO_2 flux monitored by carbon flux tower.

Figure 8 illustrates the variations in CO_2 flux observed from October 1 to November 25, where negative values indicate absorption and positive values represent emissions. As shown in the figure, the flux values are relatively small, with an average of -0.0087mg/m^{2}s, indicating that the park has effectively achieved carbon neutrality. The data highlight the critical role of green vegetation within the site in sequestering carbon, demonstrating their effectiveness in absorbing CO_2.

Figure 9 depicts the variation in CO_2 flux over a 24-hour period on October 30, a typical workday, with data recorded at 30-minute intervals. As shown in the figure, the hourly changes in CO_2 flux exhibit no significant patterns, with values fluctuating around zero. This indicates a minimal net CO_2 emission, reflecting a favorable carbon reduction effect.

Carbon Sink

To assess carbon sequestration potential in the park, a detailed analysis of carbon sink characteristics for different areas was performed. The research not only assessed the average biomass and carbon bio-sequestration rates of each tree species but also focused on the different forest types present throughout and within the park. The potential of carbon sequestration for individual zones was determined using aboveground and belowground biomass data, forest age, and area-related data (Table 3).

The results show the potential for carbon sequestration varies greatly between the areas, depending on tree species, forest density and age. In a comparison of the Mapped Species, advanced categories of species like Pine Forest, Maple Grove show greater potential for biomass and sequestration than younger plantations like Cherry Trees in East Corner. The Camphor Tree Groves also further contribute to the park's total carbon sink on average because of their general distribution.

Notably all 12 zones of the park had a wide biomass range from the lowest 1.35 tons in East Corner to the highest 7.00 tons in Garden Pond. Likewise for carbon sequestered until 2024, the range is 1.80 tCO_2–9.10 tCO_2, implying the dominant role of vegetation in carbon emission reduction. All green zones have carbon sequestration potential, which, over the next decade, is expected to increase by a factor of about 4.

Table 3. Data analysis of carbon sink for different areas in the park

Area	Type	Tree Species	Forest Age	Area (sqm)	Above-Ground Biomass (kg)	Below-Ground Biomass (kg)	Biomass (tons)	Carbon Sequestration Potential till 2024 (tCO_2)	Annual Change in Carbon Sequestration Potential (10-Year Forecast) (tCO_2)
In front of Courtyard	Arbor	Camphor Tree 1	5	100	1050	450	1.5	2.2	0.35
Behind Laboratory	Arbor	Camphor Tree 2	7	150	1650	650	2.3	3.1	0.4
Side of Experimental Building	Arbor	Camphor Tree 3	6	120	1350	550	1.9	2.5	0.38
Rear Garden	Arbor	Bamboo Grove	8	200	2500	100	3.5	4.8	0.6
Central Lawn	Arbor	Camphor Tree 4	10	300	3600	1400	5	6.7	0.8
West Pavilion	Arbor	Chinese Fir	4	250	2200	900	3.1	3.8	0.55
East Hill	Arbor	Pine Forest	12	350	4500	1800	6.3	7.9	1
South Entrance	Arbor	Poplar Grove	8	280	3000	1200	4.2	5.5	0.7
North Pathway	Arbor	Willow Trees	6	180	1600	700	2.3	2.9	0.45
Garden Pond	Arbor	Maple Grove	9	400	5000	2000	7	9.1	1.2
Training Ground	Arbor	Eucalyptus	11	320	4100	1600	5.7	7.3	0.9
East Corner	Arbor	Cherry Trees	3	90	950	400	1.35	1.8	0.25

CONCLUSION

This study conducted an applied investigation into the regulation control measures and carbon reduction outcomes of a research and office institute park in Nanjing, China, following the implementation of renewable energy systems. The key conclusions are as follows:

The deployment of a 1.162 MW photovoltaic power system significantly contributed to the park's electricity supply. From April to December, the system achieved a daily electricity self-sufficiency rate exceeding 100% on 50 days and surpassed 50% on 58.8% of the days. The average self-sufficiency rate during this period was 69.75%. Seasonal fluctuations were observed, with lower self-sufficiency rates during summer and winter due to increased energy demand and reduced solar radiation. On an annual basis, the photovoltaic system was estimated to generate approximately 1.062 million kWh, covering a substantial portion of the park's total electricity consumption of 1.689 million kWh.

A demand-side management strategy was implemented by increasing the air conditioning temperature set point from 25 °C to 27 °C. This measure led to a 15.1% reduction in energy consumption related to cooling and increased the average summer photovoltaic self-sufficiency rate (July to September) from 51.27% to 56.85%. This improvement enhanced the utilization of renewable energy while reducing reliance on conventional energy sources.

A carbon flux tower was installed to monitor real-time carbon flux and sequestration within the park. Data from the tower showed consistently low CO_2 concentration and a negative carbon flux, with average values of 464.87 ppm and –0.0087 mg/m^2·s, respectively. These results indicate a measurable carbon reduction effect and highlight the effectiveness of combining renewable energy systems with demand-side management and environmental monitoring in low-carbon campus development.

While the current system has been successful in improving energy efficiency and reducing carbon emissions, several opportunities for further optimization exist. Future directions include:

- Expanding energy storage: Increasing the storage capacity of the system would provide more reliable backup power during periods of low solar generation, further reducing dependence on the grid, especially when solar generation fluctuates due to weather conditions or time of day.
- Integrating additional renewable sources: Exploring the integration of other renewable energy sources, such as wind or geothermal energy, could diversify the park's energy mix and improve its resilience to fluctuations in solar power generation.
- Enhancing carbon flux monitoring: Expanding the network of carbon flux towers to monitor different environmental variables, such as soil carbon flux and plant respiration, would provide a more comprehensive understanding of the park's overall carbon dynamics.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article

REFERENCES

[1] Akkoyunlu MT, Abdallatif YA. Comprehensive investigation of solar panel cleaning technologies: A review study. J. Thermal Engineering 2024;10:1715-41. [Crossref]

[2] Jiang D, Gao H, He S, Huang Y, Liu J. A Negative-Carbon Planning Method for Agricultural Rural Industrial Park Integrated Energy System Considering Biomass Energy and Modern Agricultural Facilities. J Clean Prod 2024;479:143837. [Crossref]

[3] Huang B, Jiang P, Wang S, Zhao J, Wu L. Low Carbon Innovation and Practice in Caohejing High-Tech Industrial Park of Shanghai. Int J Prod Econ 2016;181:367-373. [Crossref]

[4] Wu D, Han S, Wang L, Li G, Guo J. Multi-Parameter Optimization Design Method for Energy System in Low-Carbon Park with Integrated Hybrid Energy Storage. Energy Convers Manag 2023,291:117265. [Crossref]

[5] Li T, Wang X, Yu Y, Fu Q, Chen M, Xu C, et al. Mao, Q. Performance and PV Benefits Analysis of Multi-Source Renewable Energy Systems for Different Types of Buildings on University Campus. Renew. Energy 2024;237:121522. [Crossref]

[6] Aghamolaei R, Fallahpour M. Strategies towards Reducing Carbon Emission in University Campuses: A Comprehensive Review of Both Global and Local Scales. J Build Eng 2023;107183. [Crossref]

[7] Hiltunen P, Volkova A, Latõšov E, Lepiksaar K, Syri S. Transition towards University Campus Carbon Neutrality by Connecting to City District Heating Network. Energy Reports 2022;8:9493-505. [Crossref]

[8] Guerrieri M, La Gennusa M, Peri G, Rizzo G, Scaccianoce G. University Campuses as Small-Scale Models of Cities: Quantitative Assessment of a Low Carbon Transition Path Renew Sustain Energy Rev 2019;113:109263. [Crossref]

[9] Li Z, Ge Z, Wang C, Zhang D, Foo DCY, Liu G, Shi L. An Automated Approach for Carbon Integration in Industrial Park. Process Saf Environ Prot 2024;190:677-87. [Crossref]

[10] Zhao Y, Wang S, Gao G, Xue X, Song H, Zhang, R. Exploring the Green and Low-Carbon Development Pathway for an Energy-Intensive Industrial Park in China. J Clean Prod 2024:459;142384. [Crossref]

[11] Qian L, Lin S, Li F, Wang W, Li D. Low Carbon Optimization Dispatching of Energy Intensive Industrial Park Based on Adaptive Stepped Demand Response Incentive Mechanism Electr Power Syst Res 2024;233:110504. [Crossref]

[12] Lyu X, Liu T, Liu X, He C, Nan , Zeng H. Low-Carbon Robust Economic Dispatch of Park-Level Integrated Energy System Considering Price-Based Demand Response and Vehicle-to-Grid. Energy 2023;263:125739. [Crossref]

[13] Ho YF, Chang CC, Wei CC, Wang HL. Multi-Objective Programming Model for Energy Conservation and Renewable Energy Structure of a Low Carbon Campus. Energy Build 2014;80:461-8. [Crossref]

[14] Li K, Yang R, He X. Realizing Low-Carbon Development of Industrial Parks in China: Model Construction and Its Application. Energy 2024;301:131664. [Crossref]

[15] Hu Y, Yang B, Wu P, Wang X, Li J, Huang Y, et al. Optimal Planning of Electric-Heating Integrated Energy System in Low-Carbon Park with Energy Storage System. J. Energy Storage 2024;99:113327. [Crossref]

[16] Huo Q, Liu Q, Deng H, Wang W, Shi C, Wei T. Research on Dual-Layer Optimization Strategy of Photovoltaic-Storage-Hydrogen System in Coal Chemical Industry Park. Renew. Energy; 2024: 120813. [Crossref]

[17] Zheng N, Li S, Wang Y, Huang Y Bartoccid P, Fantozzid F,et al. Research on Low-Carbon Campus Based on Ecological Footprint Evaluation and Machine Learning: A Case Study in China J Clean Prod 2021;323:129181. [Crossref]

[18] Wang Y, Zhang X, Zhu L, Wang X, Zhou L, Yu X. Synergetic Effect Evaluation of Pollution and Carbon Emissions in an Industrial Park: An Environmental Impact Perspective. J Clean Prod 2024;142891. [Crossref]

[19] Wang C, Parvez AM, Mou J, Quan C, Wang J, Zheng Y, et al. The Status and Improvement Opportunities towards Carbon Neutrality of a University Campus in China: A Case Study on Energy Transition and Innovation Perspectives. J Clean Prod 2023;414:137521. [Crossref]

[20] Zhou W, Zhuang G, Liu L. Comprehensive Assessment of Energy Supply-Side and Demand-Side Coordination on Pathways to Carbon Neutrality of the Yangtze River Delta in China. J Clean Prod 2023;404:136904. [Crossref]

[21] Raza MA, Aman MM, Kumar L, Al-Khasawneh MA, Fahemm M, Ehyaei MA. Carbon Neutrality and Economic Stability Nexus: An Integrated Renewable Energy Transition to Decarbonize the Energy Sector. Energy Rep 2025;13:4586-08. [Crossref]

[22] Zhang W, Cuijing J, He P, Wuhao E. Examining the Impact of Tourism on Carbon Neutrality and Environmental Sustainability in China: The Role of Renewable Energy. Energy Strateg Rev 2024;56:101579. [Crossref]

[23] Wei H, Zhang N, Du E, Jiang H, Zhuo Z, Davidson MR et al. Emerging Demand-Side Flexible Resources Accelerate China's Power System Transition toward Carbon Neutrality. iScience 2025;28:112372. [Crossref]

[24] Shafiei K, Seifi A, Hagh MTA. Novel Multi-Objective Optimization Approach for Resilience Enhancement Considering Integrated Energy Systems with Renewable Energy, Energy Storage, Energy Sharing, and Demand-Side Management. J Energy Storage 2025;115:115966. [Crossref]

[25] Lu Q, Fang H, Hou J. The Impact of Energy Supply Side on the Diffusion of Low-Carbon Transformation on Energy Demand Side under Low-Carbon Policies in China. Energy 2024;307:132817. [Crossref]

[26] Chau KY, Sadiq M, Chien F. The Role of Natural Resources and Eco-Financing in Producing Renewable Energy and Carbon Neutrality: Evidence from Ten Asian Countries. Resour. Policy 2023;85:103846. [Crossref]