

Renewable Energy Integration through Semi-Transparent Photovoltaic Windows: A Framework for Sustainable Urban Development in Hot Climates

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Abstract: As cities in hot climate regions face escalating challenges from rapid urbanization and climate change, there is a pressing need for innovative strategies that reduce building energy demands while ensuring occupant comfort and environmental quality. Semi-transparent photovoltaic (STPV) windows present a promising solution by enabling on-site renewable energy generation through building façades, without compromising daylight access or architectural integrity. This study proposes a practical framework for integrating STPV technologies to support urban sustainability in hot climates, based on a multi-dimensional analysis of energy performance, thermal behaviour, and visual comfort under intense solar exposure. Critical design and operational challenges—such as overheating, glare, and dust accumulation—are examined to inform climate-responsive integration strategies. Insights from the Msheireb Smart City case study in Qatar illustrate how mixed-use developments can leverage STPV technologies to enhance energy efficiency, align with climate adaptation goals, and maintain cohesive architectural aesthetics. Findings suggest that STPV systems have the potential to reduce cooling loads by up to 25% and provide on-site electricity generation that could meet 10–20% of a building’s energy needs, depending on factors such as glazing type, orientation, and integration method. This study also highlights the potential of STPV to contribute to policy recommendations on sustainable energy practices in hot climates. By positioning STPV systems at the intersection of renewable energy innovation and urban climate resilience, this research offers actionable guidance for advancing sustainability in hot-climate cities through integrated building design, energy strategy, and urban planning.

Keywords: renewable energy strategies; sustainable urban development; building integrated photovoltaic (BIPV); semi-transparent photovoltaic (STPV); hot climate architecture; smart cities

1. Introduction

As cities expand and global energy demands continue to rise, the integration of renewable energy technologies into the built environment has become a critical pillar for achieving sustainability. Urban areas, especially in hot climate regions, face compounding challenges driven by rapid urbanization, increasing population density, and the growing intensity of climate change impacts. These conditions have led to substantial energy consumption in buildings—currently among the largest contributors to global energy use and carbon emissions (Liu and Wu, 2022). In hot climates, such as those found in the Gulf region, the problem is further exacerbated by extreme solar exposure, high cooling loads, and a strong dependency on fossil fuels to power energy-intensive systems for indoor thermal comfort.

Windows play a pivotal role in shaping a building’s energy and environmental performance. They significantly influence daylight availability, visual comfort, and thermal behavior. Poorly designed or



unoptimized glazing systems can lead to excessive heat gain, increased cooling demands, and glare issues—challenges that are particularly severe in hot climates. Improving the performance of building envelopes, particularly window systems, is therefore essential for reducing operational energy use and enhancing urban sustainability (Mustafa et al., 2023, Tippu et al., 2023).

In this context, semi-transparent photovoltaic windows (STPWs) emerge as a promising, multifunctional solution. As a form of building-integrated photovoltaics (BIPV), STPWs merge solar energy generation with architecture (Scibetta et al., 2023) (Liu and Wu, 2022). Moreover, advancements in solar cell materials, glazing technology and environmental performance (Romaní et al., 2022). Unlike traditional opaque PV panels, these advanced glazing systems allow natural light to penetrate interior spaces while simultaneously generating electricity. This dual functionality helps reduce reliance on artificial lighting, supports thermal comfort by managing solar heat gain, and contributes to the overall energy efficiency of the building. Moreover, AI-powered energy management systems have further enhanced the performance and viability of STPWs, particularly for applications in net-zero energy buildings (NZEBS) and smart cities (Lou and Hsieh, 2024).

The potential of STPWs is particularly relevant in hot-climate cities like Doha, Qatar, where balancing daylight use, visual comfort, and cooling demand is essential. However, despite their promise, challenges such as high initial costs, material durability under harsh conditions, and dust accumulation continue to hinder large-scale adoption (Setyantho et al., 2021, Shi and Zhu, 2023). Regulatory and policy barriers also remain a critical issue, emphasizing the need for robust frameworks that facilitate integration of these systems into existing urban infrastructure.

This study proposes a practical, climate-responsive framework for integrating STPWs into urban developments in hot climates. It focuses on evaluating the energy, thermal, and visual performance of STPW technologies under intense solar exposure, while also addressing key design challenges such as glare, overheating, and dust accumulation that can impact their effectiveness and occupant comfort. Through the case study of Msheireb Downtown Doha, the research illustrates how STPWs can be architecturally and functionally integrated into smart urban environments. Ultimately, the study offers actionable recommendations for architects, urban planners, and policymakers to guide the effective adoption of STPWs in support of sustainable, energy-efficient, and climate-resilient urban development.

In addition to environmental and technical benefits, social sustainability is a critical factor in the successful adoption and long-term performance of STPWs within urban contexts. By improving visual comfort, reducing glare, and enhancing indoor environmental quality, STPWs directly contribute to occupant well-being and satisfaction. Moreover, integrating these technologies within socially inclusive urban developments promotes equitable access to sustainable energy solutions, fosters community engagement, and supports the creation of healthier, more resilient neighborhoods. This social dimension complements the environmental and economic advantages of STPWs, reinforcing their importance in a holistic approach to sustainable urban design.

Beyond environmental and technical benefits, social sustainability is vital for the successful adoption and lasting performance of STPWs in urban settings. By enhancing visual comfort, reducing glare, and improving indoor environmental quality, STPWs promote occupant well-being. Furthermore, their integration within socially inclusive developments fosters equitable access to sustainable energy, encourages community engagement, and helps build healthier, more resilient neighborhoods. This social aspect complements the environmental and economic benefits, highlighting the holistic value of STPWs in sustainable urban design.

The study's key contribution is the development of a multi-layered, climate-responsive framework that integrates environmental, architectural, and urban-scale dimensions—specifically adapted to the conditions of hot, arid regions. In contrast to previous reviews that primarily emphasize technical performance or isolated design elements, this framework incorporates vernacular architecture, urban morphology, and practical integration criteria. Using Msheireb Downtown Doha as a real-world case study, the research bridges the gap between theory and application, delivering actionable insights for the effective implementation of STPWs in dense urban contexts.

2. Methodology

This study adopts a qualitative and analytical approach to develop a multi-layered, climate-responsive framework for integrating semi-transparent photovoltaic (STPV) windows in hot-climate urban environments. The process includes a structured literature review, conceptual performance analysis, and case study application.

The literature review focuses on recent developments in STPV technologies, emphasizing their roles in energy generation, daylighting, thermal behavior, visual comfort, and urban integration. Key research gaps and best practices are extracted to inform the framework.

A conceptual performance analysis is conducted using validated insights from prior simulation studies, along with climate-specific assumptions relevant to Doha, Qatar—such as average annual solar radiation, peak sunlight hours, and extreme summer conditions. Parameters including building orientation, glazing properties, and urban density are assessed to understand their influence on STPV performance. Although new simulations were not performed in this study, key performance metrics were informed by tools such as Radiance (for daylight and glare analysis) and EnergyPlus, as commonly used in similar hot-climate studies. The inclusion of these tools in the review strengthens the methodological foundation.

Msheireb Downtown Doha is used as a contextual case study due to its status as a leading example of sustainable urban redevelopment in an extreme climate. Data were drawn from architectural documentation, published environmental performance evaluations, and studies on its use of renewable energy and shading strategies. The case supports practical insights into STPV integration and the role of design and policy in successful implementation.

The proposed framework was synthesized by linking recurring themes from the literature to contextual features identified in the Msheireb case. This includes material selection, façade integration, building-level performance, and urban-scale planning. The framework aims to support architects, urban designers, and policymakers by bridging theoretical knowledge with application strategies.

This methodology acknowledges certain limitations. It does not include original simulation outputs or field-tested prototypes. While grounded in credible sources and applied to a real-world case, future research should advance this work through simulation validation, economic feasibility studies, and pilot demonstration projects to test performance under real conditions. [Figure 1](#) represent the methodology framework used in this paper.

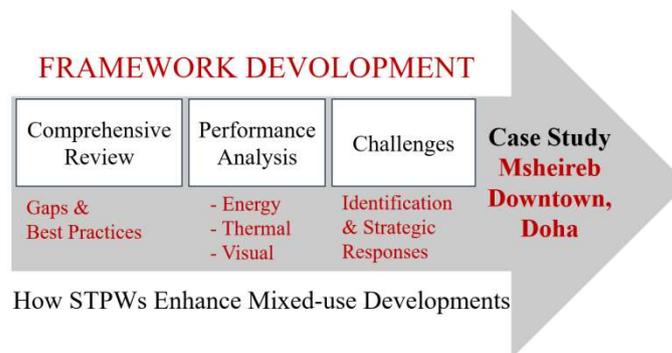


Figure 1. Methodology framework.

2.1. Comprehensive Literature Review

The global transition to renewable energy is driven by the need to mitigate climate change, ensure energy security, and foster sustainable urban development. Between 2010 and 2023, global renewable energy capacity more than tripled—from 1,223 GW to 3,869 GW—with solar photovoltaic (PV) systems leading due to affordability, scalability, and supportive policies ([Liu et al., 2022](#)). However, large-scale solar deployment continues to face challenges such as land use demands, intermittency, and environmental impacts related to production and disposal of PV materials ([Al Zaabi and Ghosh, 2024](#)).

To overcome these barriers, innovative solutions like semi-transparent photovoltaic windows [STPW] have gained attention. These technologies integrate solar generation directly into the building envelope—particularly windows and façades—transforming passive surfaces into active energy contributors ([Chen et al., 2024](#)). Unlike conventional PV panels, STPWs allow visible light transmission while harvesting non-visible solar wavelengths, thereby generating electricity without compromising indoor daylight quality or comfort ([Bizzarri et al., 2011](#)).

STPWs are a subclass of building-integrated photovoltaics (BIPVs) and are especially suited for dense urban environments with limited rooftop area ([Yeom et al., 2023](#)). Their dual functionality—combining solar power generation with daylight enhancement and thermal control—makes them particularly valuable for Net-Zero Energy Buildings (NZEBS) and smart city developments ([Ziapour et al., 2024](#)). In hot climates, such as Qatar’s, where solar irradiance is abundant and air conditioning significantly drives energy demand, STPWs can effectively reduce cooling loads while improving natural light availability and occupant comfort ([Scibetta et al., 2023](#)).

Despite these benefits, the deployment of STPWs in urban design remains limited. Most existing research focuses on the material science or isolated energy performance evaluations of STPVs, with

relatively few studies addressing architectural integration, long-term durability under extreme conditions, or urban planning strategies (Roy et al., 2020). Issues such as glare control, overheating, dust accumulation, and maintenance in harsh climates are underexplored, particularly in the context of high-density, sun-intensive regions (Zhu et al., 2020).

Qatar’s Vision 2030 outlines a national commitment to sustainability, aiming to balance economic growth with environmental protection (Hajimineh et al., 2024). Projects like Msheireb Downtown Doha and Lusail City reflect this vision by blending modern energy-efficient technologies with vernacular design principles (Furlan et al., 2019). While Qatar has made progress in utility-scale solar deployment (e.g., the Al Kharsaah Solar Plant), building-level technologies like STPWs remain underutilized.

A review of the existing literature reveals several critical themes associated with the integration of STPWs in buildings, particularly under hot climatic conditions. These include energy performance, visual comfort, thermal behavior, architectural integration, and operational challenges. Recent studies highlight that STPWs offer notable benefits in hot climates by improving daylight quality, reducing glare, and decreasing cooling energy demand. In Riyadh, perovskite STPWs combined with light shelves enhanced visual comfort and energy savings (Ghosh et al., 2021, Mesloub and Ghosh, 2020). These findings affirm STPWs’ potential as a viable solution for sustainable, energy-efficient building design in arid urban contexts. Table 1 presents a synthesis of the key findings in each area, identifies major research gaps, and outlines their specific relevance to high solar radiation regions such as Qatar.

Table 1. Summary of STPW Research Themes and Gaps in Hot-Climatic Urban Contexts.

Research Theme	Key Findings	Identified Gaps/ Opportunities	Relevance to Hot Climates
Energy Performance	STPWs contribute to on-site electricity generation; effective for NZEBs	Limited real-world data in urban buildings	High solar irradiance potential in Qatar
Visual Comfort	Allows daylight while reducing glare	Lack of occupant-centric visual comfort assessments	Potential to reduce reliance on artificial lighting
Thermal Behaviour	Reduces solar heat gains; lowers cooling loads	Limited simulation and in-situ data for thermal modeling in extreme climates	Reduces cooling energy demand
Architectural Integration	Suitable for façades and curtain walls	Few case studies on integration with vernacular and modern architecture	Compatibility with Qatar’s hybrid design trends
Operational Challenges	Dust, maintenance, and overheating concerns	Minimal urban-scale performance evaluations	Essential for MENA-region deployment strategies
Best Practices	STPWs enhance daylight, reduce glare, and save energy; ventilation helps manage heat; dust and maintenance remain challenges.	Few large-scale studies; need local guidelines.	Demonstrated success in hot desert regions; requires tailored solutions.

2.2. Performance Analysis

This section assesses the performance of semi-transparent photovoltaic windows (STPWs) across three critical dimensions essential for effective application in hot climates like Qatar: energy efficiency, thermal behavior, and visual comfort. These parameters are deeply interrelated, and their optimization is vital for achieving sustainable building integration in regions with high solar exposure and cooling demands.

The energy efficiency of STPWs depends on the photovoltaic material type, solar heat gain coefficient (SHGC), and sensitivity to ambient temperature. Recent research demonstrates that perovskite solar cells (PSCs) and hybrid organic-inorganic photovoltaics (HOPVs) offer power conversion efficiencies (PCEs) of up to 26% and 25%, respectively, whereas organic photovoltaics (OPVs) exhibit superior transparency levels—ranging between 30% and 70%—but deliver lower efficiencies, around 10% (Khalifeeh et al., 2021); (Chen et al., 2021). This ongoing trade-off between transparency and energy yield continues to pose a significant design challenge. In the context of Qatar’s hot desert climate, a balance can be achieved

by adopting configurations such as STPWs with a visible light transmittance (VLT) of 0.3 and a 60% window-to-wall ratio (WWR), which have been shown to optimize both daylight access and energy generation (Nsair et al., 2025).

Beyond energy production, thermal performance is a crucial factor in reducing air-conditioning loads. STPWs using cadmium telluride (CdTe) technology, for instance, provide both shading and thermal insulation. Alrashidi et al. (2022) demonstrated that CdTe-based glazing systems significantly lower solar heat gain and consequently reduce cooling energy demand. These materials are also well-suited for dusty environments, maintaining effective operation with minimal degradation, especially when enhanced by self-cleaning coatings that reduce dust accumulation (Uddin et al., 2023). Additional improvements are achieved by integrating photovoltaic-insulated glass units (PV-IGUs), which further enhance thermal resistance and reduce envelope heat transfer, as noted by (Qiu and Yang, 2020).

Visual comfort represents another key performance parameter, particularly in office spaces where glare and insufficient daylight can impact productivity and well-being. Daylighting simulations—using tools such as Radiance and Honeybee—combined with post-occupancy evaluations and glare analysis, are used to assess factors such as illuminance levels, daylight distribution, and discomfort glare. STPWs with moderate transmittance values (typically in the 20–40% range) can effectively provide natural light while limiting visual discomfort, especially when integrated with shading elements (Nsair et al., 2025).

The methodology for evaluating STPWs in hot climates typically involves a combination of energy simulations, thermal modelling, and daylighting analysis. As shown in Table 2, each component—energy performance, thermal behavior, and visual comfort—is assessed using dedicated tools and metrics. These include annual energy yield, cooling load reductions, surface temperature profiles, U-values, VLT, glare indices, and illuminance levels. The integration of these evaluation methods is essential to ensure that STPWs deliver measurable benefits in terms of electricity generation, thermal efficiency, and occupant satisfaction in high-temperature environments.

Table 2. Methodological Components for Evaluating STPWs in Hot Climates.

Analysis Component	Objective	Methods/Tools	Key Variables/Outputs	Relevance for Hot Climates
Energy Performance	Assess electricity generation & efficiency	Energy simulation (e.g., DesignBuilder), monitoring	Annual energy yield, conversion efficiency, shading impact	Maximizes renewable energy use under high solar radiation
Thermal Behaviour	Evaluate impact on cooling loads and envelope heat gain	Thermal modelling, CFD, on-site monitoring	Cooling load, U-values, surface temperatures	Reduces HVAC demand and heat stress
Visual Comfort	Ensure optimal daylighting and glare control	Daylighting simulations (Radiance, Honeybee), occupant surveys	VLT, glare indices (e.g., DGP), illuminance levels	Balances daylight access with visual well-being and glare mitigation

2.3. Challenges

Despite the strong potential of STPWs to enhance energy efficiency, thermal regulation, and daylighting in hot climates, several practical and economic challenges must be addressed to ensure their effective and sustainable implementation. One of the most pressing operational concerns in arid regions like Qatar is dust accumulation. Fine airborne particles settle on the surface of STPWs, gradually reducing light transmittance and degrading photovoltaic performance. The severity of this soiling effect depends on local variables such as dust type, wind speed, panel inclination, and rainfall frequency. Studies by the Qatar Environment and Energy Research Institute (QEERI, 2021) have contributed predictive maintenance models that optimize cleaning schedules, while emerging anti-soiling solutions—such as self-cleaning and anti-reflective coatings—are also being developed to enhance long-term efficiency in dusty climates (Syafiq et al., 2022).

Thermal stress presents another significant challenge. In desert environments where ambient temperatures are consistently high, photovoltaic performance declines by approximately 0.42% for every 1 °C increase in temperature (Peng et al., 2019). To counteract this effect, heat-resistant materials, spectrally selective coatings, and adaptive shading devices are increasingly being integrated to improve thermal resilience and preserve energy output. These solutions are especially important in double-glazed or PV-insulated glass configurations where passive cooling benefits can complement energy production.

From an economic perspective, the high initial capital costs of STPWs, coupled with relatively long payback periods, hinder widespread adoption—particularly in regions with subsidized electricity tariffs, such as Qatar. While STPWs offer considerable long-term benefits in reducing operational energy use and carbon emissions, the immediate financial incentives for developers and building owners remain limited (Abu-Rub et al., 2010). Pilot installations, however, have shown promise in identifying cost-saving strategies, such as integrating daylight-responsive lighting controls, which reduce both lighting electricity consumption and internal heat gains (Sun et al., 2018). Encouragingly, optimized STPW systems have achieved energy payback times as short as 3 to 3.2 years by reducing solar heat gain by up to 65% (Barman, 2022), demonstrating their long-term economic viability when coupled with smart design and control strategies. Targeted policy interventions—such as financial incentives, locally-adapted technical guidelines, and performance-based subsidies—are crucial to accelerate market penetration.

Another complex challenge lies in achieving an optimal balance between daylight transparency, solar control, and visual comfort. Overly transparent systems may cause glare and thermal discomfort, while overly tinted ones can reduce daylight availability, increasing artificial lighting demand. Effective STPW performance in hot climates depends on context-sensitive variables such as solar angle, façade orientation, and urban morphology. Case studies from Qatar, Saudi Arabia, the UAE, Algeria, and China emphasize the need for climate-responsive STPW designs. For example, semi-transparent perovskite modules with a 60% window-to-wall ratio and 0.3 visible light transmittance in Qatar have demonstrated an effective compromise between glare control, natural light distribution, and cooling load mitigation (Mesloub et al., 2020, Nsair et al., 2025). Conversely, thin-film amorphous silicon modules may require the integration of external shading elements to avoid excessive glare and overheating.

The key operational challenges and their mitigation strategies are summarized in Table 3, which outlines the technical and environmental barriers—dust accumulation, thermal stress, high upfront costs, and the complexity of balancing daylight and heat control—and identifies corresponding solutions such as predictive maintenance, adaptive materials, financial mechanisms, and context-sensitive design strategies. These considerations reinforce the importance of integrated design approaches tailored to hot climate contexts, ensuring that the full sustainability potential of STPWs can be realized in practice.

Table 3. Operational Challenges and Mitigation Strategies for STPWs in Hot Climates.

Operational Challenge	Description	Impact	Mitigation Strategies
Dust Accumulation	Fine particles reduce light transmittance and energy output on STPW surfaces.	Decreased efficiency and reduced daylight penetration.	Predictive cleaning schedules; anti-soiling/self-cleaning coatings.
Thermal Stress	High ambient temperatures reduce PV efficiency (~0.42% loss per 1°C increase).	Lower power output and reduced system performance.	Use of heat-resistant materials, advanced glazing, adaptive shading.
High Upfront Costs	Installation costs are significant; payback periods are long in subsidized grids.	Limits adoption despite long-term savings.	Pilot projects; daylight-linked lighting controls; financial incentives and subsidies.
Balancing Transparency & Glare	Finding the right balance of daylight, heat control, and comfort is complex	Poor balance can increase glare or cooling energy use.	Climate-specific STPW design; optimal WWR/VLT; shading and façade orientation.

2.4. Case Study: Msheireb Downtown Doha—A Model for Sustainable Urban Regeneration and Potential for STPW Integration

The rapid urbanization of Doha since the mid-20th century, largely driven by hydrocarbon wealth, led to a departure from traditional compact urban patterns toward low-density, car-oriented suburbs, resulting in the decline of the historic urban core (Amleh, 2023). In response, Msheireb Downtown Doha was conceived as the world’s first large-scale sustainable downtown regeneration project. Led by Msheireb Properties, a Qatar Foundation initiative, the project aims to revive the old commercial center of Doha through a mixed-use development rooted in sustainability and Qatari architectural identity (Al

Fadala, 2018).

Spanning 31 hectares with an investment of over QAR 20 billion, the district is strategically located near key landmarks such as Souq Waqif and the Amiri Diwan. It includes more than 100 buildings ranging from 3 to 30 storeys, comprising residential, commercial, civic, and cultural functions. The masterplan, see Figure 2, is structured around five interconnected quarters—each designed to foster livability, community, and walkability while maintaining architectural coherence and environmental performance (Msheireb.com, Eman Saleh AL Fadala, 2018).

A core strength of the project lies in its comprehensive sustainability strategy, combining passive design techniques with advanced building technologies. The urban layout promotes natural ventilation and minimizes solar heat gain through optimal orientation, dense street shading, high thermal mass, and reflective materials. High-performance glazing is widely used to reduce cooling loads, presenting an ideal foundation for integrating STPWs that offer both daylighting and energy generation benefits.

The renewable energy infrastructure includes 6,400 rooftop photovoltaic panels and 1,400 solar thermal collectors, which contribute to a 32% reduction in total energy demand and meet 75% of hot water needs (powergreen.com). These measures demonstrate the project's strong alignment with Qatar National Vision 2030 and its commitment to reducing carbon emissions and enhancing energy resilience.

Although STPWs have not yet been deployed in Msheireb, the district's architectural typologies—characterized by generous window-to-wall ratios, consistent façade geometry, and integrated shading elements—provide a highly compatible context for future STPW integration. STPWs could complement the district's sustainability goals by reducing glare, offsetting electricity use, and enhancing visual comfort in office and civic buildings. The orientation and density of buildings offer controlled solar exposure, making them ideal candidates for climate-responsive STPW deployment, particularly on east- and west-facing façades where shading and solar control are most critical.

Further reinforcing its leadership, Msheireb Downtown Doha boasts one of the highest concentrations of LEED-certified buildings worldwide, with most targeting Gold and Platinum levels. This commitment to green building performance makes it not only a benchmark for sustainable urbanism but also a fertile context for integrating next-generation solar façade technologies like STPWs.

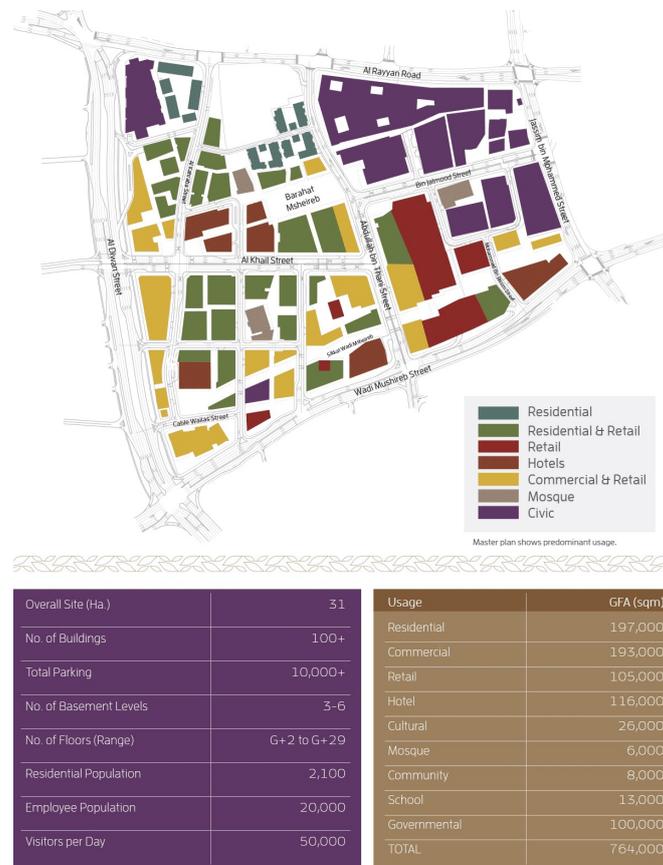


Figure 2. Msheireb Downtown Masterplan with Predominant Usage (Msheireb.com).

3. Framework Development and Discussion

This section presents a conceptual framework for integrating semi-transparent photovoltaic windows (STPWs) into sustainable urban design in hot climates, drawing on the earlier methodology that combined systematic literature review, multi-criteria analysis, and case study synthesis. The framework highlights the interplay between architectural strategies, energy performance, and urban sustainability, offering practical and policy-oriented pathways for implementing STPWs in high-temperature regions like the Gulf.

The literature review identified four key thematic domains, see [Figure 3](#), emphasizing STPWs' dual role in providing daylight and generating electricity. When properly configured, STPWs significantly reduce both lighting and cooling energy demands, making them well-suited for hot, sunny environments.

Performance optimization depends on responsive integration to climate variables. Critical parameters—visible light transmittance (VLT), solar heat gain coefficient (SHGC), and power conversion efficiency (PCE)—must be tailored to orientation, glazing ratios, and solar angles. Studies from climates similar to Qatar show that STPW effectiveness varies seasonally, with higher VLT and deeper shading proving advantageous in summer to reduce glare and cooling loads.

External shading elements—such as fixed overhangs, louvers, and biomimetic forms—further enhance STPW performance by mitigating solar heat gain without compromising daylight access. These findings underscore the importance of holistic façade design and seasonal adaptability in maximizing the benefits of STPWs in hot climates.

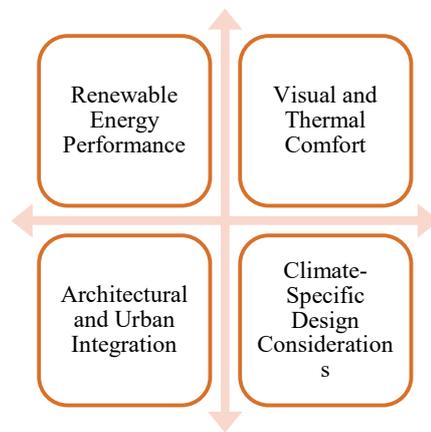


Figure 3. Core Domains of STPWs in Advancing Sustainable Urban Development.

3.1. Architectural and Urban Integration Strategies

Effective integration of STPWs requires a holistic design approach. Beyond individual window units, STPWs must be coordinated with passive design strategies, façade orientation, and interior layouts to optimize energy efficiency and visual comfort. At the urban scale, the framework stresses contextual integration. Elements such as street orientation, urban density, building heights, and mutual shading significantly impact solar access and, consequently, the effectiveness of both STPWs and rooftop PV systems. Msheireb Downtown Doha exemplifies how these technologies can work together in a dense, hot-climate district to improve building and urban performance.

Msheireb employs 6,400 rooftop PV panels (1.4 MW) generating approximately 2.45 GWh/year, based on standard performance estimation using the equation:

$$\begin{aligned} \text{Annual Output} &= \text{Installed Capacity} \times \text{Avg. Sunlight Hours} \times 365 \times \text{Performance Ratio} \\ &= 1,400\text{Kw} \times 6\text{h/day} \times 365 \text{ days/year} \times 0.80 = 2,452,800 \text{ kWh/year} \end{aligned}$$

The performance ratio of 0.80 reflects typical system efficiencies in hot climates with good system design and moderate soiling ((IEA), 2020). Based on an estimated annual consumption of 2.5–3.0 GWh for medium-sized office buildings in hot climates, this output can offset 75–85% of total operational energy use, and is sufficient to supply 800–1,000 average homes/year, depending on local usage patterns ((IEA), 2020). Additionally, the rooftop PV array contributes to passive cooling by reducing surface temperatures by 5–10°C, resulting in 10–16% cooling load savings (Koç and Maçka Kalfa, 2021). However, in dense urban environments, the limited availability of roof space poses constraints on large-scale deployment.

STPWs address this by converting façades into active energy surfaces. Though less efficient per m²

than rooftop PVs, they provide the added benefits of glare control, natural lighting, and passive cooling. When tailored to façade orientation and window-to-wall ratios (WWR), STPWs can reduce cooling loads by up to 15% while enhancing indoor comfort, as demonstrated in recent studies incorporating passive radiative cooling coatings (Wang et al., 2024). This makes them especially suitable for mid-rise buildings like those in Msheireb, where façades receive consistent sun exposure without disrupting urban aesthetics. Table 4 below compares the roles of rooftop PV systems and STPWs in Msheireb Downtown Doha.

Table 4. Comparative Analysis of Rooftop PV Systems and STPWs in Msheireb.

Aspect	Rooftop PV Systems	STPWs
Installation Location	Roof (flat or tilted)	Vertical façades
Energy Generation	~2.45 GWh/year (1.4 MW installed)	Moderate; depends on VLT, SHGC, and PCE
Cooling Load Reduction	10–16% via roof shading	Up to 15% via glare control and solar gain reduction
Visual & Lighting Impact	No direct impact	Improves natural light and occupant comfort
Space Requirement	Needs unshaded roof area	Utilizes existing façades—ideal for mid-rise structures
Urban Suitability	Limited in compact urban blocks	High compatibility in dense, vertical developments
Urban Heat Island Mitigation	Reduces rooftop heat gain	Indirectly lowers ambient heat through reduced cooling demand
Limitations	Structural load, limited roof space	Lower efficiency per m ² ; needs careful orientation/design

Together, rooftop PV and STPWs form a complementary system. While PV panels offer substantial energy generation and thermal buffering, STPWs enhance façade performance by combining electricity generation with visual and thermal comfort. This dual approach aligns architectural innovation with urban sustainability—particularly in hot, compact environments like Doha.

3.2. Policy, Technology, and Scalability Considerations

The proposed framework also accounts for policy, technological maturity, and scalability challenges critical to the widespread adoption of STPWs. While semi-transparent photovoltaic technologies—particularly perovskite-based variants—are advancing rapidly, their deployment in urban contexts requires enabling regulatory environments.

To facilitate adoption, the framework recommends integrating STPW performance criteria into regional sustainability assessment systems like GSAS and LEED, tailored to hot-climate contexts. Inclusion in these rating systems can incentivize developers to adopt STPWs through credits linked to daylighting, energy efficiency, and glare control.

Scalability also depends on supportive economic mechanisms. Cost-benefit analyses, lifecycle assessments, and financial incentives for net-zero buildings are essential for motivating investment. In addition, fostering local R&D partnerships can enhance STPW durability and adapt system configurations to regional climatic and construction conditions.

By aligning technology readiness with supportive policy and market structures, the framework outlines a pathway for mainstreaming STPWs as integral components of sustainable urban development in hot climates.

3.3. Proposed Framework Overview

The proposed framework integrates four interlinked layers: technological, architectural, urban design, and policy, see Figure 4. Each layer addresses a specific scale of STPW deployment. This multi-scalar framework supports context-sensitive STPW adoption in hot climates, offering a roadmap for architects, urban planners, and policymakers to balance energy performance, visual comfort, and urban sustainability.

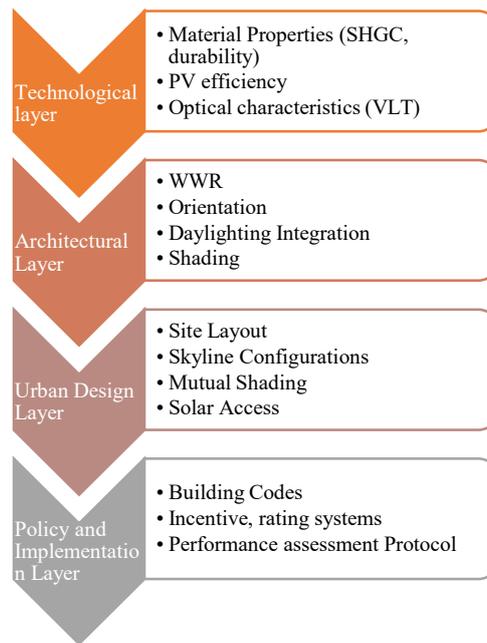


Figure 4. The proposed Framework.

4. Case Study Application: Msheireb Downtown Doha

An increasing trend towards incorporating people, places, ecology, culture, and climate into built environment sustainability initiatives is taking shape, to improve people's health and well-being. In this context, this review has scrutinized the conceptualization and improvement of neighborhood social sustainability. By directing attention towards the neighborhood level, this research amalgamates an extensive array of scholarly works, providing a logical outline valuable for subsequent investigations as well as pragmatic implementations.

The study outlines indicators interrelated and essential for understanding the social sustainability of Neighborhoods. These factors, which encompass equity in society, participation, inclusion, sense of belonging, interaction, sense of place, infrastructure, community satisfaction, safety, and security collectively define the characteristics of a viable community. The research argues that social sustainability goes beyond physical infrastructure and is strongly influenced by the experiences of individuals reflected in the proposed framework that incorporates physical and non-physical components. Discussion surrounding social sustainability holds more importance for small-scale urban environments, such as urban neighborhoods.

This research adds to the debate on the social sustainability of Neighborhoods., establishing a strong basis for future exploration. It addresses a significant gap in existing knowledge on social sustainability, particularly within neighborhood studies. The findings contribute to the advancement of knowledge and practice by providing a clearer understanding and improvement of the conceptualization and enhancement of neighborhood social sustainability. This study offers a comprehensive examination of how the socio-spatial characteristics of Neighborhoods influence social sustainability. By employing this approach, scholars may develop an exhaustive knowledge of societal sustainability. This aids in determining the Neighborhoods that exhibit higher levels of social sustainability and explains their characteristics.

The literature demonstrates that social sustainability is an evolving notion that has advanced from traditional, measurable features to intangible and adaptable dimensions over time. Static and cross-sectional research approaches may be insufficient in capturing the complexities of social sustainability and its various components. Hence, this study might be expanded by employing a longitudinal study to investigate the dynamics and progression of changes in social sustainability over time. For evaluating the connection between design quality and social sustainability, it is recommended that future research adopts a mixed-methods approach. By combining qualitative research methods with quantitative data analysis, it is possible to gain a deeper understanding of the reasons, methods, and circumstances in which design quality might improve people's perceptions of social sustainability and their overall quality of life.

Given the contextual nature of social sustainability, it would be useful to examine the factors that contribute to residents' satisfaction with their living environments and the social sustainability of a specific geographical and cultural neighborhood. This would allow for a comprehensive set of methods and solutions applicable to enhance the social sustainability characteristics of an urban Neighborhood.

Msheireb Downtown Doha demonstrates a real-world application of the proposed four-layer framework for integrating STPWs in hot climate cities. At the technological level, the district uses high-performance glazing systems, adaptable to future STPW integration. The architectural layer incorporates passive design features such as optimized window-to-wall ratios, Mashrabiya-inspired shading, and enhanced daylight strategies. At the urban design level, Msheireb's compact blocks, varied building heights, and solar-responsive layouts reduce mutual shading while maximizing solar access and microclimate comfort. On the policy level, the development meets QSAS and LEED standards, supported by government incentives and ongoing performance monitoring.

A summary of Msheireb's alignment with each layer of the framework is provided in [Figure 5](#) illustrating its relevance as a real-world case study for multiscale sustainable design and the practical potential of STPW deployment in hot climates.

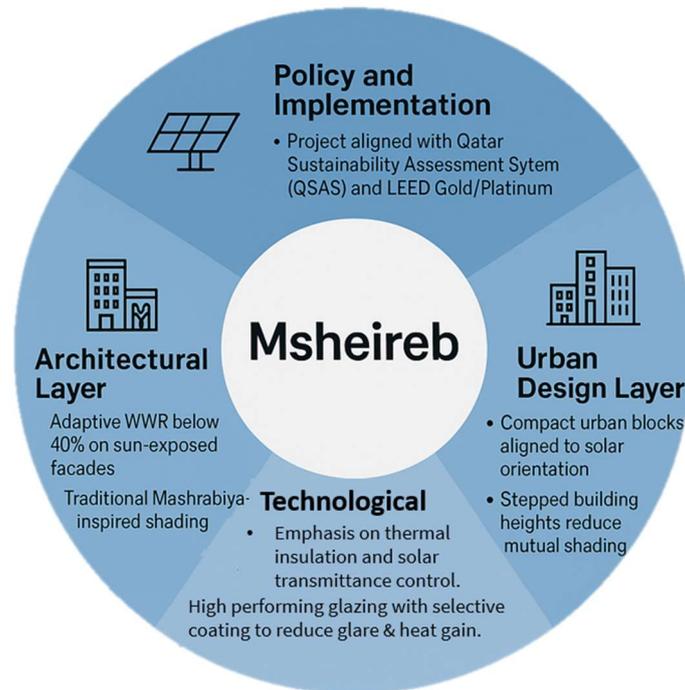


Figure 5. The alignment of the proposed framework with Msheireb case study.

The district also integrates rooftop PV systems effectively. A total of 6,400 solar panels with a 1.4 MW capacity generate about 2.45 GWh annually—offsetting 75–85% of the energy use in a typical medium-sized office building. Additionally, the panels reduce rooftop temperatures by 5–10°C, contributing to cooling load reductions of 10–16%. While rooftop systems offer substantial energy and thermal benefits, their performance is limited by roof area in dense settings.

STPWs complement these systems by transforming façades into energy-generating surfaces. Though less efficient per square meter due to transparency, STPWs offer dual benefits—generating electricity while enhancing daylight and visual comfort. With thoughtful integration of orientation, shading, and design compatibility, they can reduce cooling demand by up to 15%. This synergy makes STPWs especially suitable for Msheireb's mid-rise typologies, where façades receive strong solar exposure and space efficiency is essential.

In summary, Msheireb Downtown Doha illustrates how combining rooftop PVs with STPWs provides a layered, multifunctional strategy for energy efficiency, thermal comfort, and urban sustainability in hot climates.

5. Conclusion and Future Work

This study presents a multi-layered framework for integrating semi-transparent photovoltaic windows (STPWs) in hot-climate cities, with Msheireb Downtown Doha serving as a practical case. While rooftop

PVs demonstrate strong energy generation and cooling benefits through roof shading, STPWs complement this by providing daylighting, glare control, and additional energy production from the vertical building envelope.

Together, these technologies offer a synergistic approach to sustainable urban design, particularly suited for dense, high-temperature environments. Rooftop PVs are ideal for buildings with sufficient roof area, while STPWs provide added value in mid-rise urban blocks where façades are key energy-active surfaces. Combined, they can reduce mechanical cooling demand, enhance visual comfort, and support Qatar's renewable energy and sustainability targets.

This integrated approach not only advances technical and environmental objectives but also addresses social sustainability by enhancing occupant comfort and promoting equitable access to clean energy solutions in urban settings.

Future research priorities include:

- **Design optimization** of integrated STPW systems at both building and district scales, employing climate-responsive simulations to maximize energy efficiency and occupant comfort.
- **Economic and lifecycle analysis** to evaluate cost-effectiveness, material durability, and maintenance requirements, ensuring the long-term viability of STPWs in harsh climates.
- Development of **smart façade strategies** that incorporate adaptive shading, dynamic transparency, and energy management to enhance building performance and user well-being.
- **Urban-scale modeling** to assess cumulative impacts on urban heat island effects and electricity grid demands, supporting sustainable city planning.
- Implementation of **pilot projects and validation studies** in real-world contexts such as Msheireb Downtown Doha, aimed at calibrating simulation models and generating practical design guidelines for widespread adoption.

This integrated approach supports the creation of energy-positive, resilient urban environments, combining architectural innovation with climate-responsive photovoltaic technologies.

Conflict of Interest Statement

The authors have no competing interests to state.

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