Challenges of large-scale facade PV systems in dense urban environments in China

Weili Liu,[1,2] Hongzhi Mao,[1,2] Zhiyong Tian,[1,2,*] Yongqiang Luo,[1,2] Ling Ma,[3,4] Xinyu Chen,[5] Maomao Hu,[6] Jiayu Li,[7] and Jianhua Fan[8]

[1]School of Environmental Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[2]Hubei Key Laboratory of Multi-media Pollution Cooperative Control in Yangtze Basin, School of Environmental Science & Engineering, Huazhong University of Science and Technology, Hubei 430074, China
[3]National Center of Technology Innovation for Digital Construction, Huazhong University of Science and Technology, Wuhan 430074, China
[4]School of Civil and Hydraulic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[5]School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[6]Department of the Built Environment, National University of Singapore, Singapore 119077, Singapore
[7]Center for the Built Environment, University of California, Berkeley, 110 Sproul Hall, Berkeley CA 94720, USA
[8]Department of Civil and Mechanical Engineering, Technical University of Denmark, Lyngby 2800 Kgs, Denmark
*Correspondence: zhiyongtian@hust.edu.cn

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The world is facing growing challenges posed by climate change and resource depletion. In response, the Paris Agreement has prompted countries to pay great attention to climate issues by setting carbon peak and carbon neutrality goals and accelerating energy transition. Simultaneously, the Russia-Ukraine war has triggered sharp fluctuations in global energy prices, exacerbating the energy security crisis and underscoring the urgent need to develop renewable energy sources.

Solar energy, as a clean and renewable resource, is widely recognized as a key solution to mitigating climate change. Over the past decade, photovoltaic (PV) technology has advanced rapidly, with substantial reductions in cost. From 2010 to 2021, the average cost of PV systems decreased by 88%, making PV power generation cheaper than traditional fossil fuels in some regions.[1] From 2021 to 2025, solar PV prices transitioned from subsidy dependence to fully market-driven pricing. Meanwhile, the conversion efficiency of PV cells has improved significantly, rising from an average of 8% in the 1990s to over 22% in 2018,[2] demonstrating remarkable progress in both the economic and technical aspects of PV systems.

Amid the global energy transition, China's photovoltaic industry has experienced rapid growth, particularly in residential distributed photovoltaics. In 2021, China added 21.6 gigawatts of residential photovoltaic capacity, equivalent to the total capacity installed during the entire 13th Five-Year Plan period. In 2023, the newly installed capacity further increased to 43.48 gigawatts, more than double that of 2021. The cumulative installed capacity exceeded 100 gigawatts.[3] By the end of 2024, China's cumulative installed capacity of residential distributed photovoltaic power generation had reached over 145 gigawatts. This demonstrates that distributed photovoltaics have achieved record-breaking growth and large-scale development.

Building-integrated photovoltaics (BIPV) is a form of combining photovoltaics with buildings by directly integrating PV modules into facade and roof. This allows power generation without using extra land and is gradually becoming a mainstream trend in future building design. With the acceleration of urbanization, high-density and high-rise buildings have become the norm in cities, where rooftops are often occupied by air conditioning units, elevator shafts, and other equipment. This limits the space available for rooftop photovoltaics. In contrast, facade areas in cities are significantly larger than rooftops, offering greater potential for facade photovoltaics. In addition, in high or low latitude regions, during cold seasons or under specific sunlight conditions, facade photovoltaics show better power generation efficiency than rooftop photovoltaics.

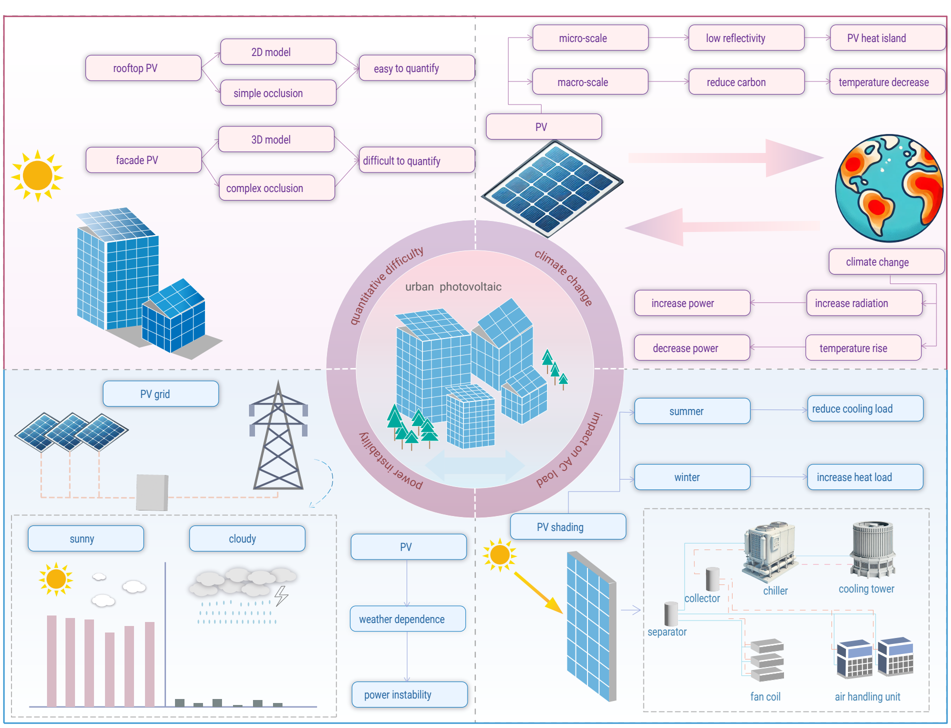

Figure 1. Research perspectives on urban photovoltaics. The top left figure highlights the challenges in quantifying facade photovoltaics; The top right figure illustrates the relationship between photovoltaics and climate change; The bottom left figure depicts the instability of photovoltaic power generation; The bottom right figure shows the impact of facade photovoltaics on building heating and cooling loads.

Photovoltaic research and applications currently focus primarily on rooftop systems, while urban facade photovoltaics remain underexplored. Facade photovoltaics involve complex issues such as light angles, shading effects, and dynamic energy optimization, requiring further targeted research.

THE CHALLENGE OF QUANTIFYING FACADE PHOTOVOLTAIC POTENTIAL

Compared to rooftop photovoltaics, facade photovoltaics face more complex challenges in quantification. The potential of rooftop photovoltaics has been evaluated in many city- and national-level studies, thanks to the relatively simple two-dimensional layout of rooftops and the availability of surface data. These studies often rely on remote sensing, GIS, or deep learning techniques combined with solar radiation models to calculate suitable rooftop areas and solar radiation, thus quantifying rooftop photovoltaic potential.

In urban environments, due to the density of high-rise buildings, shading from nearby structures, and differences in building heights and shapes, more detailed spatial analysis and 3D modeling are needed to assess the potential of facade photovoltaics. Additionally, the performance of facade photovoltaics is affected by factors such as orientation, tilt, and sunlight exposure of the building facade. These factors make quantifying the potential of facade photovoltaics more complex than rooftop photovoltaics.

Due to the lack of high-resolution 3D model data at the city or national level, most studies remain limited to small-scale pilot projects. Recent advances in cost-effective technical solutions have addressed these data constraints: UAV (Unmanned Aerial Vehicle) photogrammetry coupled with open-source GIS tools (e.g., QGIS) enables rapid generation of building facade point clouds. Deep learning-based point cloud processing automatically reconstructs textured 3D models while extracting critical geometric features for simplified BIM generation. Additionally, AI-powered dynamic simulation predicts spatiotemporal irradiance distribution on facades under varying meteorological conditions, facilitating precise time-series PV potential assessment.

THE RELATIONSHIP BETWEEN CLIMATE CHANGE AND PHOTOVOLTAIC POWER GENERATION

Climate change alters photovoltaic potential by affecting key factors such as solar radiation, temperature, and wind speed. The study shows that global warming may reduce photovoltaic efficiency. For every 1°C increase in temperature, PV efficiency decreases by about 0.4% to 0.5%.[4] However, in some regions, increased solar radiation may partially offset the negative impact of rising temperatures.

On the other hand, large-scale photovoltaic installations may have complex effects on local climate. For example, the low albedo of photovoltaic plants causes more solar radiation to be absorbed, increasing local heat release. This phenomenon, called the Photovoltaic Heat Island (PVHI) effect, can raise daytime temperatures in urban areas by 1.5°C while lowering nighttime temperatures. Furthermore, PVHI leads to a reduction in relative humidity at 2m height by 1.2-5.6% (daytime) and 0.7-2.1% (nighttime), while increasing wind speed at 10m height by 0.5-1.2 m/s during the day and decreasing it by 0.2-0.6 m/s at night.[5] Although the Photovoltaic Heat Island (PVHI) effect may have negative impacts locally, at a macro level, urban photovoltaic systems can lower global temperatures and mitigate global warming by reducing the use of traditional energy and greenhouse gas emissions.

Currently, research on the relationship between climate change and photovoltaic power generation mainly focuses on calculating photovoltaic potential based on solar radiation data or studying the impact of rooftop photovoltaics on climate. However, research on the relationship between building-integrated photovoltaics, especially facade photovoltaics, and climate change remains limited. Most studies have not fully considered the complex variables in urban environments, such as the shading effects of facade photovoltaics and the interactions with dynamic climate changes.

PHOTOVOLTAIC POWER GENERATION STABILITY

Solar photovoltaic power generation is highly weather-dependent, and its intermittent nature poses challenges to grid stability. Under extreme weather conditions, photovoltaic systems may experience unusually low power generation. The issue is often mitigated through energy storage, load control, and geographical distribution, but prolonged extreme weather can still significantly impact the system.

Compared to traditional rooftop photovoltaics, building facade photovoltaics have a significant advantage in time distribution. Facades face different directions, such as east, south, west, and north, allowing them to receive sunlight and reach peak generation at different times of the day. This distribution feature reduces reliance on energy storage and helps match the grid load curve, decreasing the need for traditional fossil fuel backup power. When combined with demand-side response strategies (such as time-of-use pricing), it can further align commercial and residential electricity loads with the peak generation periods of facade photovoltaics (e.g., morning peaks for east-facing facades and afternoon peaks for west-facing facades), thereby enhancing grid peak-shaving capability. By optimizing the design and layout of building facade photovoltaics, combined with energy storage and smart grid technologies, the stability of photovoltaic power generation can be improved to some extent.

FACADE PHOTOVOLTAICS AND HUMAN COMFORT

Research on the impact of facade photovoltaics on air conditioning loads is still limited. Its potential in high-density urban environments has not been fully explored. Photovoltaics installed on building walls can block solar radiation, reducing heat absorbed by exterior walls in summer and lowering indoor temperatures and cooling loads. However, in winter, it reduces solar heat gain and increases heating loads. Therefore, it is necessary to combine building design, regional climate characteristics, and photovoltaic technology optimization to fully assess the impact of facade photovoltaics on energy use and indoor comfort.

Regarding daylighting, semi-transparent photovoltaic (STPV) windows - an advanced PV technology - effectively balance power generation and natural lighting, particularly suited for curtain-walled buildings. Meanwhile, dynamically adjustable PV shading systems enhance energy yield through real-time angle optimization, while colored PV modules transcend traditional aesthetic constraints. Collectively, these technological advances systematically address PV's impacts on building daylighting, thermal performance, and architectural appearance.

CONCLUSION

The scaled deployment of building-integrated photovoltaic (BIPV) facades necessitates coordinated policy and economic innovations. Existing building codes lack provisions for PV facade integration, maintaining high retrofit costs. Prevailing feed-in tariffs fail to capture the distinctive spatiotemporal generation patterns of vertical systems, constraining economic viability. The absence of equitable benefit-sharing mechanisms among stakeholders in high-density urban areas further impedes adoption. Life-cycle analysis indicates that while BIPV systems require higher initial investment, their operational benefits—including measurable reductions in HVAC loads—coupled with carbon trading and green financing mechanisms can deliver competitive returns. Realizing this potential mandates cross-sector collaboration among policymakers, construction industries, and energy utilities.

Future research should prioritize three key breakthroughs for urban PV integration: 1） AI-driven dynamic shading algorithms for cost-effective potential assessment in dense urban canyons; 2） Quantify large-scale PV-climate interactions to develop climate-adaptive photovoltaic systems that mitigate efficiency losses under extreme weather. 3） Multi-objective optimization frameworks balancing energy yield, building performance, and architectural aesthetics. As cities evolve and energy demands increase, facade photovoltaics could become a key component of sustainable urban energy systems

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the version.

DECLARATION OF INTERESTS

The authors declare no competing interests.