

Research Article

Application of Light Storage Direct Flexible Energy Management System in Low Carbon Campus Construction in Cold Regions

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Abstract

In the context of the policy of "carbon peaking and carbon neutralization", campuses in cold regions are characterized by high per capita energy consumption, high total carbon emissions, low utilization of renewable energy and concentrated power consumption. At the same time, campuses have the social attributes of teaching and educating people and disseminating low-carbon ideas, so reducing campus carbon emissions is of great significance. With the development of science and technology and renewable energy application technology, photovoltaic power generation, energy storage technology, DC power distribution and flexible management are integrated in the light storage direct flexible energy management system, which improves the utilization efficiency and local absorption rate of renewable energy, and can solve the problems of high energy consumption and low utilization rate of renewable energy in cold areas, and help the construction of low-carbon campus. The author first analyzes the feasibility and advantages of the combination of light storage, direct and flexible system and low-carbon campus construction, and then takes the light storage, direct and flexible demonstration project of the sunken square of a teaching building in the north as an example to discuss the system construction scheme and intelligent adjustment strategy, so as to provide the basis and reference for the construction and promotion of light storage, direct and flexible energy management system in low-carbon campus in cold regions.

Keywords

Low Carbon Campus, Light Storage Straight and Soft, Renewable Energy Utilization, Energy Management, Cold Climate Zone

1. Preface

According to the "Research Report on Carbon Peak and Carbon Neutrality in China's Construction Industry" (2024) [1], the energy consumption of the construction industry accounts for 30% of the global total energy consumption, and the carbon

emissions during the operation phase of buildings account for 55.66% of the national carbon emissions from building and housing construction, and 21.7% of the national energy related carbon emissions [2]. With the rapid development of education

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in China, the number and area of campus buildings have increased rapidly. The campus population density is high, and the problem of high energy consumption per student is also increasingly prominent. According to the statistics of China Energy News, the total energy consumption of colleges and universities accounts for about 8% of the total domestic energy consumption in China, and the per capita energy consumption is about three times of the national per capita energy consumption [3].

On the one hand, campuses are major energy consumers, and on the other hand, they also bear the social responsibility of practicing education and promoting energy conservation and emission reduction. In the context of the national strategy of "carbon peak and carbon neutrality" [4], it is urgent to build low-carbon campuses [5]. The important path of low-carbon campus construction includes several aspects such as low-carbon campus buildings, renewable energy substitution, and energy conservation and efficiency improvement [6].

The photovoltaic storage direct flexible system [7] integrates photovoltaic power generation, energy storage, DC distribution, and flexible control technology, which is an innovative and comprehensive energy solution in the field of construction. It can effectively improve the efficiency of renewable energy utilization, peak shaving and valley filling, and balance the load of the power grid. The superior performance of the system can effectively solve the problems of high campus energy consumption and high centralized electricity load [15]. Driven by the dual carbon goal, the combination of low-carbon campus construction and photovoltaic storage direct flexible energy management system can effectively improve campus energy utilization efficiency, reduce carbon emissions during campus operation, and provide scenario demonstrations for the application of new power systems.

2. Characteristics of Campus Energy Consumption and Carbon Reduction Pathways in Cold Regions

2.1. Energy Consumption Characteristics of Campuses in Cold Regions

2.1.1. High Heating Energy Consumption

The climate characteristics of cold regions are mainly characterized by four distinct seasons, hot summers and cold and dry winters. Building energy-saving design mainly considers winter heating while also taking into account summer cooling. Taking Tianjin as an example, the winter heating cycle is from November 15th to March 15th of the following year, lasting about 120 days [8]. According to statistics, in 2020, the heating energy consumption in the campus energy structure of cold regions reached more than 60%, and the electricity consumption was about 40%.

On the one hand, the heating time does not match the teaching building, resulting in waste of heating energy. In cold regions, the heating source for winter campus heating is mostly municipal heat, and the end system forms often use radiators. Some tall spaces use floor radiation heating, with a heating time of 24 hours a day. Except for dormitories, the usage time of most campus buildings is about 10-12 hours, resulting in a large waste of municipal heat energy.

On the other hand, in recent years, with the development of economy and technology and the popularization of green buildings, the energy-saving effect of campus buildings has been improved. During winter heating, the indoor design temperature is relatively high, resulting in the phenomenon of opening windows for ventilation and cooling in campus corridors, classrooms, offices and other spaces, which once again leads to the waste of heating energy, ultimately resulting in high heating energy consumption in cold regions, accounting for a high proportion of the total campus energy consumption.

2.1.2. Low Utilization Rate of Renewable Energy

The heating source for winter heating on campus comes from municipal heating, and the electricity comes from the municipal power grid. The proportion of renewable energy utilization on campus is less than 10%. After the dual carbon target was proposed, in order to help achieve carbon neutrality in buildings, the author believes that increasing the proportion of renewable energy utilization and achieving building energy electrification through energy substitution can ultimately achieve the design goal of reducing low-carbon campuses.

The cold northern regions have good sunshine resources, and the characteristics of low campus building density, large roof area, and low floors make it suitable to use solar thermal technology. Taking Tianjin as an example, Tianjin is located in an area rich in Class II solar energy resources. The total radiation can reach $5256 \text{ MJ}/(\text{m}^2 \cdot \text{a})$, with an annual sunshine duration of 2500-2900 hours [9], indicating abundant solar energy resources. Moreover, Tianjin combines the scientific research capabilities of universities, integrates industry and education, and leads in solar thermal and photovoltaic conversion technologies nationwide.

2.1.3. Large Fluctuations in Electricity Load

The campus energy consumption in cold regions shows significant seasonal and daily changes, mainly reflected in the following two points. Firstly, due to the winter and summer vacations on campus, most buildings are idle during the holiday period, with only a small number of public buildings operating normally. The heating load in January and February, as well as the cooling load in July and August, have significantly decreased; Secondly, campus buildings, especially higher education campuses, have the characteristics of large land area, scattered buildings, and multiple building functions. The electricity load of different buildings varies with the regularity of students' learning and living. For example, during the day, the energy consumption of teaching and office

buildings on campus is higher, while the energy consumption of dormitory areas is lower; At night, vice versa.

2.2. The Path of Reducing Carbon Emissions in Cold Regions' Campuses

In 2019, the Ministry of Housing and Urban Rural Development issued and implemented the "Green Campus Evaluation Standards" [5]. In 2021, the Ministry of Education released the

"Action Plan for Carbon Neutrality Technology Innovation in Higher Education Institutions". In the same year, the State Council proposed to promote low-carbon transformation demonstration projects in campuses. The author summarizes the low-carbon campus standards issued in recent years and concludes that the low-carbon campus reduction path in cold regions mainly includes improving building energy efficiency, multi energy complementarity, intelligent regulation and operation, low-carbon education, and other aspects, as shown in Table 1.

Table 1. Comparative Analysis of Low Carbon Campus Evaluation System.

	General Requirements and Evaluation Guidelines for Zero Carbon Campus Construction Management T/TJKZS0001-2024	Green Campus Evaluation Standards GB/T51356-2019	Guidelines for Creating Low Carbon Primary and Secondary Schools T/BES001-2024	Technical Guidelines for Low Carbon Campus Evaluation in Higher Education Institutions DB11/T1404-2017
Issue unit	Tianjin Renewable Energy Society	Ministry of Housing and Urban-Rural Development	Beijing Energy Society	Beijing Municipal Quality and Technical Supervision
Stand and framework	Overall planning and design; Building equipment and energy efficiency; Renewable energy utilization; Transportation, water supply and drainage, and waste management; Zero carbon campus operation and management; Zero carbon campus education and promotion; Carbon sink and carbon offset	Planning and Ecology Energy and Resources; Environment and Health; Operation and management; Education and promotion; Characteristics and Innovation	Low carbon education and culture Low carbon technology application (low-carbon) Energy System and Water Resources Festival Appointment and utilization, building energy efficiency Improvement, Green Transportation, and Livelihood Ecological environment, garbage classification and Recycling Low carbon management and services	Campus carbon emission intensity; Construction of management mechanism; Low carbon culture construction; Renewable energy utilization; Other emission reduction measures

2.2.1. Improving Building Energy Efficiency, from Energy Consuming Entities to Capacity Carriers

By optimizing the enclosure structure of campus buildings, setting up transitional spaces, and utilizing passive energy-saving measures such as natural lighting and ventilation technology, energy consumption on campus can be saved. At the same time, the current national standard "General Specification for Building Energy Conservation and Renewable Energy Utilization" stipulates that new buildings should be equipped with solar energy systems, promote the integration of photovoltaic/solar thermal buildings, and achieve building capacity.

2.2.2. Multi Energy Complementarity and Intelligent Regulation, from a Single Power Grid to Multi Energy Complementarity

Reasonably utilize local renewable energy resources, campus building roofs, and outdoor sites for distributed energy network design, reducing the demand for municipal electricity and heat on campus; Set up energy storage facilities and intelligent energy regulation systems to reduce peak loads and dynamically adjust heating and cooling temperatures. For example, a zero carbon office building renovation project in Tongzhou, Beijing, achieved an annual photovoltaic power generation of 576000 kWh and saved 630000 yuan in electricity costs through the implementation of "photovoltaic storage direct flexible" technology and multiple low-carbon technology upgrades. The energy storage system and EMS

system further improved the stability and efficiency of the system [10].

2.2.3. Low Carbon Education, from Individual Consciousness to Collective Action

Low carbon education is the characteristic and mission of low-carbon campus construction. By educating students, the campus can cultivate students' low-carbon concepts. For example, Xuzhou Industrial Vocational and Technical College has launched the "Energy Conservation, Efficiency Enhancement, and Revitalization" campus energy conservation action in 2025, strengthening the energy-saving awareness of teachers and students, promoting low-carbon lifestyles, and encouraging the use of carbon inclusive management platform mini programs to contribute to the construction of a

low-carbon society.

3. Overview of Light Storage Direct Flexible Energy Management System

3.1. Technical Principles and Composition

Photovoltaic Storage Direct Current Flexible (PSDF) [11] is an advanced energy system that integrates photovoltaic power generation, energy storage technology, DC distribution, and flexible management. Its aim is to improve energy efficiency, enhance grid stability, and promote the consumption of renewable energy [12].

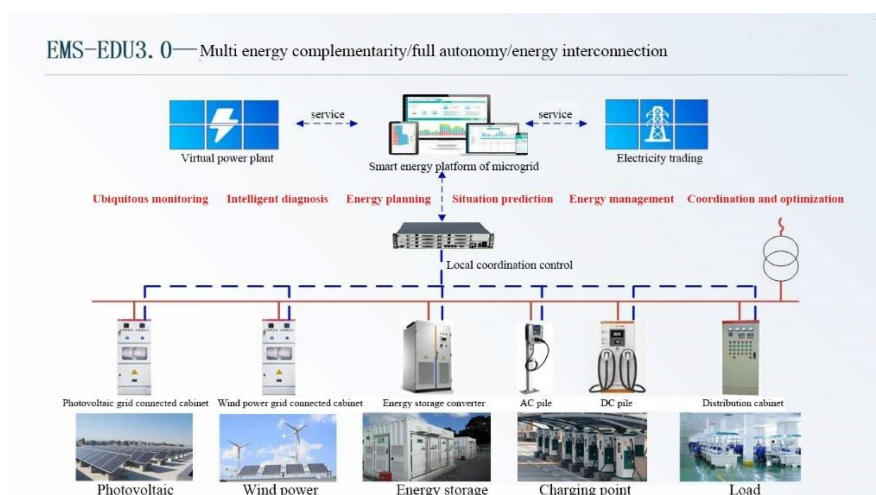


Image source: http://it.sohu.com/a/768710559_121443806

Figure 1. Schematic diagram of optical storage direct flexible energy management system.

Table 2. Composition of Optical Storage Direct Flexible Energy Management System.

Module composition	Function Description	Technical parameter diagram
Photovoltaic power generation	By converting solar energy into electricity through photovoltaic panels, it can be combined with building settings	Monocrystalline silicon photovoltaic conversion rate $\geq 22\%$, lifespan > 25 years
Energy storage system	Lithium batteries/flow batteries store surplus electricity to stabilize supply and demand fluctuations	Lithium iron phosphate battery has a cycle count of ≥ 6000 times and is effective 95% rate
Direct current distribution	Using 380V/ ± 750 V DC bus to reduce AC/DC conversion losses	Efficiency improvement of 6% -8% compared to traditional communication systems
Flexibility regulation	EMS dynamic adjustment, storage usage matching	Load response time ≤ 5 seconds, prediction accuracy $\geq 90\%$

3.2. System Advantages and Applicability

Under the national strategic goal of "dual carbon", integrating the photovoltaic storage direct flexible energy management system into the construction of low-carbon campuses through technological collaboration and innovative energy management models can significantly improve campus energy efficiency and reduce carbon emissions.

Firstly, by setting up photovoltaic power generation systems, the proportion of renewable energy consumption in low-carbon campuses can be increased; Secondly, by setting up energy storage systems to smooth out the peak electricity consumption during the day and reduce the load on the power grid; Again, by setting up a DC distribution system, the energy consumption of end devices can be reduced; Finally, through flexible adjustment, the operating status of air conditioning, lighting, and other components on campus can be dynamically adjusted to achieve energy conservation and cost reduction.

4. Integrated Design of Light Storage Direct Flexible System in Low Carbon Campus Construction

The low-carbon campus photovoltaic storage direct flexible energy management system connects the photovoltaic power generation system, energy storage system, DC power equipment, etc. through electrical interconnection or communication protocols to form a collaborative whole, ensuring coordination and optimized operation between various parts.

4.1. System Architecture Design

4.1.1. BIPV

Light is the energy source of the light storage direct flexible energy management system and also one of the main renewable energy sources. According to building regulations, the plot ratio of an ordinary campus is about 0.5, so campuses usually have large outdoor areas and roofs, and are suitable for incorporating solar energy utilization into the overall design of low-carbon campus buildings, integrating photovoltaics, architecture, and aesthetics.

With the development of technology, the cost of photovoltaic modules is rapidly decreasing, and the photoelectric conversion efficiency is gradually improving. For example, the efficiency of monocrystalline silicon photovoltaic modules reaches over 21%, with a cost of about 0.67 yuan/W (data source released by the Photovoltaic Association).

4.1.2. Energy System and Equipment Efficiency Improvement

The "energy storage" system can solve the problems of obvious time periods and load concentration in campus electricity consumption. The energy storage system can store electricity during low peak periods for use during peak periods on campus, reducing grid load and "peak shaving and valley filling".

Currently, electrochemical energy storage devices are commonly used in buildings. On the one hand, electrochemical energy storage has a low energy density and high energy conversion efficiency, and a fast response speed; On the other hand, its power and energy can be flexibly configured according to different application requirements, and are less affected by climate and geographical factors. For example, Mingpu Optoelectronics' modular energy storage system can shorten installation cycles by 50% and reduce maintenance costs by 40%, making it suitable for rapid deployment of campus energy storage modules.

Table 3. Mainstream Technologies and Characteristics of Electrochemical Energy Storage.

Technical type	Unit cost (yuan/Wh)	Cycle life (times)	Efficiency (%)	Applicable scenarios
Lead acid battery	0.5~1.0	About 1000 times	85%	Backup power supply, low-speed tram
Lithium Ion Battery	0.8~1.2	5000~10000 times	95%	Electric vehicles, smart grid
sodium sulfur battery	2.0~2.8	About 4500 times	80~90%	Mostly used for power grid peak shaving
flow battery	3.0~4.0	Over 10000 times	75%	Long term energy storage

Note: This table is sourced from the author's statistics

4.2. Smart Adjustment Strategy

The "flexible" regulation strategy converts traditional rigid loads into flexible loads, realizing "load following source" in

the photovoltaic storage direct flexible system, and enhancing the renewable energy consumption capacity. The intelligent regulation strategy is based on the status and demand of various power equipment (such as building load demand, photovoltaic power generation efficiency, climate conditions,

etc.), and makes decisions through preset optimization algorithms (MPC) or updated learning modes to achieve multi-objective collaboration (such as controlling energy storage device charging and discharging, etc.) [13]. Through the application of intelligent regulation strategy, it provides higher energy flexibility and reliability for low-carbon campus construction.

5. Project Case Analysis

5.1. Project Overview - Sunken Square Light Storage Direct Flexible Demonstration Zone of a Teaching Building

This project is located in the sunken plaza of a teaching building on a campus in Beijing. It is a nearly zero energy single story renovated building with a total construction area of 612.44 square meters, with a building height of 3.5 meters, the building functions as an exhibition hall, student activities, and multimedia room.

The demonstration project is based on the installation of photovoltaic power generation units in the roof space of buildings, and the construction of an intelligent multi energy complementary system that integrates light, energy storage, and flexibility to meet the energy needs of buildings and achieve green energy consumption.



Figure 2. Installation photo of rooftop photovoltaic system in demonstration project.

5.2. Design of Optical Storage Direct Flexible System for the Project

249 pieces of 400Wp standardized monocrystalline silicon photovoltaic panel modules are installed on the roof of the demonstration project. The installed capacity of the photovoltaic power generation system is about 99.6kWp ("light"), and a 38.4kWh outdoor lithium iron phosphate battery energy storage cabinet ("storage") is set up. The light storage power supply is connected to the photovoltaic controller through a 750V DC bus. In the integrated light storage and charging cabinet, it is converted into DC375V/DC48V DC through a DC/DC converter. The use of current power supply load ("direct") is achieved through an energy management platform (EMS system) to achieve priority balanced consumption of photovoltaic power generation within the microgrid, and flexible charging and discharging management of energy storage systems ("flexible"). The system diagram is shown in Figure 3.

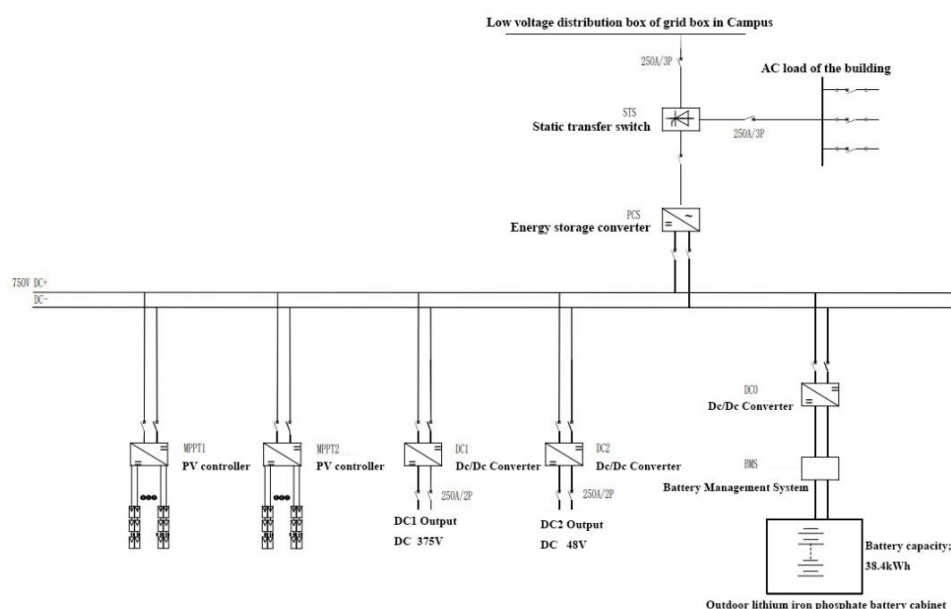


Figure 3. Demonstration project optical storage direct flexible system diagram.

The demonstration project adopts a mode of self use and surplus electricity grid connection. When the power generation of the photovoltaic power generation system exceeds the load

electricity consumption, the autonomous control function ensures local consumption by increasing the energy storage charging power or reducing the photovoltaic power generation

output; During the peak period of power generation, when the local power cannot be consumed, excess electricity is merged into the lighting power supply of nearby teaching buildings.

5.3. Benefit Analysis of Light Storage Direct Flexible System

The demonstration project has achieved efficient and flexible combination of photovoltaic power generation system and energy storage system through an energy management platform, solving the problems of uneven power grid load and unstable terminal voltage in the original construction bureau, and improving the power supply quality of the distribution system. The installed photovoltaic capacity of this project is 99.6kWp. The annual solar radiation in Beijing is 1526.1kWh/m², and the annual effective utilization hours are about 1213.95h. After calculation, the first year's power generation of the demonstration project is about 116800 kWh [14], of which about 40% is consumed locally and the rest is used for lighting in nearby teaching buildings, saving about 83300 yuan in electricity bills annually.

6. Summarize

In summary, the rational use of low-carbon campus roofs, outdoor plazas, and parking lots to install photovoltaic, direct, and flexible energy management systems can effectively solve the problems of high centralized electricity load, high heating energy consumption, and low utilization of renewable energy in low-carbon campuses, reducing dependence on municipal power grids; At the same time, promoting the construction of low-carbon campus photovoltaic storage direct flexible systems can be interconnected with surrounding areas or municipal power grids to achieve regional energy trading and surplus electricity sharing.

At the same time, promoting the application of photovoltaic direct flexible energy management systems in campuses still faces issues such as high initial investment, photovoltaic power generation volatility, and DC distribution standardization. In the future, through technological iteration, policy support, and model innovation, it is expected to not only achieve energy self-sufficiency and low-carbon transformation in low-carbon campuses, but also provide important references for urban energy system innovation.

Abbreviations

DC	Direct Current
EMS	Energy Management Platform
BIPV	Building Integrated Photovoltaics

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Conflicts of Interest

This article has no conflict of interest.

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