

Analysis of the Impact of Building-Integrated Photovoltaics Promotion on Environment and Economy in Chinese Urban Areas and Optimization Paths

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Abstract. Against the background of actively promoting energy transition and addressing climate change globally, the promotion of urban BIPV in China is of great significance for achieving energy conservation and emission reduction and promoting sustainable economic development. This article analyzes the current situation of promoting urban BIPV in China, studies its various impacts on the environment and economy, and explores optimization paths. Research has shown that the promotion of BIPV has significant environmental benefits, such as reducing carbon emissions and minimizing environmental pollution. At the same time, it has significant economic benefits such as driving industrial development, creating employment opportunities, and reducing energy costs. However, key barriers to scalability remain, including high upfront costs, technological limitations in recycling, and regulatory uncertainties. Based on this, optimization paths are proposed from the perspectives of technological innovation, policy improvement, and market mechanism optimization, aiming to provide suggestions for the promotion of urban BIPV in China and help China achieve its dual carbon goals as soon as possible.

Keywords: Chinese Urban BIPV; Environmental Impact; Economic Impact; Optimization Path.

1. Introduction

The global transition towards sustainable energy and the urgent response to climate change have become an international consensus. In order to reach carbon peaking by 2030 and carbon neutrality by 2060, it is necessary to speed up the replacement of clean energy. Urban areas are of vital importance in reducing greenhouse gas emissions, constituting nearly 70% of global CO₂ emissions [1]. In particular, buildings are accountable for over 40% of emissions and 30–40% of the total energy consumption [2]. Considering the present trend of energy consumption and carbon emissions, the building sector's proportion of emissions might increase to 50% [3]. Through the use of photovoltaics, buildings can be transformed from energy consumers to energy producers, which is an important path to reducing dependence on fossil fuels and decreasing carbon emissions. In recent years, building-integrated photovoltaics (BIPV) have shown a rapid trend of promotion in many cities in China. Although it is considered a significant way of achieving carbon peaking and carbon neutrality goals, its impact on the environment and economy still needs to be viewed dialectically. Therefore, systematically analyzing the positive and negative impacts of promoting BIPV in Chinese urban areas and proposing optimization paths are of great practical significance for its sustainable development.

Abouela and Jouane proposed an innovative method for power generation prediction and decarbonization assessment of BIPV, promoting the large-scale application of BIPV in urban areas [4]. Zheng, Bai, and Akram proposed a design method for BIPV systems, providing methodological support for the promotion of BIPV technology in China and reducing design and operational costs [5]. Moreover, Lekbir et al. presented a comprehensive energy, exergy, economic, and environmental assessment of the BIPV system of a laboratory building, emphasizing the importance of life cycle assessment in the promotion of BIPV [6].

Based on the above background, this article focuses on the promotion of BIPV in Chinese urban areas. Firstly, it reviews its current situation and driving factors. Secondly, it analyzes its positive benefits and potential negative impacts on the environment and economy. Finally, corresponding

optimization strategies are proposed to address the negative impacts. Based on the above analysis, provide a reference for the science promotion of BIPV in Chinese urban areas.

2. Current Status and Drivers of China's Urban BIPV Development

2.1. Predominant Forms and Current Market Structure

The promotion of BIPV in Chinese cities is experiencing rapid growth, primarily fueled by policy mandates, falling technology costs, and rising economic attractiveness. Under the strong promotion of policies, significant improvement in economic efficiency, reduction in technology costs, and release of huge market potential, Chinese urban BIPV is showing a high-speed growth trend with enormous potential. BIPV is one of the main forms of building photovoltaic array mounting systems; the other one is Building-Attached Photovoltaic (BAPV) [7]. BAPV is a standard photovoltaic module system installed on existing building structures, mainly roofs. Photovoltaic systems, as attachments, do not replace the structural functions of buildings[7]. Commercial rooftop photovoltaic, one of its mainstream forms, is currently the absolute mainstay of urban building photovoltaic, accounting for over 80%. BIPV integrates the photovoltaic power generation function with the building materials. Photovoltaic modules are directly used as components such as roofs, curtain walls, facades, sunshades, skylights, etc. of buildings, which not only meet the functional requirements of building envelope structures but also generate electricity [8]. This is the future development direction of building photovoltaics.

2.2. Driving Mechanisms: Policy Incentives and Market Forces

Through the joint action of policies and markets, urban BIPV has rapidly developed nationwide. The national strategies, such as the Dual Carbon goal and the 14th Five-Year Plan for renewable energy, have laid a solid foundation for the promotion of urban BIPV. More and more governments are mandating the installation of photovoltaic systems in new buildings, placing higher demands on building energy consumption. Policy incentives, local subsidies, tax incentives, special funds, rewards, and support for green finance have also provided power for the development of urban BIPV. The National Energy Administration and other departments have simplified management and service guarantees, promoted pilot demonstrations, and provided support for the promotion of urban BIPV. While policy sets the direction, market participation provides the central impetus for adoption. At the same time, market participation also played a central role. The significant reduction in equipment costs, the advantage of self-use electricity prices, and technological innovation have greatly expanded the market for urban BIPV. Market entities such as equipment manufacturers, system installers, building owners, and financial institutions have become increasingly active. Residents' interest in green and low-carbon living, reducing electricity bills, cities' pursuit of improving environmental quality, and industrial and commercial users' desire to reduce energy costs have made the market more diversified. This virtuous cycle, where policy creates markets and market feedback informs and refines policy, is the fundamental mechanism driving the sustainable development of the urban BIPV sector in China.

3. Environmental Impacts of Urban BIPV in China

3.1. Positive Impact

3.1.1 Mitigating climate change and reducing air pollution

The most significant positive environmental impact of BIPV is its direct displacement of fossil fuel-based electricity generation, leading to substantial reductions in greenhouse gas and criteria air pollutant emissions. BIPV converts solar energy into electric energy, replacing high-carbon energy directly. The annual power generation of a 1MW rooftop photovoltaic system is about 1 million kWh, which is equivalent to reducing coal by about 400 tons or reducing carbon dioxide emissions by about

1000 tons per year. The large-scale promotion of urban BIPV is crucial for achieving the city's carbon reduction goals. BIPV uses photovoltaic modules as building materials, which not only generate electricity but also replace traditional building materials, reducing the implicit carbon emissions in the production process of building materials. Moreover, as the core scoring item of green building certification, BIPV promotes the transformation of buildings from energy consumers to energy producers, achieving carbon reduction throughout the entire life cycle of buildings. In addition, BIPV also plays a significant role in controlling pollutants. It can directly reduce the emissions of atmospheric pollutants such as SO₂, NO_X, and dust, improving air quality and making significant contributions to alleviating haze in heavily polluted areas. Coal power requires a large amount of cooling water, while photovoltaic power generation consumes almost zero water, reducing the consumption and pollution of water resources and alleviating the pressure on urban water resources.

3.1.2 Optimization of urban ecology and resource efficiency

Beyond emissions reduction, BIPV systems contribute to urban ecological sustainability by optimizing land use, mitigating the urban heat island effect, and promoting resource efficiency. The promotion of BIPV has a profound impact on urban ecosystems, not only alleviating the urban heat island effect but also protecting land ecology. It utilizes existing building space to generate electricity, avoids occupying suburban green spaces or farmland to build centralized power stations, and maintains the connectivity of urban ecology. The use of photovoltaic building materials instead of traditional building materials and photovoltaic-driven building rainwater collection systems has achieved the recycling of resources. Despite these clear benefits, a holistic environmental assessment must also consider potential negative impacts across the technology's lifecycle.

3.2. Potential Negative Effects

3.2.1 Upstream environmental costs: resource intensity and manufacturing pollution

However, the environmental benefits of BIPV during its operational phase must be weighed against the resource consumption and pollution generated during its manufacturing process. Silicon material is the core of crystalline silicon batteries, but the purification, growth, and slicing processes of silicon material are energy-consuming. The entire manufacturing chain is highly dependent on electricity. If coal-fired power is the main source of electricity, the implied carbon emissions will significantly increase. At the same time, a large amount of silicon, silver, copper, aluminum, glass, etc. will be consumed during the manufacturing process, and some rare metals have resource bottlenecks. Various toxic and harmful chemicals are involved in the production process. If not handled properly, they can pose a threat to the environment and increase the risk of pollution.

3.2.2 Downstream challenges: end-of-life management and recycling barriers

A major long-term environmental challenge is the end-of-life management of photovoltaic modules, which presents significant recycling difficulties and potential waste burdens. The lifespan of photovoltaic modules is usually 25-30 years, but they may be retired prematurely due to efficiency degradation, damage, or building renovation. With the explosive growth of China's photovoltaic installed capacity, it is expected that retired photovoltaic modules will show exponential growth from 2030 onwards, with annual waste possibly reaching millions or even tens of millions of tons. The end-of-life process of these modules has become an environmental hazard that cannot be ignored, as the toxic and difficult-to-biodegrade materials they contain will cause environmental pollution if treatment measures are inadequate [9]. Due to its more dispersed distribution and closer integration with buildings, urban building photovoltaic systems may incur higher logistics and organizational costs for recycling. Due to the diversity of materials, the presence of harmful substances, and laminated packaging, the difficulty of recycling has increased. At present, China's efficient, environmentally friendly, and low-cost recycling technology has not yet fully matured and scaled up. The recycling cost may be close to or even higher than the material value, and it also faces various bottlenecks, such as the lack of mandatory recycling regulations, incomplete extended producer

responsibility systems, missing recycling networks, insufficient formal processing capabilities of enterprises, and difficulties in supervision and law enforcement.

4. Economic Impacts of Urban BIPV in China

4.1. Positive Impact

4.1.1 Microeconomic benefits: cost savings and value creation

At the microeconomic level, BIPV generates direct financial returns for building owners and tenants primarily through reduced electricity expenditures and increased property value, while also stimulating local job creation. Installing photovoltaic systems in buildings can directly reduce electricity costs through self-use, and the savings are even more significant for high-energy-consuming buildings such as shopping malls, enterprises, hospitals, and schools. For building owners, photovoltaic systems can become a stable cash flow asset through selling electricity or saving on electricity costs, which is of great benefit. For tenants or buyers, buildings equipped with photovoltaic systems have green attributes and lower operating costs, which may increase their market value and make them more attractive. At the same time, the promotion of urban BIPV has stimulated the growth and employment of related industries such as photovoltaic manufacturing, construction and installation, and financial services. The impact on the power grid is self-evident, reducing the losses of long-distance transmission and effectively alleviating the peak load pressure of the power grid through on-site power generation.

4.1.2 Macroeconomic and strategic benefits

On a macroeconomic scale, BIPV deployment enhances national energy security, fosters the growth of a high-value green industry, and generates significant positive externalities by reducing public health costs associated with air pollution. The promotion of urban BIPV has increased the proportion of clean electricity supply, reduced dependence on fossil fuels, promoted energy structure transformation, and enhanced national energy security. BIPV is an important component of the green and low-carbon industry, promoting economic development towards green, low-carbon, and high-quality directions. At the same time, they help shape the image of urban green, innovative and sustainable development, enhance the brand value of cities, attract more domestic and foreign enterprises and talents who focus on environmental protection and social responsibility to settle in and promote urban economic development. Photovoltaic systems replace fossil fuels for power generation, significantly reducing emissions of air pollutants such as carbon dioxide, improving urban air quality, and reducing public health expenditures and ecological governance costs caused by pollution.

4.2. Potential Negative Issues

Despite the promising benefits, the economic viability and scalability of BIPV face several challenges, including high upfront costs, regulatory ambiguities, and policy dependence. Although the cost of photovoltaic systems continues to decrease, installing photovoltaic systems still significantly increases initial costs compared to traditional buildings, especially for projects with high aesthetics, safety, and integration. For buildings with complex property rights, such as multi-owner residential communities, the distribution of profits and the responsible parties are relatively vague. The current promotion largely relies on subsidies, mandatory installation policies, and electricity pricing policies, and policy uncertainty may affect market expectations and investment enthusiasm. BIPV involves two major fields: construction and electricity, and the relevant technical standards and regulatory system need to be improved.

5. Optimization Path: Targeted Strategy Based on Positive and Negative Effects

5.1. Mitigating Environmental Risks Across the Life Cycle

Despite the aforementioned challenges of urban BIPV, the significant clean electricity output and carbon reduction benefits during their operational phase outweigh the negative impacts of their production and disposal, resulting in a positive overall environmental impact.

In terms of technology, using green production and improving manufacturing processes can reduce production energy consumption and carbon emissions; develop more environmentally friendly and easily recyclable materials, such as biodegradable packaging materials; and develop efficient and low-cost physical and chemical recycling technologies to improve the recovery rate and purity of materials such as silicon and silver.

In terms of policies, formulate and improve laws, regulations, and policies on mandatory recycling of photovoltaic modules and an extended producer responsibility system; develop technical and environmental standards for the recycling and disposal of photovoltaic modules; and encourage green design by considering ease of disassembly and recyclability during the design phase.

In terms of management, strict safety assessments must be conducted before installing BIPV; intelligent operation and maintenance must be promoted to reduce potential environmental impacts during the operation and maintenance process; public education and awareness must be strengthened, and the proper disposal of waste components must be guided. Through the above methods, these negative impacts can be effectively minimized, ensuring that urban BIPV truly becomes an environmentally friendly and green development path.

5.2. Enhancing Economic Viability Through Multi-Stakeholder Collaboration

The overall economic impact of promoting urban BIPV in China is positive and far-reaching, but breaking through current bottlenecks and improving economic feasibility requires multidimensional collaborative efforts. Firstly, reducing technology costs and improving performance are the core driving forces. Through increased R&D investment in high-efficiency photovoltaic modules and the promotion of industrial applications for advanced technologies, the photoelectric conversion efficiency can be enhanced, which in turn reduces the operation and maintenance costs over the entire life cycle. As the cost of photovoltaic systems decreases, the reduced investment cost for investors effectively boosts their investment enthusiasm, which drives an expansion in the total installed capacity [10]. Next, key acceleration will be achieved through the adoption of diversified business models and innovative financial tools. Mechanisms such as Energy Management Contracts (EMC), distributed photovoltaic leasing, and green power subscription should be promoted to reduce the initial investment pressure on property owners. Project financing models that combine green bonds, Real Estate Investment Trusts (REITs), and carbon finance should be explored to attract social capital participation and activate market vitality. Then, the policy mechanism needs further optimization, and the standard and regulatory system also urgently needs improvement. This serves as the fundamental guarantee for promoting the healthy development of the industry. It is essential to expedite the formulation of national standards and engineering specifications for building photovoltaic systems and components, clarify requirements in terms of safety, quality, grid connection, etc., and provide institutional support for large-scale promotion; Finally, facilitating collaborative cooperation between the photovoltaic industry and diverse sectors like construction, building materials, electricity, and finance is essential to construct an integrated development ecosystem. It is crucial to drive full-chain collaboration covering design, production, installation, operation, and maintenance, enhance market information transparency and platform development, and shape a sound market competition mechanism. Only by means of cross-sector collaboration and systematic advancement can obstacles in promotion be effectively addressed, and dual breakthroughs in the economic and social benefits of building-integrated photovoltaics be realized.

6. Conclusion

This study demonstrates that BIPV presents a multifaceted solution for advancing urban sustainability in China, offering significant environmental and economic advantages despite persistent implementation challenges. Its environmental and economic benefits are significant. In terms of environment, it has achieved carbon reduction and pollutant control, maintained urban ecology, and optimized resource efficiency. In terms of the economy, it has driven the development of photovoltaic and related industry chains, created employment opportunities, and promoted the transformation of the national energy structure. Notwithstanding these compelling benefits, the widespread adoption of BIPV is not without its obstacles. However, in the process of promotion, there are challenges encompassing high upfront costs, resource-intensive manufacturing processes, and underdeveloped end-of-life recycling infrastructures. To this end, it is necessary to resolve risks through technological innovation, policy improvement, support for green finance, and market promotion, so that urban BIPV can become the core lever of China's energy transformation. Strategic investments and policy support to address these challenges are not merely beneficial but essential to unlocking the full potential of BIPV as a cornerstone of China's low-carbon energy transition and urban development model.

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