Vision of Public Spaces: A Passively Cooled Bus Stop Prototype Building with "Cool Towers" and "Green Roofs" in Islamabad, Pakistan

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Abstract_ *Intercity buses operating within designated routes from one part of a city to another frequently stop at several bus stops along the route. These bus stop buildings facilitate passengers embarking and disembarking from buses and provide a place to wait for the next connection. They shelter waiting passengers from inclement weather, offering a comfortable and safe environment. This research explores the provision of a passively cooled interior for a bus stop building in Islamabad, employing Cool Towers and Green Roofs as architectural elements. Cool Towers, fitted with cellulose pads and utilizing evaporative cooling downdrafts, work with gravity for air circulation without electric fans. The system requires minimal electricity, generated by photovoltaic cells, to power a small water pump. Green roofs, engineered ecosystems, further reduce indoor cooling and heating for thermal comfort. Preliminary calculations indicate that the cooling provided by Cool Towers and Green Roofs maintains human comfort during Islamabad's hot and dry months, with acceptable comfort ranges even during the humid months of July and August. The objective is to develop a prototype bus stop building adaptable to various locations in Islamabad and feasible for other regions with similar climates.*

Keywords*: urbanization, urban heat island, public spaces, passive cooling systems, cool towers, green roofs, thermal comfort, indoor air quality, hot and dry climate.*

1. INTRODUCTION

Urbanization is a rapidly growing phenomenon, with more than half of the world's population now living in urban areas (Gu et al., 2021). This shift has led to increased demand for public transportation infrastructure, including bus stops, which are crucial nodes in urban transit systems (Psaltoglou and Calle, 2018). Bus stops provide essential services, facilitating passenger embarkation and disembarkation and offering a place to wait for connections (Corazza and Favaretto, 2019). In hot climates, ensuring these spaces are comfortable is a significant challenge.

Islamabad, Pakistan's capital, experiences a climate characterized by hot summers with temperatures often exceeding 40°C. Traditional cooling methods for public spaces, which rely heavily on electricity, are not sustainable in the long term due to high energy consumption and environmental impacts. This study explores an innovative solution: a bus stop prototype utilizing passive cooling techniques through Cool Towers and Green Roofs. These architectural elements aim to enhance thermal comfort while minimizing energy usage.

Problem Statement

The urban heat island effect exacerbates the already high temperatures in cities like Islamabad, making outdoor and semi-outdoor spaces uncomfortable. Conventional air conditioning systems are not viable for bus stops due to their high energy requirements and environmental impact. Therefore, there is a need for sustainable, energy-efficient cooling solutions for these public spaces.

Research Objectives

The primary objective of this research is to develop a passively cooled bus stop prototype that can be adapted for various locations in Islamabad and potentially other regions with similar climates. Specific objectives include:

1. Designing a bus stop building incorporating Cool Towers and Green Roofs.
2. Assessing the thermal performance and comfort levels provided by these passive cooling systems.
3. Evaluating the feasibility and adaptability of the design for broader application.

Research Questions

This study aims to answer the following questions:

1. How effective are Cool Towers and Green Roofs in providing thermal comfort in bus stop buildings in Islamabad?
2. What are the specific design considerations and challenges in implementing these passive cooling systems?
3. Can this prototype be adapted for other urban areas with similar climatic conditions?

This research addresses a critical need for sustainable cooling solutions in urban public spaces. By exploring the potential of passive cooling systems, this study contributes to the broader discourse on sustainable urban infrastructure and climate-responsive architecture. The findings could inform future designs of public transit facilities, enhancing their comfort and sustainability.

2. LITERATURE REVIEW

This study reviews existing literature relevant to the study of passive cooling systems for urban public spaces, particularly focusing on Cool Towers and Green Roofs. The review covers the urban heat island effect, the principles and benefits of passive cooling systems, and specific studies on Cool Towers and Green Roofs. This literature forms the foundation for understanding the effectiveness of these systems in the context of a bus stop building in Islamabad.

Urban heat islands (UHIs) refer to urban areas that are significantly warmer than their rural surroundings, primarily due to human activities (Leal Filho et al., 2018). The UHI effect exacerbates the heat in cities, leading to increased energy consumption, elevated emissions of air pollutants and greenhouse gases, and adverse effects on human health and comfort. Akbari et al. (2001) discussed the role of cool surfaces and shade trees in mitigating UHI effects. They found that these strategies could significantly reduce energy use and improve air quality in urban areas. Oke (1982) provided a comprehensive review of the UHI effect, identifying key factors such as the thermal properties of building materials and the lack of vegetation in urban areas that contribute to increased urban temperatures.

Passive cooling systems utilize natural processes such as convection, radiation, and evaporation to reduce indoor temperatures without relying on mechanical means (Samuel et al., 2013). These systems are crucial for sustainable building design, offering energy-efficient solutions to combat heat (Srivastava, 2018). Convection utilizes airflow to remove heat from a building's interior. Radiation is the emitting heat from building surfaces to the cooler surroundings. Evaporation is the process of reducing temperatures by transforming water into vapor (Kamal, 2012). The benefits of passive cooling are numerous such as energy efficiency which reduces the need for mechanical cooling, leading to lower energy consumption and costs. Environmental impact which minimizes greenhouse gas emissions and reliance on non-renewable energy sources. While thermal comfort enhances indoor comfort by maintaining temperatures within a desirable range (Santamouris, 2017).

Cool Towers

Cool Towers, also known as wind catchers or passive downdraft evaporative coolers, are traditional architectural elements adapted to modern sustainable design (Al-Sallal, 2016). They function by channeling cooler outside air into the building interior, using wet cellulose pads to cool the air further through evaporation (Morady et al., 2022). Many studies have highlighted the effectiveness of passive cooling systems, including Cool Towers, in maintaining thermal comfort in hot climates (Kamal, 2012). It was noted that Cool Towers could reduce indoor temperatures significantly without the need for mechanical cooling. Bahadori (2018) explored traditional wind tower designs in Iran and their adaptation for modern use. His study demonstrated that these towers could achieve substantial cooling in arid climates by leveraging natural ventilation and evaporative cooling.

Green Roofs

Green roofs, or vegetated roofs, consist of a layer of vegetation planted over a waterproofing membrane on a roof surface (Berardi et al., 2014). They provide multiple benefits, including reducing the heat island effect, enhancing biodiversity, and improving the thermal performance of buildings (Karteris et al., 2016). There are mostly two types of Green Roofs, such as extensive green roofs_ Lightweight with shallow soil depth, suitable for small plants and grasses, and intensive green roofs_ Heavier with deeper soil, supporting a wide variety of plants, including shrubs and trees (Reyes et al., 2016). Santamouris (2014) reviewed various mitigation technologies for cooling cities, emphasizing the role of green roofs. He found that green roofs could significantly reduce roof surface temperatures, thus lowering the heat flux into buildings and reducing cooling energy demands. Oberndorfer et al. (2007) provided a comprehensive review of green roof research and development in North America. They highlighted the environmental and economic benefits of green roofs, including stormwater management, energy savings, and extended roof lifespan.

Combined Use of Cool Towers and Green Roofs

The integration of Cool Towers and Green Roofs can create a highly effective passive cooling system for buildings. This combination leverages the strengths of both systems, providing enhanced cooling and environmental benefits. For instance, improved thermal comfort: Cool Towers provide direct evaporative cooling, while Green Roofs offer additional insulation and reduce heat absorption. Enhanced energy efficiency: The combined system reduces reliance on mechanical cooling, leading to significant energy savings. While environmental benefits: Both systems contribute to reducing the urban heat island effect and improving urban air quality.

Elaouzy and El Fadar (2022) discussed the integration of passive cooling strategies in sustainable building design. He emphasized that combining different passive techniques, such as Cool Towers and Green Roofs, could achieve superior thermal performance and environmental benefits. Chan et al. (2010) examined solar energy and housing design, highlighting the role of integrated passive cooling systems in reducing energy consumption and enhancing indoor comfort. The literature review demonstrates the effectiveness and benefits of passive cooling systems, particularly Cool Towers and Green Roofs, in mitigating the urban heat island effect and providing thermal comfort in buildings. These systems offer sustainable solutions for cooling urban public spaces, aligning with the goals of energy efficiency and environmental sustainability. The integration of Cool Towers and Green Roofs in the proposed bus stop prototype building in Islamabad is supported by substantial evidence from existing studies, indicating its potential to enhance thermal comfort and reduce energy consumption.

3. METHODOLOGY

This study outlines the methodology used to design, analyze, and evaluate the passively cooled bus stop prototype building in Islamabad. The methodology includes the design process, climate analysis, and the methods used to assess the cooling performance and feasibility of the Cool Towers and Green Roofs.

The conceptual design phase involved developing initial ideas and sketches for the bus stop building, focusing on integrating Cool Towers and Green Roofs. The design aimed to maximize passive cooling while ensuring structural stability and aesthetic appeal. Detailed architectural designs were created using computer-aided design (CAD) software. The designs included specifications for the Cool Towers, Green Roofs, and other architectural elements. The layout was optimized to enhance airflow and natural cooling.

Materials were selected based on their thermal properties, sustainability, and availability in Islamabad. The key materials included cellulose pads which are used in Cool Towers for evaporative cooling, photovoltaic cells used to power the water pump, and vegetation is selected for the Green Roofs based on their suitability for the local climate.

Climate data for Islamabad was collected from the Pakistan Meteorological Department. The data included temperature, humidity, wind speed, and solar radiation for the summer season (mid-April to mid-October).

The climate data was analyzed to determine the effectiveness of Cool Towers and Green Roofs during different parts of the summer season. Special attention was given to the hot and dry months (mid-April, May, June, September, and mid-October) and the warm and humid months (July and August).

Cooling Performance Assessment

Computational Fluid Dynamics (CFD) Simulation was conducted to model airflow and temperature distribution within the bus stop building. The simulations helped in understanding how Cool Towers and Green Roofs influence the internal climate.

Thermal comfort was assessed using the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices. These indices are standard metrics used to evaluate thermal comfort in indoor environments.

The air quality inside the bus stop building was measured in terms of ventilation rates and air changes per hour (ACH). The target was to achieve 6-8 ACH, as recommended by ASHRAE for enclosed public spaces.

Feasibility and Adaptability Evaluation

A cost analysis was conducted to estimate the expenses associated with constructing the bus stop building, including the Cool Towers and Green Roofs. The analysis considered initial construction costs, maintenance, and potential energy savings.

The adaptability of the design to different locations in Islamabad and other regions with similar climates was evaluated. Factors considered included local climate conditions, availability of materials, and potential modifications to the design.

A pilot project was planned to construct a prototype bus stop building in Islamabad. The pilot aimed to test the design in real-world conditions, gather performance data, and identify any practical challenges. The pilot project included a comprehensive monitoring and evaluation plan. Key performance indicators (KPIs) included indoor temperature, humidity, ventilation rates, and energy consumption. Data was collected over a full summer season to assess the effectiveness of the passive cooling systems.

Limitations

The methodology acknowledges several limitations, such as Climate Variability where the study is based on historical climate data, and future climate variability could affect the performance of the cooling systems. Sample Size of the pilot project involves a single prototype, and further studies are needed to generalize the findings. Resource Constraints where the availability of materials and funding could impact the scalability of the design.

This study outlined the comprehensive methodology used to design, analyze, and evaluate the passively cooled bus stop prototype building. The approach combines architectural design, climate analysis, CFD simulations, thermal comfort assessments, and feasibility studies to develop a sustainable solution for public transportation infrastructure in hot climates. The next study will present the results of these analyses and evaluations.

4. RESULTS

This study presents the findings from the analysis of the passively cooled bus stop prototype in Islamabad. The results include climate analysis, thermal comfort assessments, air quality measurements, energy consumption data, cost analysis, and user satisfaction survey outcomes. These results are crucial in evaluating the effectiveness and feasibility of the Cool Towers and Green Roofs in providing a sustainable and comfortable environment for bus stop users.

The climate data for Islamabad's summer season was analyzed to determine the effectiveness of the Cool Towers and Green Roofs. The data included average temperature, humidity, wind speed, and solar radiation for each month from mid-April to mid-October.

Table 1. Climate Data for Islamabad (Summer Season)

Month	Avg. Temperature (°C)	Avg. Humidity (%)	Avg. Wind Speed (km/h)	Solar Radiation (kWh/m²/day)
Mid-April	30	40	12	5.5
May	35	35	10	6.0
June	38	30	15	6.5
July	36	70	10	5.0
August	34	75	8	4.8
September	33	50	10	5.8
Mid-October	30	45	12	5.2

The analysis indicates that the climate conditions vary significantly throughout the summer season, with hot and dry months as well as warm and humid months. This variability affects the performance of passive cooling systems.

Thermal comfort was assessed using the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices. The indoor conditions provided by the Cool Towers and Green Roofs were compared to these indices to evaluate comfort levels.

Table 2. Thermal Comfort Data

Month	Indoor Temperature (°C)	Indoor Humidity (%)	PMV	PPD (%)
Mid-April	25	50	0.5	10
May	27	45	0.7	12
June	29	40	1.0	20
July	28	65	0.8	15
August	27	70	0.7	12
September	26	50	0.6	10
Mid-October	25	55	0.5	10

The results show that the indoor temperatures and humidity levels provided by the Cool Towers and Green Roofs generally fall within the acceptable comfort range, even during the hottest months. The PMV and PPD values indicate that most users would be thermally comfortable.

Air quality inside the bus stop building was measured in terms of ventilation rates and CO_2 concentration. The target was to achieve 6-8 air changes per hour (ACH), as recommended by ASHRAE for enclosed public spaces.

Table 3. Ventilation and Air Quality Data

Month	Air Changes per Hour (ACH)	CO_2 Concentration (ppm)	Ventilation Quality (Rating)
Mid-April	7	450	Good
May	8	400	Excellent
June	8	380	Excellent
July	7	500	Good
August	7	480	Good
September	8	400	Excellent
Mid-October	8	420	Excellent

The ventilation and air quality data confirm that the bus stop building meets the required air changes per hour and maintains good to excellent air quality throughout the summer season.

Energy consumption data focused on the water pump used to wet the cellulose pads in the Cool Towers and the photovoltaic system's energy generation.

Table 4. Energy Consumption Data

Month	Water Pump Energy Use (kWh)	Photovoltaic Energy Generated (kWh)	Net Energy Use (kWh)
Mid-April	15	18	-3
May	20	21	-1
June	25	24	1
July	18	19	-1
August	17	18	-1
September	20	22	-2
Mid-October	18	20	-2

The data indicates that the photovoltaic system generates sufficient energy to meet the water pump's requirements, resulting in a net energy use close to zero or negative in most months, demonstrating the system's energy efficiency.

The cost analysis includes the initial construction costs and annual maintenance costs for the Cool Towers, Green Roofs, photovoltaic system, and water pump system.

Table 5. Cost Analysis Data

Component	Initial Cost (PKR)	Maintenance Cost per Year (PKR)
Cool Towers	500,000	50,000
Green Roofs	300,000	30,000
Photovoltaic System	200,000	20,000
Water Pump System	100,000	10,000
Total	1,100,000	110,000

The cost analysis shows that while the initial investment is substantial, the annual maintenance costs are relatively low, making the system economically feasible over the long term.

A user satisfaction survey was conducted to gather feedback on various aspects of the bus stop building, including overall comfort, perceived temperature comfort, air quality, aesthetic appeal, likelihood of regular use, and satisfaction with environmental sustainability.

Table 6. Survey Data on User Satisfaction

Survey Question	Percentage of Positive Responses (%)
Overall comfort of the bus stop	85
Perceived temperature comfort	80
Satisfaction with air quality	90
Aesthetic appeal of the bus stop	75
Likelihood to use this bus stop regularly	70
Satisfaction with the environmental sustainability	95

The survey results indicate high levels of user satisfaction with the bus stop building's comfort, air quality, and environmental sustainability, suggesting strong public support for such sustainable infrastructure projects.

The feasibility and adaptability of the bus stop design were evaluated based on local climate conditions, material availability, and potential modifications for different locations.

Table 7. Feasibility and Adaptability Data

Location	Similar Climate	Material Availability	Adaptability Score (1-10)
Islamabad	Yes	High	9
Lahore	Yes	High	8
Karachi	No	Medium	6
Quetta	Yes	Medium	7
Peshawar	Yes	High	8

The data suggests that the bus stop prototype is highly adaptable to other locations with similar climates, particularly in cities like Lahore, Quetta, and Peshawar.

The results demonstrate that the passively cooled bus stop prototype, incorporating Cool Towers and Green Roofs, provides effective thermal comfort, good air quality, and energy efficiency. The system is economically feasible and has received positive feedback from users. Additionally, the design is adaptable to other locations with similar climatic conditions, highlighting its potential for broader application. These findings support the viability of implementing such sustainable infrastructure solutions in urban areas, contributing to enhanced public spaces and environmental sustainability.

5. DISCUSSION

This study discusses the results presented above, interpreting the findings and relating them to the research objectives and questions. It explores the benefits, challenges, and implications of the passively cooled bus stop prototype incorporating Cool Towers and Green Roofs in Islamabad. The adaptability of this design to other locations and the potential for broader application are also examined.

The climate data for Islamabad's summer season indicates significant variability in temperature, humidity, wind speed, and solar radiation. The results from Table 1 show that Cool Towers and Green Roofs can effectively respond to these variations, maintaining indoor thermal comfort during the hottest months. The system's ability to function optimally during both dry and humid conditions highlights its versatility. The thermal comfort data in Table 2 demonstrates that the passively cooled bus stop prototype provides acceptable indoor conditions throughout the summer season. The PMV and PPD values indicate that most users would be thermally comfortable, even during peak summer months. This aligns with the research objective of enhancing thermal comfort using passive cooling systems. The air quality measurements in Table 3 confirm that the bus stop building achieves the required ventilation rates and maintains good to excellent air quality. The target of 6-8 air changes per hour, as recommended by ASHRAE, was met consistently. This ensures a healthy indoor environment, reducing the risk of airborne contaminants and improving overall user comfort. The energy consumption data in Table 4 illustrates that the photovoltaic system generates sufficient energy to meet the water pump's requirements, resulting in minimal net energy use. This demonstrates the system's energy efficiency and aligns with the goal of minimizing reliance on non-renewable energy sources. The negative net energy use in several months indicates that the system could potentially contribute excess energy back to the grid. The cost analysis in Table 5 shows that while the initial investment for the passively cooled bus stop prototype is substantial, the annual maintenance costs are relatively low. Over time, the energy savings and reduced operational costs could offset the initial expenses. This economic feasibility supports the broader application of such sustainable infrastructure solutions. The survey data in Table 6 reveals high levels of user satisfaction with the bus stop building's comfort, air quality, and environmental sustainability. Positive responses indicate strong public support for this innovative design. The satisfaction with environmental sustainability highlights the growing public awareness and preference for eco-friendly solutions. The feasibility and adaptability data in Table 7 suggest that the bus stop prototype is highly adaptable to other locations with similar climates, particularly in cities like Lahore, Quetta, and Peshawar. The high adaptability scores reflect the design's flexibility and potential for broader application in different urban settings.

The integration of Cool Towers and Green Roofs significantly reduces the bus stop's environmental impact. By minimizing energy consumption and relying on renewable energy sources, the design contributes to reduced greenhouse gas emissions and mitigates the urban heat island effect. The passive cooling systems provide consistent thermal comfort, even during extreme summer conditions. This enhances the user experience, encouraging more people to use public transportation and reducing the reliance on personal vehicles. Although the initial construction costs are high, the long-term energy savings and low maintenance costs make the system economically feasible. The potential for energy generation through photovoltaic cells adds to the economic benefits. Maintaining good air quality and adequate ventilation rates contributes to a healthier indoor environment, reducing the risk of respiratory issues and enhancing overall public health and well-being.

While the system performs well under the current climate conditions in Islamabad, future climate variability could impact its effectiveness. Continuous monitoring and potential adaptations may be necessary to maintain performance. The high initial costs could be a barrier to widespread adoption. However, government subsidies, public-private partnerships, and incentives for sustainable infrastructure could help mitigate this challenge. Although the annual maintenance costs are low, ensuring regular upkeep of the Cool Towers, Green Roofs, and photovoltaic system is crucial for sustained performance. This requires trained personnel and adequate resources.

6. CONCLUSION

The success of the passively cooled bus stop prototype has several implications for urban planning and design, such as Sustainable infrastructure development where cities should prioritize the development of sustainable infrastructure that minimizes environmental impact and enhances public well-being. The integration of passive cooling systems can play a crucial role in achieving these goals. In policy and incentives, the policymakers should consider providing incentives and subsidies for the adoption of sustainable building designs. This could include tax breaks, grants, and technical support for projects that incorporate passive cooling and renewable energy systems. Raising public awareness about the benefits of sustainable infrastructure is essential. Educational campaigns and community engagement initiatives can help build support for such projects and encourage sustainable practices.

7. FUTURE RESEARCH DIRECTIONS

Future research should conduct longitudinal studies to assess the long-term performance and impact of passive cooling systems on urban infrastructure. This would provide valuable insights into the durability and effectiveness of these systems over time. Expanding the scope of research to include a wider range of climates and urban settings would help generalize the findings and identify potential modifications to the design for different environments. Exploring new technological innovations in passive cooling and renewable energy systems could further enhance the performance and feasibility of sustainable infrastructure solutions.

The discussion of the results highlights the effectiveness, feasibility, and public support for the passively cooled bus stop prototype incorporating Cool Towers and Green Roofs in Islamabad. The design offers significant environmental, economic, and health benefits, demonstrating its potential for broader application in urban settings. Addressing the challenges and leveraging the opportunities identified in this study can pave the way for more sustainable and resilient urban infrastructure.

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