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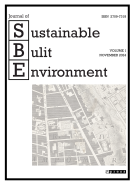

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Research on Optimization of Industrial Building Facades Integrating With Photovoltaic Power

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KEYWORDS

industrial Buildings,
photovoltaic,
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building integrated photovoltaic(BIPV),
CdTe Photovoltaic Glasses

ABSTRACT

Industrial buildings are important production carriers in urban space, but they also have problems such as high production energy consumption, serious environmental pollution, and poor built interface, which have attracted much attention. Building environment optimization and energy structure adjustment have become the focus of industrial building research. In the context of the national carbon neutral policy, this paper studies the impact of industrial buildings on the urban environment, combines photovoltaic power generation technology, explores the integrated design strategy of CdTe generation glass and industrial building facades, and uses the southwest cement plant project in Lijiang, Yunnan as an example, a practical study was carried out, aiming to use industrial building facade resources to improve the aesthetics and functionality of the building facade at the urban interface of the park. Research shows that the strong plasticity of CdTe photovoltaic glass can not only provide necessary power energy for industrial buildings and optimize the building's energy structure, but its color and material ductility can also improve the aesthetics of industrial building facades. This article provides certain reference and reference significance for subsequent related research.

1. Introduction

According to research by the international research agency IEA, China's industrial sector ranks second among all industries with a 36% share of carbon emissions, second only to the energy production industry with a 48% share. The "2022 China Building Energy Consumption and Carbon Emissions Research Report" points out that in 2020, the total energy consumption of Chinese buildings was 2.27 billion tce, and the total carbon emissions of buildings were 5.08 billion tCO^2. Among them, the energy consumption and carbon emissions in the production stage of building materials, mainly cement and steel, accounted for 22.3% and 28.2% of the total, respectively. The "Implementation Plan for Carbon Peaking in the Industrial Sector" released by China states that by 2025, the energy consumption of industrial units above designated size will decrease by 13.5% compared to 2020. In the "3060" target, by 2060, China's industrial carbon dioxide emissions will decrease by nearly 95%, the use of coal without emission reduction technologies will decrease by 90%, and the remaining emissions will be offset by negative

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emissions from the power and fuel conversion industries. Therefore, in the important period of China's transition from an incremental economy to a stock economy, the transformation of brownfield industrial buildings has become one of the important components of the transformation, and it is urgent to promote the adjustment of building energy structure with industrial buildings as the core.

In recent years, the development of the photovoltaic industry has received increasing attention from the country, and photovoltaic have also been regarded as one of the main strategies to achieve the national "dual carbon" goals. In the national "The 14th Five-year Plan" for the development of renewable energy, it is explicitly stated to "vigorously promote the development of wind and photovoltaic power bases" and "actively promote the distributed development of wind and photovoltaic power generation". Compared with the rapid rise of photovoltaic manufacturing, the launch of China's photovoltaic terminal application market is significantly lagging behind*(Wang Hongwei, Zhu Xueting,Yin Chenxi ,2022)*. At present, the application of PVs is still mainly focused on centralized photovoltaic power stations and distributed energy stations. However, this type of power station requires a large amount of land resources as a carrier, and cannot be widely promoted in urban spaces with tight construction land. With the emergence of thin-film cells, various application scenarios of photovoltaic cells have begun to appear in urban spaces, and photovoltaic building integration technology has emerged. However, the integrated technology of photovoltaic buildings in China is still in its infancy, and its applications are mainly concentrated in residential buildings, public buildings, office buildings, and landscape ornaments. There are few studies and cases related to the integrated design of photovoltaic modules and industrial buildings.

The innovation of this article lies in the integration of photovoltaic building technology, focusing on the energy structure adjustment and facade optimization of productive industrial buildings, and exploring the technical path of combining photovoltaic modules with industrial buildings. On the one hand, by utilizing the strong plasticity of cadmium telluride (CdTe) photovoltaic glass, the overall texture of industrial building facades was stitched together, improving the production environment and appearance of industrial buildings; On the other hand, fully utilizing the idle facade space resources of industrial buildings, constructing distributed photovoltaic power stations, empowering buildings and parks, and promoting the energy structure adjustment of buildings and even parks.

2. Literature Review

2.1. Research on Industrial Architecture and Heritage

In the context of the current climate crisis, research on industrial architecture and related fields in China mainly focuses on three aspects: planning and design strategies for new industrial parks, investigation and evaluation of industrial heritage, and spatial and functional transformation of industrial heritage. At the level of design strategies for industrial buildings, scholars are enthusiastic about using sustainable and green building design theories to study new industrial parks and their architectural spaces. Scholars have integrated low-carbon and sustainable concepts into industrial building design, and proposed design foundation suggestions for industrial buildings from three levels: cultivating industrial rootedness, researching park ecology, and sustainable industrial building design (*Wangyi,Chenjing,2008*). Modular and modular design is beneficial for controlling carbon emissions throughout the entire lifecycle of industrial buildings, in order to achieve energy-saving and emission reduction goals(*Yang Chunhong,Pu Yunyun,2023*). Scholars have proposed the use of BIM technology to construct a digital information model for industrial buildings, in order to achieve the goal of innovative transformation of existing industrial building spaces, in response to issues such as poor access ports for industrial heritage informationization(*Deng Yuanyuan,Lihan,Yangnan,Zhu Yiwen,2023*).

In addition, China has a large amount of industrial heritage resources, and scholars' investigation, research, analysis, and evaluation of industrial heritage have laid a solid foundation for the renewal and transformation of China's industrial heritage. Non industrial transformation of existing industrial buildings is currently the main transformation strategy, which mainly studies and evaluates the spatial form of existing industrial building structures from the perspectives of architecture and structure, in order to introduce new functional formats(*Liu Boying,Hu Rongrui,Lirong,2018*). The transformation model of industrial heritage based on the theory of symbiosis explores the strategies of industrial architecture in achieving cultural symbiosis, pattern symbiosis, and environmental symbiosis through symbiosis in different eras, different buildings, and different activities(*Gao Changzheng,Yanfang,Long*

Wenyan,2017). Based on the theory of spatial production, this study investigates the morphological evolution of historical industrial spaces in Chinese cities, mainly focusing on the influencing factors in the transformation process of industrial building spaces, and can analyze the laws of typical industrial space transformation, cultural transformation, and functional transformation(*Huanglei,2023*). A quantitative evaluation of the vitality of Tianjin's industrial heritage was conducted using diverse data from dimensions such as cultural vitality, social vitality, economic vitality, and population vitality. Based on the research results, renovation strategies were proposed from three levels: spatial quality, functional replacement, and facility layout (*Ren Binbin,Wang Jingshuang,Xiao Shaoying,2023*).

The spatial and functional transformation of industrial heritage is an important means of testing research results. Practice mainly combines the historical value, aesthetic value, and spatial value of industrial relics to revitalize and utilize abandoned industrial buildings. This type of research mainly focuses on the practice of industrial building renovation. Based on more than 10 years of industrial heritage engineering practice in *Jingdezhen*, some scholars have proposed a technical system consisting of four dimensions: inheritance and protection, coexistence of old and new, functional adaptation, and green enhancement, to support the protection and utilization of industrial heritage(*Zhangjie,Li Minhua,Xieyang,2023*). The renovation of the former site of *Huaxin* Cement Plant in *Huangshi* City, Hubei Province, explores the planning strategies for industrial heritage protection in the urban center from three aspects: protection concept, functional configuration, and utilization mode(*Liuna,Huang Jingnan,Zhoujun,2023*). Based on the concept of "fiber block", spatial integration and functional activation were carried out on the industrial heritage style, lane historical style, and historical protected buildings of Shanghai *Binjiang*. Spatial definition and design guidance strategies were proposed from six dimensions: scale, functionality, and density(*Lijian,Chen Changqing,Ma Xiyin,2021*).

2.2. Development of energy-saving technology in industrial buildings

Industrial building energy efficiency is different from traditional industrial energy efficiency technologies. Traditional industrial energy-saving technologies mainly focus on two aspects: equipment and energy. The energy-saving technologies discussed in this article mainly focus on the energy end. The core of industrial energy conservation is the conservation of electrical energy, which mainly focuses on the utilization of clean energy. The application of new energy technologies is manifested in the use of clean energy sources such as wind, solar, and geothermal energy. The utilization of solar energy is still at the stage of centralized energy stations. Centralized power stations feed back industrial energy by constructing large-scale power stations, utilizing clean energy for power generation, and delivering electricity to industrial parks through power infrastructure. This method does indeed reduce the electricity demand in urban areas, decrease the electricity load, and decrease the city's reliance on traditional energy sources. However, large-scale clean energy power plants require power transmission infrastructure, which requires a high level of infrastructure construction. The emergence of BIPV technology has enabled centralized energy stations to gradually transform into distributed ones. The so-called distributed power station refers to the establishment of power stations near the energy demand end to meet the small-scale usage needs in the vicinity. BIPV technology has the characteristics of small land occupation and nearby consumption, and requires less infrastructure for high-power power transmission.

2.3. Development of integrated photovoltaic building technology

The integration of photovoltaic technology with building utilization began in the mid-20th century, with Solar One becoming the first solar powered building. And China's solar roof plan, which began in 1996, has since opened up projects that combine solar energy with buildings. BAPV and BIPV are two ways of combining photovoltaic with building scenarios. BAPV (Building Attached Photovoltaic) is a passive photovoltaic application strategy that independently attaches distributed photovoltaic modules outside the building structure. With the development of photovoltaic technology, photovoltaic glass has begun to possess characteristics such as transparency and low light intensity, which can meet the requirements of building thermal performance and structural strength. Integrated photovoltaic building technology has begun to emerge. BIPV (Building Integrated Photovoltaic), also known as photovoltaic building integration, is an active design strategy that uses photovoltaic modules as building materials and integrates building design.

BAPV is a passive adaptation strategy in which photovoltaic modules are attached to buildings. BAPV is a combination of distributed photovoltaic modules and building surfaces, with photovoltaic panels fixed to the building (*Zhangjian,Xie Yingming,Yang Yuanhao,2017*). The two sides are independent and integrated, with clear boundaries. In this case, distributed photovoltaic modules are ancillary facilities of buildings. As an external installation device, photovoltaic modules provide electrical energy for buildings, while buildings provide spatial carriers for photovoltaic modules. Under this design strategy, photovoltaic modules are usually made of crystalline silicon photovoltaic materials and are commonly installed on building roofs, affecting the overall appearance of the building. In addition, centralized photovoltaic power plants require a large amount of land, and in the context of extremely scarce construction land resources, this technology is more commonly located in suburban areas of cities. Even as photovoltaic modules used as roofs, their dazzling effect can cause light pollution to urban spaces, and they cannot be organically integrated with buildings, resulting in visual damage, making them difficult to widely promote in urban spaces. BIPV, also known as photovoltaic building integration, is an active adaptive strategy for the integrated design of photovoltaic modules and buildings. In BIPV, photovoltaic modules appear in the form of a building material, and the photovoltaic array becomes an integral part of the building (*Huang Xinyu,Chenwen,2022*). With the gradual maturity of thin-film solar cell technology, photovoltaic modules can better participate in building structures and spaces. The integration of photovoltaic modules and buildings forms a symbiotic relationship. Photovoltaic modules cannot operate independently without buildings, and the building structure without photovoltaic modules is incomplete. Under this strategy, photovoltaic modules can already meet the relevant requirements of building materials in terms of structural strength, and their characteristics such as transparency, color, and texture can ensure the uniformity of building appearance.

3. Characteristics and problems of production-oriented industrial buildings

3.1. Review of China's Industrialization Process

Industrial buildings refer to the general term for buildings, structures, and industrial facilities engaged in various industrial production activities in urban activities. The main functions of buildings or facilities include production, equipment, storage, transportation, etc. On the one hand, when cities plan their land use, they usually consider the land value and industrial attributes, and allocate industrial land to the suburbs of the city. On the other hand, the industrial production content engaged in by industrial buildings may have potential problems such as noise pollution, dust pollution, and air pollution, which also result in the uniqueness of industrial building design. In summary, industrial buildings exhibit characteristics such as large building space scale, diverse combination forms, single function, and high energy consumption.

The development of industrial architecture is closely related to the industrialization process in China. China's industrial development can be divided into the primitive industrial period, the modern industrial period, and the modern industrial period*(Wang Yunke,2021)*. The primitive industrial period was before 1840, based on the traditional workshop style handicrafts of old China. The modern industrial period lasted from the Opium War to the establishment of New China. As the beginning of modern industrialization, since the Westernization Movement, due to the input of foreign technology, Chinese industry has grown from scratch, reflecting the characteristics of regional development.

The modern industrial stage can be divided into a period of recovery and a period of rapid development after the founding of the People's Republic of China. After the establishment of the People's Republic of China, with the "Third Front Construction" as the starting point, it has driven the vigorous development of industries in mainland China. After the reform and opening up, China's modern industry developed rapidly. A comprehensive industrial category system has been established, and a regional coordinated development strategy centered on industrial parks has led to rapid development of the industrial economy. Modern industrial parks have become the main feature, and industrial buildings are showing a trend of centralization.

3.2. Traditional Industrial Architecture and New Era Industrial Parks

The construction of industrial parks is an important strategic deployment since China's reform and opening up, and it is also one of the driving forces for China's economic development and urbanization. It should be clarified that the industrial park described in this article is different from an industrial park. At present, China's industrial parks have diversified industrial forms. After industrial transformation, China's industrial parks are developing towards new technologies and new economies. The industrial park mentioned in this article refers to a park with the secondary industry as its main content, which has the characteristics of remote geographical location, harsh production environment, high energy consumption, and high carbon emissions. According to the Catalogue of Review and Announcement of China Development Zones, in 2018, 219 national economic and technological development zones and 169 national high-tech industrial development zones, which mainly serve the function of carrying industrial clusters and represent typical industrial parks in China, achieved a total regional GDP of about 21.3 trillion yuan, accounting for 23.7% of the national GDP that year. The development process of industrial parks in China can be roughly divided into the following four stages:

1) *Initial and budding stage (1979-1991)*

In 1979, China's first industrial park, the China Merchants *Shekou* Industrial Park, was completed, marking the official beginning of the development of industrial parks in China. Under the background of reform and opening up and global industrialization, China has implemented the "three processing and one compensation" strategy in economic zones such as *Shenzhen* and *Zhuhai*, and has begun to integrate into the world industrialization process as a manufacturing base.

2) *Rapid Development Stage (1992-2002)*

At this stage, China's economy began to enter a stage of rapid development, and the boom of development zones followed. Second generation industrial parks such as *Zhangjiang* High tech and Suzhou Industrial Park were established during this stage, and industrial parks began to spread from the Pearl River Delta to other regions.

3) *Adjustment and Exploration Stage (2003-2015)*

China's accession to the WTO has injected new vitality into the construction of industrial parks. However, in the context of the hot development zone in the previous stage, housing construction has exposed some problems such as unreasonable planning, blind development, and vicious local governments. In 2003, the government began to rectify and adjust industrial parks.

4) *Transformation and upgrading stage (2016 present)*

During the 13th Five Year Plan period, China proposed strategies such as supply side reform, ecological civilization construction, and strategic emerging industries. In this context, industrial parks have also begun to devote themselves to ecological environment protection, and industries have gradually shifted from low-quality energy, chemical, processing and manufacturing industries to high-tech industries.

In this context, with the iteration of industrial functions in China, industrial buildings centered on the secondary industry are gradually being replaced by commercial and office buildings centered on the tertiary industry.

3.3. The problems of industrial buildings

3.3.1. Lack of unified design

Existing productive industrial buildings are mostly built before the 21st century, with main industries including energy and chemical engineering, building materials, and manufacturing. During this period, industrial buildings had different design standards and specifications due to their industry-specific characteristics. In terms of park location, the park is usually located in the suburbs of the city, but as the city expands, this part of the park gradually borders the urban space. At the same time, industrial buildings only meet basic production needs in design, lacking long-term considerations in architectural aesthetics, energy structure, spatial layout, and other aspects. This leads to exaggerated spatial dimensions, inconsistent proportions, or chaotic facade window openings caused by special process requirements in contemporary industrial architecture, which affects the image of the urban interface*(Hanxu,Chen Shizhao,2014)*.

3.3.2. High energy consumption and high carbon emissions

The existing productive industrial buildings are the main force providing important production materials and strategic goods for urban construction during China's rapid urbanization period, characterized by large scale, high energy consumption, and high carbon emissions. At the same time, this type of industrial park is facing the impact of new economy, new industry, and new technology, as well as the dual contradiction of continuing to provide production materials for urban construction, making it difficult to achieve industrialization transformation. Industrial heritage has lost its production function, making it more adept at functional transplantation, spatial optimization, and other aspects of transformation. However, it is difficult to carry out renovation and renovation work on existing productive industrial buildings without affecting their production order.

3.3.3. Serious waste of resources

The waste of resources in industrial buildings is not only reflected in their high energy consumption, but also in their extensive planning strategies, which result in a significant waste of land resources and building space resources. The building facade is an important component of urban space and a significant spatial resource. In the core area of the city, the utilization of facade resources for buildings is relatively sufficient. In contrast, the facade space resources of industrial buildings have not been fully activated and there is still room for development.

4. Research on the Coupling between Photovoltaic Technology and Existing Productive Industrial Buildings

4.1. The Development Process of Photovoltaic Technology

The main basis for photovoltaic new energy technology is the "Photovoltaic Volta" effect. In 1893, French scientist Becquerel discovered the "photovoltaic effect". In 1954, American scientists Chapin and Pearson first developed a solar cell using single crystal silicon as the photovoltaic material*(Hernández-Callejo L, Gallardo-Saavedra S, Alonso-Gómez V,2019)*. The so-called solar cell is a type of optoelectronic semiconductor wafer that directly generates electricity using sunlight*(Yang Qianmiao,Wang Yanting,Wangjiang,2022)*. However, due to the immaturity of the technology, the power generation efficiency of this battery is less than 6%.

The rapid development of the photovoltaic industry began in the mid-20th century and is mainly divided into three stages. The first stage is the crystalline silicon photovoltaic cell stage, characterized by using single crystal silicon and polycrystalline silicon as optoelectronic materials. This type of solar cell has a high energy conversion rate, reaching 26.7%, but it has disadvantages such as high environmental requirements and unstable power. Crystalline silicon solar cells are mainly promoted and applied in centralized energy stations laid on the ground, and there are relatively few application scenarios related to their combination with buildings. The second stage focuses on flexible thin film technology for solar cells. The optoelectronic materials for flexible thin film technology mainly include cadmium telluride, copper indium gallium selenide, and gallium arsenide. Thin film photovoltaic cells have the characteristic of light transmission and are beginning to explore integrated design and application with buildings. But so far, there are still problems such as low energy conversion rates and high costs. The conversion efficiency of thin-film PV modules is 7% to 10%, while the average conversion efficiency of crystalline silicon is 15% *(Qian Bozhang,2008)*. The third stage is diversified material batteries. Such as perovskite photovoltaic cells, dye-sensitized photovoltaic cells, polymer photovoltaic cells, etc. (*Jelle B P , Breivik C , R?Kenes H D,2012*). It has made significant improvements in light sensitivity, plasticity, and conversion rate, but the technology is not yet mature and cannot be widely applied and promoted.

4.2. Study on the Adaptability of Thin Film Photovoltaic Cells to Building Facades

Thin film photovoltaic cells are the second generation of photovoltaic cells after crystalline silicon photovoltaic cells. Unlike the first generation photovoltaic cells, the second generation photovoltaic cell technology involves making conductive media (such as GaAs, CIGS, CdTe) into thin film layers and combining them with glass to form transparent photovoltaic modules. In 2000, researchers such as WuX, Dhere R. G, Aibin D. S developed a solar cell using cadmium telluride (CdTe) as the photovoltaic medium, with an efficiency of 16.4%(*Lee, T. D., & Ebong, A. U. ,2017*). China is in a leading position in the technology of thin-film solar cells. In 2014, the conversion rate of cadmium telluride (CdTe) promoted by the Chinese Academy of Sciences reached 14.4%. In 2021, the energy conversion rate of copper indium gallium selenide (CIGS) solar cells developed by China National Building Materials Group reached 19.64%. In 2023, the energy conversion rate of copper indium gallium selenide (CIGS) solar cells of the same specification by China National Building Materials Group exceeded 20.3%, becoming the first thin-film photovoltaic module to break through 20%. The advancement of thin-film solar cell technology has directly driven the innovation of photovoltaic application scenarios.

4.3. Feasibility of using thin-film photovoltaic cells as building facades

Unlike traditional photovoltaic glass, thin-film photovoltaic cells have characteristics such as transparency and plasticity, and can be applied to various scenarios such as building facades, roofs, and floors.

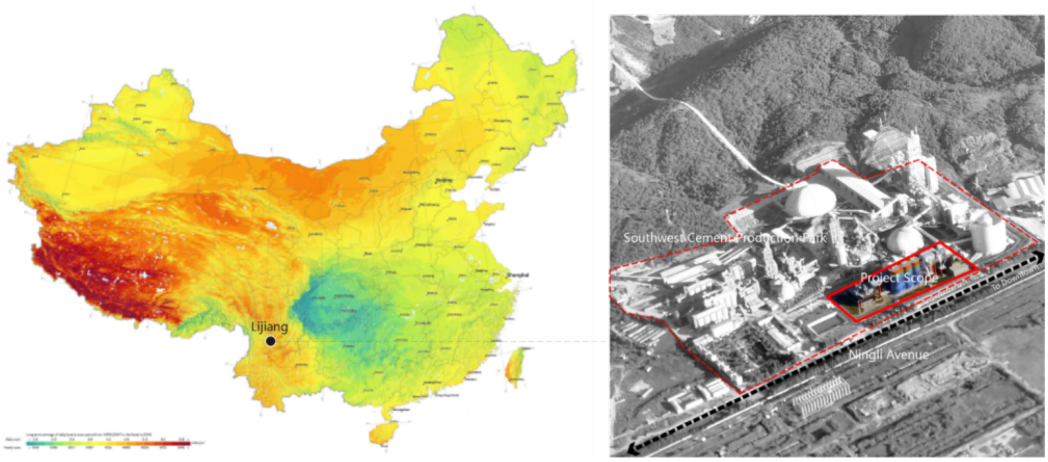

Fig.1. Location of the case

4.3.1. Transparency and Weakness of Thin Film PV Glass

Traditional crystalline silicon photovoltaic cells, due to their opacity, can only be used as carrier spaces on roofs when combined with buildings. The new type of thin-film photovoltaic cells have transparency and can be adjusted according to the needs by adjusting the coating rate to meet different transparency requirements. At the same time, compared with traditional crystalline silicon photovoltaic cells that have higher requirements for the solar azimuth and inclination angle, thin-film photovoltaic glass has better weak light effect and is less restricted by azimuth and inclination angle when deployed. Therefore, this type of photovoltaic glass can be perpendicular to the ground and used as a building curtain wall to ensure good lighting in the internal space of the building.

4.3.2. Structural Strength of Thin Film PV Glass

The structure of thin-film photovoltaic modules has designability. The main manifestation is that the core optoelectronic material components can be combined with glass of different strengths and types, and the combination method can be customized and designed. This also determines to some extent that photovoltaic modules have the characteristics of windproof, waterproof, sound insulation, and impact resistance, making the structural strength of the modules adaptable to the relevant requirements of different building facades. Meanwhile, the weak light effect of thin-film photovoltaic modules enables them to generate electricity continuously even without an optimal tilt angle.

4.3.3. High plasticity of thin-film PV glass

Photovoltaic glass using cadmium telluride, copper indium gallium selenide, and gallium arsenide as dielectrics is an organic combination of new optoelectronic materials and glass carriers, also known as thin-film photovoltaic. As a new photovoltaic technology, thin-film photovoltaic modules have stronger plasticity than crystalline silicon photovoltaic modules. Firstly, it has the functionality of generating electricity through traditional photovoltaic modules; Secondly, it has the translucent characteristics of glass, and the transparency can be customized according to needs, which can be widely used in scenarios such as building curtain walls, roofs, and building ceilings; Finally, its specifications can be customized according to different scenario requirements.

5. Case Study

5.1. Background

The research was carried out in the 5000t/d intelligent production line park of the Old Town of Lijiang Southwest Cement Co., Ltd. The project is located in Lijiang City, Yunnan Province, adjacent to the tourist artery, the Lining Highway. The project involves renovating the facades of cement packaging areas, cement storage areas, and cement grinding areas along the highway. The usable building facade area of the park exceeds 30000 square meters, and the first phase includes a renovated facade area of approximately 12400 square meters. The goal of the project renovation is to: (1) convert the abundant local solar energy resources into electricity and consume it nearby to reduce the demand for traditional energy in the park; (2) Using new photovoltaic glass to beautify building facades and

Fig.2. Status of building facade

improve the working environment of building production.

5.2. *Analysis of Existing Problems and Strategies*

Yunnan is a region with abundant solar energy resources in China, and belongs to the "I" category in the distribution of solar energy resources in China. The total annual solar radiation in the research area is 1719kWh/m^2, and the full load illumination time is about 6 hours. Photovoltaic power generation is the optimal choice. The overall orientation of the park is towards the south. According to research, there are several problems with the architecture in the park, including: 1)Lack of unified design for building facades, inconsistent materials and colors for facades, making it difficult to form an overall architectural style, especially for buildings along *Ningli* Road where the facade space is severely fragmented and fragmented; 2)The building structure is complex, with various structures such as steel-concrete, brick concrete, and color steel. There are many external ancillary facilities on the building facade, which affect the beauty of the building, such as ladders, ventilation pipes, etc. In response to the above issues, the project has adopted the following design strategies:

1) *Weaving and repairing space, beautifying the facade*

Differentiated design is carried out for different facade conditions of buildings. The facade of the cement storage area is complete and has a good display surface, designed with colored photovoltaic glass. The cement batching area, grinding area, and packaging area have complex building facades and fragmented spaces. Black cadmium telluride glass material is used to reorganize the building facades based on the principle of integrity.

2) *Innovate technology and improve efficiency.*

In order to fully utilize solar energy resources, the project space mainly consists of building facades, and traditional crystalline silicon photovoltaic cells have high requirements for solar azimuth and inclination angles. Therefore, the project selects a new type of cadmium telluride power glass as the material, fully utilizing the high plasticity and weak light effect of cadmium telluride power glass, and adopts a design method of overall veneer tiling without setting inclination angles.

5.3. *System Design*

5.3.1. *Section Division*

According to the different functions, facade features, and building heights of the buildings in the park, the project will divide the renovated building complex into three different areas and implement differentiated design. Among them, Area A is a cement packaging workshop with a building height of 29.5 meters, Area B is a cement batching workshop and grinding workshop with a building height of

Table1. The Planning of CdTe PV Glasses

Section	Building Function	Facade Area（m2）	PV Module(Blocks)	Installed Cpacity（kWp)
A	Packaging area	1755	704	158
B	Storage area	4223	2012	391
C,D	Ingredient and grinding area	2120	793	180
Total		5978	2716	549

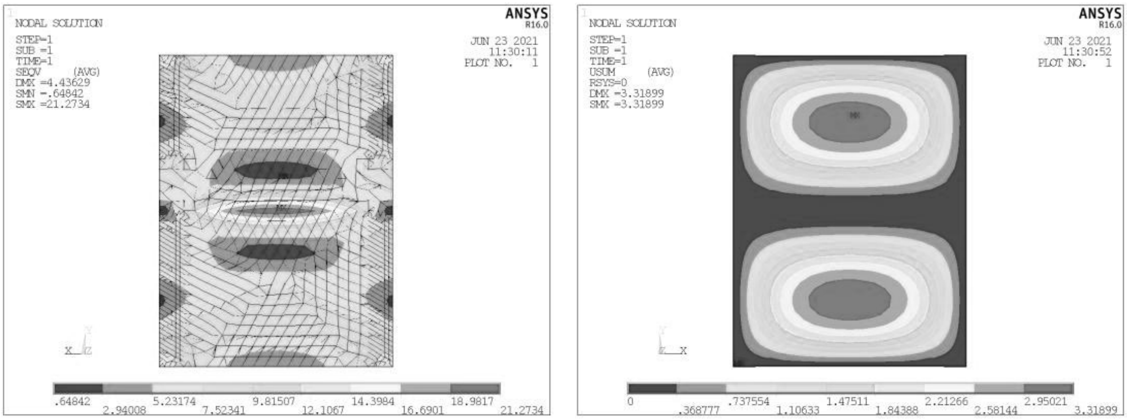

Fig. 3. The performance test parameters of CdTe PV Glasses

about 29 meters, and Area AB is a flat facade with a relatively low building height, designed as a black photovoltaic glass curtain wall. Area C is a cement storage area with a building height of 50 meters and good visibility, using colored photovoltaic glass curtain walls. Meanwhile, according to the composition of different facades, the photovoltaic modules and installed capacity also vary, as shown in the table 1.

5.3.2. Material selection and performance testing

Cadmium telluride (CdTe) photovoltaic glass is a new type of photovoltaic module that uses cadmium telluride as the photovoltaic medium. It is a new type of thin-film photovoltaic cell that can be used for building facades and is considered a green, recyclable, and power generating multifunctional building material that can replace traditional building materials such as bricks and curtain walls(*Ma Liyun,Fu Ganhua,Guanmin,2022*). Cadmium telluride photovoltaic glass has the following characteristics: (1) strong power generation capacity and high energy conversion efficiency; (2) Low temperature coefficient and good weak light power generation performance; (3) The installation angle has minimal impact and thermal spot effect, making it suitable for application in distributed, component-based, and integrated green energy buildings.

Unlike traditional BAPV technology, when BIPV photovoltaic modules are installed and applied on building facades, in addition to their own power generation performance, they also need to meet the requirements of building thermal performance and safety performance. The photovoltaic modules installed on the building facade need to meet the requirements of thermal insulation, sound insulation, load and fire prevention of the building. The cadmium telluride power generation glass panel used in the project currently has no current standard specification reference. In order to ensure the strength and stiffness requirements of the panel, a structural analysis of the panel will be conducted separately based on the corresponding product testing report. For panels that do not meet the requirements, reinforcement measures will be added to the back of the panel to improve its strength and stiffness. A policy simulation was conducted on photovoltaic glass modules using ANSYS-R16.0 software, with a maximum stress of 21.7N/mm2 on the surface material and a maximum displacement of 3.3mm. The components meet the requirements of the Technical Code for Glass Curtain Wall Engineering (JGJ102-2003) in terms of strength and stiffness(Fig.3).

5.3.3. Design of Photovoltaic Facade Structure System

The project adopts standard cadmium telluride glass components with dimensions of 1600mm*1200mm, with 2-3cm reserved for deformation joints, and 4-5 components are electrically connected in series. At the same time, in order to meet the requirements of curved building facades, the installation method of curtain walls adopts a "horizontally hidden and vertically visible" keel skeleton. Embedding cadmium telluride power generation glass components in the glass curtain wall structure not only ensures that the appearance of the curtain wall is not affected, but also protects the normal operation of cadmium telluride power generation glass components from external environmental factors such as wind loads and rainwater. In this structure, the glass panels can float in all directions up, down, left, and right with seismic waves, meeting the requirements for displacement, and the waterproof and anti air infiltration methods are simple and reliable. The front end of the frame is equipped with a heat-insulating strip made of

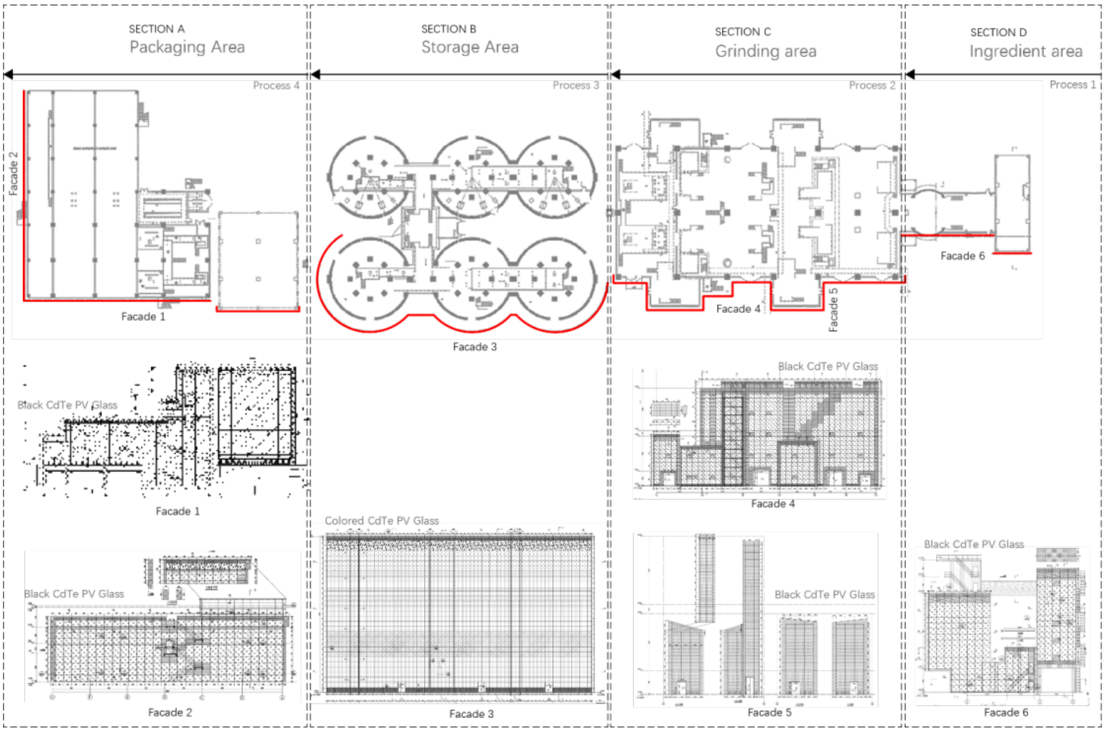

Fig. 4. Photovoltaic Facade Structure System

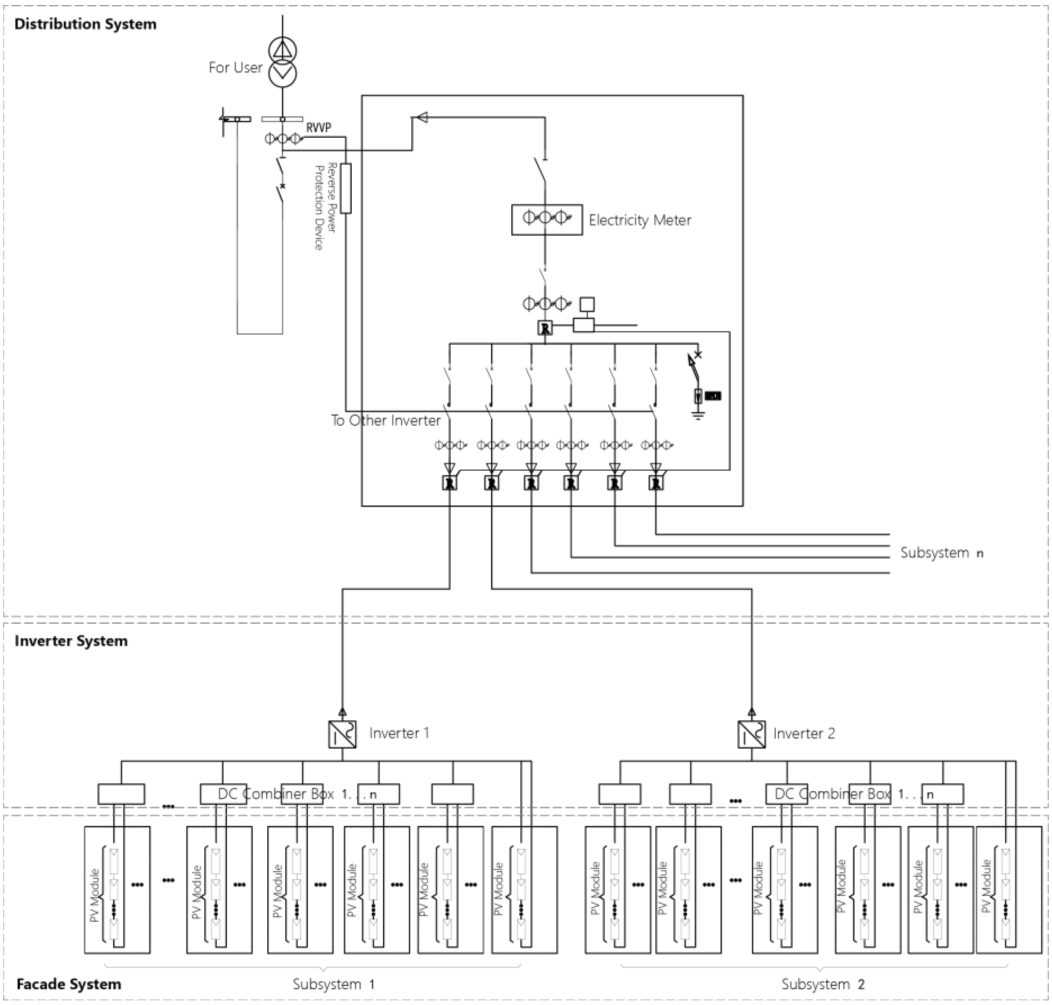

Fig. 5. Electrical system design

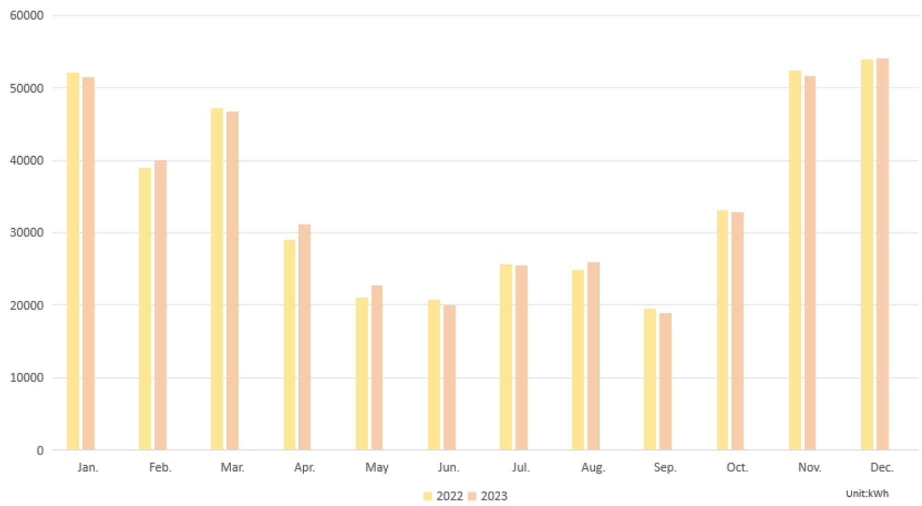

Fig. 6. Power Generation Statistical Table of Photovoltaic Facade

non-conductive material, which can better block the conduction of indoor and outdoor cold and warm air, prevent the occurrence of indoor condensation water in cold seasons, meet the environmental protection concept of energy conservation and emission reduction, and save energy indoors.(Fig.4)

5.3.4. Electrical system design

The building photovoltaic system can be divided into independent photovoltaic power generation system and grid connected photovoltaic power generation system according to the connection mode with the public power grid. The project adopts a low-voltage grid connection strategy, and the electrical system architecture diagram is shown in Figure *. Due to the attachment relationship between photovoltaic modules and curtain walls, photovoltaic modules are greatly influenced by the building facade shape, and there are local differences in the power generation efficiency of photovoltaic modules in various parts. Therefore, in order to ensure the overall power generation efficiency of the project, the project design fully considers the different lighting conditions and adopts a zoning distribution method. On the one hand, the project has made differentiated adjustments in the combination of photovoltaic arrays, incorporating photovoltaic glass of the same power into a unified array; On the other hand, the project will connect photovoltaic arrays of different colors, specifications, and orientations to different inverters, or different MPPTs of the same inverter.

6. Research Results and Discussion

6.1. Result

The total installed capacity of the project is 726KW, with 4 low-voltage grid connection points, 36 string inverters, 208 DC combiner boxes, and 2 AC combiner boxes. The average annual power generation of the project is about 678400 kWh. According to local industrial electricity prices, it is expected to save 346000 yuan in electricity and energy costs annually. At the same time, using solar energy for power generation can save 206.9 tons of standard coal, reduce carbon dioxide emissions by 552.2 tons, sulfur dioxide emissions by 4.2 tons, and nitrogen oxide emissions by 1.4 tons.

Although there are currently no relevant technical specifications for cadmium telluride power glass, the special support design also ensures the stability of project operation. The structural stability of the photovoltaic glass makes it capable of withstanding wind, water, earthquake, and impact in building structural strength. Therefore, its feasibility in participating in the integrated design of photovoltaic buildings has been evaluated.

The cement storage area is designed with colored cadmium telluride power glass due to its high building height and large display area. Adhering to the design concept of "Colorful Yunnan", seven different colored components are arranged to highlight the regional cultural characteristics. In addition, the aesthetic characteristics of texture, color, and modularity of the photovoltaic glass can promote the secondary utilization of building facade space resources while ensuring the overall style of

Fig. 7. Status Photo of the Industrial Building Facade after Renovation

the building, even in urban spaces where large areas of idle land resources cannot be provided.

The research results can be applied to other similar industrial building facades, such as building structure maintenance, energy-saving curtain walls, and roofs. Not only can it improve residents' stereotypical impression of traditional industrial buildings as dirty, messy, and poor, but it can also fully utilize the facade space resources and abundant solar energy resources of the buildings. The produced electricity can not only be self absorbed, optimizing the energy structure of the park to reduce dependence on traditional energy, but also the excess electricity can be connected to the internet and fed back to other industrial energy sources.

6.2. Discussion

6.2.1. BIPV application scenarios lag behind

The application efficiency of photovoltaic buildings is still affected by installation costs and natural climate. Improving the service life of photovoltaic modules, reducing the installation cost of photovoltaic systems, and enhancing the power generation efficiency of photovoltaic buildings in winter are still key considerations for photovoltaic building integration.

6.2.2. Aesthetics and functionality cannot be fully integrated yet

Due to the efficiency of photovoltaic module power generation, the material size and aesthetics cannot be fully integrated at present. In order to achieve better power generation efficiency, different types of thin-film photovoltaic modules have fixed sizes. Taking CdTe thin film components as an example, a top domestic material research and development institution can only provide three sizes: 1200mm*1600mm, 1200mm*800mm, 1200mm*400mm. The rest of the customized sizes will have an impact on the product's energy absorption. Although customization of the size, transmittance, shape, and combination form of photovoltaic modules is allowed in research and development, their high modification costs and unstable energy performance make their application not widespread. That is to say, if power generation efficiency is prioritized, existing specifications of boards need to be designed. If aesthetics are prioritized, existing specifications of boards need to be customized, which will affect power generation efficiency.

6.2.3. The power generation efficiency of photovoltaic modules is still not stable enough

The installation angle of cadmium telluride power generation glass components is arranged on the curved facade of the building. Therefore, in winter, the distributed power station has a high solar altitude angle, which leads to the direct laying of light that is relatively parallel to the facade components and cannot form a strong incident angle, resulting in a lower energy conversion rate of solar energy. Therefore, in terms of power generation, there is a trend of the highest in winter and the lowest in summer.

7. Conclusion

This research demonstrates the significant potential of integrating photovoltaic technology with industrial building facades, offering a sustainable approach to energy structure optimization and architectural aesthetics. By employing cadmium telluride (CdTe) photovoltaic glass in the renovation of industrial buildings, particularly in production-oriented settings, the study validates the feasibility of utilizing thin-film photovoltaic technology to meet both energy and structural demands. The practical application in Lijiang's Southwest Cement Co. highlights how innovative design strategies can transform industrial architecture, improving energy efficiency and aesthetic value while reducing environmental impacts.

However, challenges remain in the widespread application of Building Integrated Photovoltaics (BIPV), particularly in balancing aesthetics with functionality, optimizing power generation efficiency, and managing installation costs. Future research should focus on advancing material customization technologies, developing standardized guidelines for photovoltaic building integration, and exploring cost-effective methods to increase the adaptability of photovoltaic systems in various architectural contexts.

The findings of this study provide a valuable reference for future projects aiming to modernize industrial buildings while contributing to carbon neutrality goals. This approach can be scaled to similar industrial contexts, fostering sustainable development and redefining the role of industrial architecture in urban spaces.

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