Transforming Windows into Active Energy Systems in a Hot Built Environment: Msheireb Downtown Doha as a Case Study



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As cities in hot-climate regions continue to expand, the built environment faces increasing pressure to reduce energy consumption while maintaining high levels of indoor comfort. In countries such as Qatar, where cooling demand accounts for the majority of electricity use, climate-responsive architectural design has become an urgent priority rather than a design preference. Addressing this challenge requires innovative solutions that simultaneously improve energy efficiency, occupant well-being, and environmental performance.

This research explores one such solution: the transformation of conventional windows into active energy-generating systems through the integration of semi-transparent photovoltaic (STPV) technologies. Unlike traditional opaque solar panels, STPV systems are embedded within glazing, allowing facades to generate electricity while maintaining daylight access and visual connectivity. This dual functionality makes STPV windows a promising solution for dense urban environments (Figure 1), where building facades represent a largely untapped source of renewable energy.

The findings presented here are grounded in three complementary peer-reviewed studies that collectively examine STPV performance across indoor, building, and urban scales. Together, these studies provide a comprehensive framework for their application in Qatar's hot desert climate.

At the indoor scale, the first study [1] investigates the relationship between daylighting performance and visual comfort in office environments. In hot climates, excessive solar radiation often leads to glare and visual discomfort, negatively affecting occupant productivity and well-being. Using advanced simulation tools, including Grasshopper for Rhino and Radiance, the study evaluates how variations in window-to-wall ratio (WWR) and visible light transmittance (VLT) influence daylight distribution and glare levels.

The results demonstrate that these two parameters are critical in achieving a balanced indoor environment. A configuration of 60% WWR with 0.3 VLT was identified as the optimal solution, providing sufficient daylight while effectively controlling glare and minimizing reliance on artificial lighting. Alternatively, a 40% WWR with 0.4 VLT also performs well but may require supplemental lighting under certain seasonal conditions. These findings offer practical design guidelines tailored to Qatar's climatic context and highlight the importance of integrating daylight optimization strategies into facade design. Importantly, the study addresses a key research gap by providing localized data for desert environments, contributing to both regional and global discussions on sustainable building design.

At the building scale, the second study [2] examines the energy and thermal performance of STPV windows as part of an integrated building system. By filtering solar radiation, STPV glazing reduces unwanted heat gain, which directly lowers cooling demand—an essential benefit in Qatar's high-temperature environment. At the same time, these systems generate renewable electricity on-site, contributing to the building's energy supply.

The findings indicate that STPV windows can reduce cooling loads by up to 25%, while generating approximately 10–20% of a building's electricity needs, depending on factors such as facade orientation, glazing properties, and system integration. This dual performance underscores the value of STPV as both a passive and active design element. The study further emphasizes that the effectiveness of these systems depends on careful design optimization, including material selection and facade configuration, to balance thermal performance with daylighting and energy generation.

Expanding beyond individual buildings, the urban-scale analysis proposes a framework for integrating STPV technologies into sustainable city development. Using Msheireb Downtown Doha as a case study (Figure 2), the research demonstrates how combining facade-integrated STPV systems with rooftop photovoltaic installations can create a synergistic energy strategy. While rooftop systems maximize solar exposure and electricity generation, STPV windows activate vertical surfaces, enhancing energy production in high-density urban areas where roof space is limited.

This integrated approach not only improves overall energy efficiency but also enhances urban resilience by reducing reliance on centralized energy systems. Additionally, it contributes to social sustainability by improving indoor environmental quality and promoting access to clean energy solutions within urban communities. The framework provides actionable guidance for architects, planners, and policymakers seeking to align urban development with Qatar's sustainability goals.

Complementing these applied studies, the third paper [3] offers a comprehensive review of STPV technologies and their role in advancing sustainable urban design in hot climates. The review examines key aspects of STPV systems, including material innovations such as perovskite-based photovoltaics, performance metrics related to energy generation and thermal behaviour, and strategies for architectural integration. It also highlights emerging trends, including AI-driven energy management systems and adaptive facades capable of dynamically responding to environmental conditions.

However, the review also identifies several challenges that must be addressed to enable widespread adoption. These include issues related to dust accumulation, which can significantly reduce system efficiency in desert environments, as well as concerns regarding material durability, long-term performance, and economic feasibility. Furthermore, the lack of standardized simulation methods and real-world validation studies presents a barrier to scaling these technologies. Addressing these challenges requires interdisciplinary collaboration and context-specific research tailored to the unique environmental conditions of regions like Qatar.

Across all three studies, a consistent theme emerges: the need to balance multiple performance criteria energy efficiency, visual comfort, and thermal regulation—within a single integrated system. STPV windows offer a unique

opportunity to achieve this balance by combining renewable energy generation with advanced facade design. However, their successful implementation depends on careful optimization, informed by both simulation-based analysis and real-world testing.

Looking ahead, the integration of smart technologies presents new opportunities for enhancing STPV performance. Future facades could incorporate adaptive features such as dynamic shading, variable transparency, and real-time energy management systems powered by artificial intelligence. These innovations would enable buildings to respond dynamically to changing environmental conditions, further improving energy efficiency and occupant comfort.

In conclusion, this research demonstrates that semi-transparent photovoltaic windows are more than a technological innovation; they represent a transformative approach to sustainable architecture in hot climates. By converting building facades into active energy systems, STPV technologies contribute to reducing cooling demand, generating renewable energy, and improving indoor environmental quality. In doing so, they support Qatar's broader vision for sustainable development and resilient urban growth.

As cities continue to evolve, the integration of such technologies will be essential in shaping a future where buildings are not merely consumers of energy but active contributors to a more sustainable and energy-efficient urban environment.

To view the published research outputs, please click the link or scan the QR code:

[1] https://doi.org/10.13189/cea.2025.130304

[2] https://doi.org/10.13189/cea.2025.130441

[3] https://doi.org/10.70917/fce-2026-001

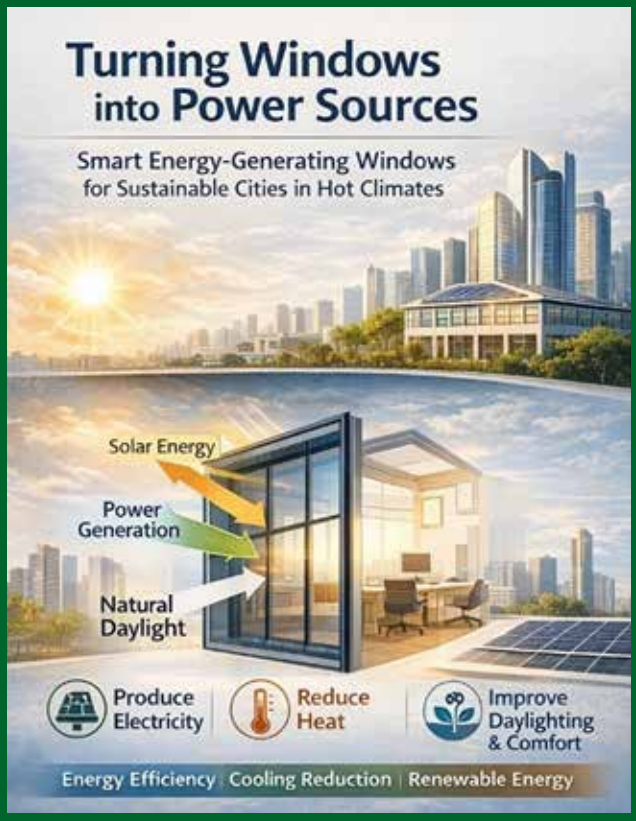


Figure 1: Solar windows for sustainable cities in hot climates.

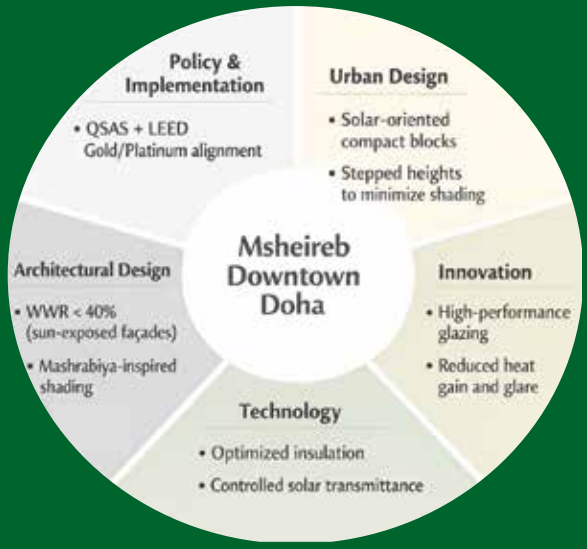


Figure 2: The alignment of the proposed framework with Msheireb case study.