Daylight Harvesting Systems for Energy Efficiency in the Tropics: A Review

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Abstract

This paper delves into daylight harvesting systems and their vital role in enhancing energy efficiency in the tropics. Growing energy consumption in these areas, driven by factors like urbanization and population growth, makes addressing this issue a pressing concern. Buildings are significant contributors, accounting for 20-40% of global energy use. Tropical regions, facing unique challenges, can benefit from daylight harvesting to curtail energy consumption. Through qualitative analysis via desktop reviews, fundamental principles and technologies of daylight harvesting are explored, alongside successful case studies showcasing successful daylight harvesting implementations in tropical regions, emphasizing energy savings and improved indoor comfort. Despite challenges like intense sunlight and humidity, opportunities abound in leveraging abundant daylight, integrating passive design, and reaping environmental and economic benefits. This study emphasizes addressing energy consumption in tropical regions, focusing on daylight harvesting systems for significant efficiency gains and improved indoor comfort. Region-specific research is crucial for tailored strategies, while integrated design and continuous monitoring ensure optimal performance. Awareness, policy support, innovation, and collaboration are essential for widespread adoption and sustainable development in tropical building practices.

***Keywords**: Daylight, Harvesting Systems, Energy Efficiency, Tropics.*

Introduction

Addressing energy consumption in the tropics is crucial due to factors such as population growth and rapid urbanization. The building sector, in particular, has experienced significant growth in energy consumption worldwide (Verma et al., 2023). This is attributed to various factors, including population expansion, industrial development, urban expansion, and improved living standards (Orkpeh & Adedire, 2024). As a result, there is a higher demand for thermal comfort and indoor air quality in buildings (Pérez-Lombard, Ortiz,& Pout, 2008).

Buildings, globally account for about 40% of the total final energy consumption, with regional variations. For instance, in European Union Member States, buildings contribute approximately 40% to total final energy consumption and 36% to carbon emissions (Roth, Larocque, Kleinman, & Doe, 2004).

Electricity is widely utilized in buildings, with an estimated 60% of global electricity consumption attributed to this sector. Between 2010 and 2018, the use of electricity in buildings increased by more than 19% (Melo, Carrilho da Graça, & Panão, 2023).

The energy consumption of buildings is influenced by various weather factors, including temperature, humidity, air velocity, precipitation, solar radiation, and wind speed, as well as building characteristics and the operational conditions of building systems. (González-Torres et al., 2022). These weather parameters directly impact the heating, cooling, and ventilation requirements of buildings, affecting their energy usage. For instance, higher temperatures may increase the demand for air conditioning, while colder temperatures may necessitate heating systems.

Similarly, humidity levels can influence the effectiveness of HVAC systems and indoor comfort. Solar radiation affects heating and cooling loads, while wind speed can impact natural ventilation strategies and building envelope performance. Therefore, understanding and accounting for these weather-related variables are essential for optimizing energy efficiency in buildings.

Heating, ventilation, and air-conditioning (HVAC) systems, which are crucial for maintaining indoor thermal comfort, account for around 40% of the energy consumed in buildings (Roth, et al., 2004). The demand for HVAC systems is primarily affected by the local climate, building design, and internal loads. In warm climate locations, the thermal properties of the building envelope (walls, floors, roofs, doors, windows, etc.) have a significant impact on the energy requirements for HVAC (Ismaeel, 2019).

Artificial lighting is the second largest energy-consuming system in buildings, ranging from 20% to 45% of the total energy consumption (Melo, et al., 2023). Therefore, implementing daylight harvesting systems in the tropics can play a vital role in enhancing energy efficiency. These systems leverage natural daylight to reduce reliance on artificial lighting, resulting in energy savings and reduced carbon emissions (Cole, 2018).

Considering these factors, it becomes necessary to seek initiatives that improve energy efficiency in buildings while maintaining user comfort at minimal cost and reducing carbon footprints. By adopting measures such as daylight harvesting systems, it is possible to optimize energy utilization in tropical buildings and contribute to sustainable practices.

Fundamentals of Daylight Harvesting

The fundamental principles of daylight harvesting revolve around understanding and harnessing the characteristics of natural daylight (Rambhad, 2014) to optimize its utilization for energy efficiency. These principles include:

Availability and Intensity of Daylight: Daylight harvesting relies on the availability and intensity of natural daylight in the built environment. The amount of daylight received depends on factors such as geographical location, orientation of the building, and surrounding obstructions (Mahawan & Thongtha, 2021). Understanding the variations in daylight availability throughout the day and year is essential for designing effective daylight harvesting systems.

Daylight Measurement Metrics: Various metrics are used to quantify and measure daylight in buildings. These metrics include illuminance, which refers to the amount of light falling on a surface, and luminance, which describes the brightness of a light source or surface. These measurements help assess the adequacy of daylight in different spaces and guide the design of daylight harvesting systems (Mahawan & Thongtha, 2021).

Building Design and Layout: The design and layout of a building play a crucial role in daylight harvesting. Factors such as the placement and size of windows, skylights, and light wells can maximize the penetration of daylight into interior spaces (**National Institute of Building Sciences**, 2001). Additionally, the selection of materials, such as glazing types and light-transmitting surfaces, can impact the distribution and diffusion of daylight.

Glare Control: Glare, caused by excessive contrast or brightness, can reduce visual comfort and hinder productivity (Litardo et al., 2021). Proper design and control measures, such as shading devices, light diffusers, and light redirecting systems, help mitigate glare while still allowing sufficient daylight to enter the space.

Lighting Controls: Daylight harvesting systems often incorporate lighting controls to balance natural and artificial lighting. Photo sensors and occupancy sensors detect the presence of natural light and adjust the artificial lighting accordingly (Gan et al., 2019). Dimming or switching off lights in areas with sufficient daylight reduces energy consumption while maintaining appropriate illumination levels.

User Preferences and Comfort: Daylight harvesting systems should consider user preferences and visual comfort. Adequate lighting levels, colour rendering, and visual balance contribute to a visually pleasing and comfortable environment. User feedback and engagement are crucial for optimizing daylight harvesting strategies to meet the needs and preferences of building occupants (Gentile, Dubois, & Laike, 2015).

Energy Savings and Environmental Impact: The primary objective of daylight harvesting is to save energy by reducing reliance on artificial lighting. By utilizing natural daylight effectively, energy consumption associated with lighting can be significantly reduced, leading to lower carbon emissions and environmental impact (Pellegrino, Cammarano, Lo Verso, & Corrado, 2017).

Daylight Harvesting Technologies: Daylight harvesting technologies encompass a range of strategies and systems designed to capture and utilize natural daylight in buildings (Shankar, Vijayakumar, Babu, & Durusu, 2020). These technologies can be categorized into passive and active daylight harvesting approaches. Here are some key examples:

Passive Daylight Harvesting:

Window Design: Proper window sizing,

placement, and orientation can maximize the entry of daylight into the interior spaces. Design features like clerestory windows, large glazed areas, and light wells can enhance daylight penetration. In tropical regions, optimal fenestration design is crucial for effective daylight penetration while minimizing heat gain. Typically, fenestration areas in buildings located in the tropics range from 20% to 40% of the total wall area (Kalaimathy,2023). This range allows for sufficient natural light to enter indoor spaces while balancing thermal comfort and energy efficiency considerations.

However, specific percentages may vary based on factors such as building orientation, climate conditions, and shading strategies employed. It's essential to consider local climate data and conduct thorough daylighting analysis during the design process to determine the most appropriate fenestration percentages for buildings in tropical regions. (Ifeanyichukwu, Evan, Faruq, & Abdulqadirkabir, 2021).

Light Shelves: Horizontal surfaces placed above eye level inside a building can reflect and redirect daylight deeper into the space, reducing the need for artificial lighting and minimizing glare (Shankar et al., 2020).

Light Tubes/Solar Tubes: These systems use reflective tubes or pipes to channel daylight from the roof or exterior to interior spaces, especially in areas with limited access to windows or skylights (Shankar et al., 2020).

Skylights and Roof Windows: Installing skylights or roof windows allows direct entry of natural daylight, particularly in areas where vertical windows are not adequate. Proper design and glazing choices are crucial to control heat gain and glare (Ifeanyichukwu, Tolani, Shakantu, & Ikemefuna, 2021).

Active Daylight Harvesting:

Automated Lighting Controls: Photo sensors or light sensors detect the level of natural light and adjust the artificial lighting accordingly. This ensures that the artificial lighting is dimmed or switched off when sufficient daylight is available (Alva, Vlachokostas, & Madamopoulos, 2020).

Occupancy Sensors: These sensors detect occupancy in a space and adjust lighting levels accordingly. They can work in conjunction with daylight sensors to optimize energy usage based on both natural light and occupancy patterns (Alva et al., 2020).

Electrochromic Glazing: Electrochromic windows can electronically control the tint of the glass, allowing for modulation of daylight and solar heat gain. The tint can be adjusted automatically based on daylight conditions or manually by occupants.

Dynamic Facades: Advanced facade systems can actively respond to changing daylight conditions and adjust transparency or shading to optimize daylight penetration while minimizing glare and heat gain (Shankar et al., 2020).

Light Redirecting Films: These films or coatings are applied to windows or glass surfaces to redirect and diffuse incoming light, improving distribution and reducing glare (Shankar al., 2020).

Daylighting Sensors and Controls: Sensors measure the daylight level and adjust electric lighting to maintain a desired illumination level. This ensures that artificial lighting is used only when necessary (Onubogu, Chong, & Tan, 2021).

Automated blinds and shades represent a notable active daylight harvesting technique, offering the potential to optimize natural light utilization while mitigating issues such as heat gain and glare (Onubogu et al., 2021). By integrating these motorized systems with daylight sensors, buildings can dynamically adjust shading levels in response to changing daylight conditions.

However, it is essential to consider the diverse environmental and architectural factors that influence the efficacy of these technologies, particularly in tropical regions Tropical climates display considerable diversity in solar exposure, temperature, and humidity, influencing the effectiveness of automated blinds and shades. For instance, in equatorial regions across continents like Africa, South America, and Asia, where sunlight is consistently intense year-round, customized calibration of automation algorithms may be essential to optimize energy efficiency and occupant comfort.

Similarly, countries situated within the tropics but not directly along the equator, such as Malaysia, Vietnam, and Singapore in Southeast Asia, experience tropical climates marked by warm temperatures and distinct wet and dry seasons. Despite not being crossed by the equator itself, these nations share characteristics of tropical climates, necessitating tailored approaches for daylight harvesting systems.

Moreover, building orientation and design play a crucial role in determining the effectiveness of automated shading systems.

Factors such as prevailing wind patterns and local building codes influence design choices, highlighting the need for region-specific considerations. By exploring case studies and research findings, we aim to elucidate best practices for integrating automated blinds and shades into building designs across diverse tropical environments.

Furthermore, occupant comfort and preference must be carefully considered when deploying these technologies. The diverse needs and expectations of building occupants across different tropical regions necessitate adaptable shading solutions that balance daylight penetration with glare control and thermal comfort. Through our review, we will examine how automated blinds and shades can be customized to meet the distinct requirements of occupants, fostering a conducive indoor environment while maximizing energy efficiency.

Case Studies:

The S11 House, Malaysia:

The S11 House, located in Kuala Lumpur, Malaysia, which lies in Southeast Asia and is situated near the equator, incorporates various daylight harvesting strategies to achieve energy efficiency. As Malaysia is not precisely crossed by the equator itself, but is very close to it, with some parts of the country lying within the equatorial region, it experiences a tropical climate characterized by high temperatures and humidity throughout the year (Wong, Ismail, Md Zhahir & Zaini).

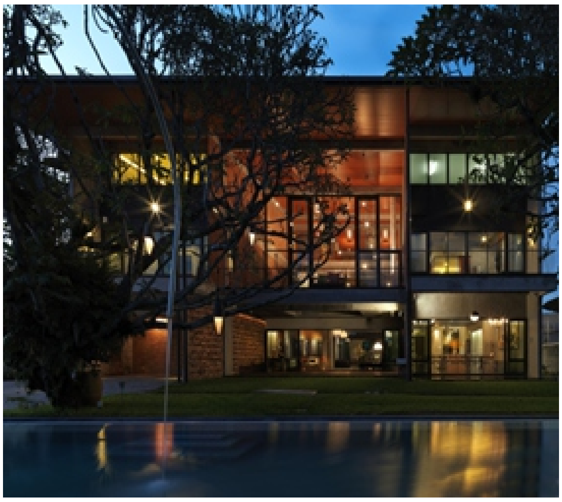

Figure 1: *View of S11 house from pool*
Source: *Archdaily.com, 2024*

Figure 2: *S11 house showing skylight*
Source: *Archdaily.com, 2024*

The S11 house features large windows as seen in Figure 1, with a clear north-south orientation for all its openings. Skylights are strategically positioned as seen in Figure 2 to maximize natural daylight penetration while minimizing heat gain. A screen wall of old bricks is used to allow for light penetration into the outdoor dining space as seen in Figure 3.

Additionally, motorized blinds and light shelves are employed to control glare and optimize daylight distribution. The integration of automated lighting controls ensures that artificial lighting is used only when necessary, resulting in reduced energy consumption and enhanced visual comfort (Alias, Basrah, Majid, & Rahim, 2021).

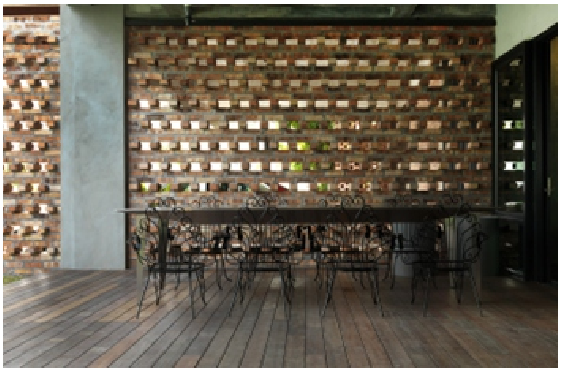

Figure 3: *S11 house screen wall at outdoor dining*
Source: *Archdaily.com, 2024*

The Green One United Nations House, Thailand:

The Green One United Nations House in Hanoi, Vietnam, a sustainable office building that incorporates daylight harvesting systems, exemplifies sustainable architecture in a tropical setting. Although Vietnam is not situated along the equator, it is within the tropical region, with the Tropic of Cancer passing through southern Vietnam. Consequently, Hanoi experiences a tropical climate, marked by warm temperatures year-round and distinct wet and dry seasons. The building design includes extensive glazing and light shelves to capture and distribute natural daylight throughout the workspace (United Nations, 2021).

Advanced lighting controls, including photo sensors and occupancy sensors, are employed to dim or switch off artificial lighting in areas with sufficient daylight. This integration of daylight harvesting technologies has resulted in significant energy savings and improved working conditions for building occupants (Ifeanyichukwu et al., 2021).

Figure 4: *Architecture of the Green One United Nations House*
Source: *United Nations Institute for Training and Research (2024)*

The Capita Green Building, Singapore:

The Capita Green building in Singapore's CBD, a 40-storey commercial tower, showcases innovative daylight harvesting strategies in a location close to the equator. Situated just 137 kilometres (85 miles) north of the equator, Singapore lies within the equatorial region, experiencing a tropical climate marked by high temperatures and humidity throughout the year. The building design features a unique double-skin facade as seen in Figure 5, with external shading devices and light shelves that optimize daylight penetration while reducing solar heat gain.

Automated blinds and lighting controls are used to balance natural and artificial lighting based on daylight availability and occupancy. This holistic approach to daylight harvesting has led to substantial energy savings and a visually appealing indoor environment (Noraziemah et al., 2021).

***Figure 5:** Double skin façade*
***Source:** Capita Green. com*

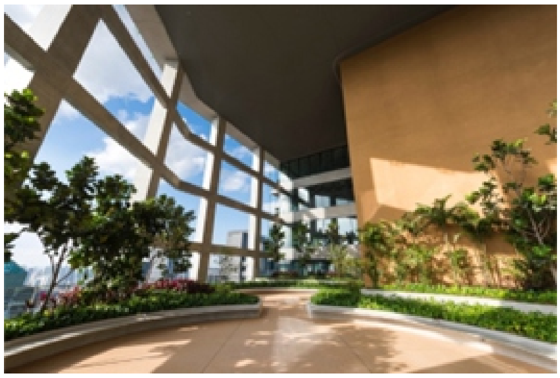

***Figure 6:** Interior*
***Source:** Capita Green. Com*

The EDEN Building, Brazil:

The EDEN Building in Sao Paulo, Brazil, is a sustainable office complex featuring daylight harvesting systems. Brazil, mostly within the tropics and crossed by the Tropic of Capricorn, experiences warm temperatures year-round, distinct wet and dry seasons, and lush vegetation. Its vast size results in diverse climate types, including subtropical and equatorial climates in the northern and southern regions.

The building design includes large windows, skylights, and light tubes to capture natural daylight and distribute it throughout the interior spaces. Smart lighting controls with daylight sensors adjust artificial lighting levels based on available natural light, to ensure optimal energy efficiency. The incorporation of daylight harvesting technologies in the EDEN Building has resulted in reduced energy consumption, improved occupant comfort, and enhanced visual aesthetics (Ifeanyichukwu et al., 2021).

These case studies highlight successful implementations and adoption of daylight harvesting systems in the tropics. They demonstrate the effectiveness of various strategies, such as window design, light shelves, advanced lighting controls, and integration with sustainable building practices. These buildings have achieved significant energy savings, improved indoor comfort, and minimized their environmental impact in the tropics.

Challenges and Opportunities of Daylight Harvesting Systems for Energy Efficiency in the Tropics;

Challenges:

High Solar Intensity: Tropical regions often experience intense sunlight, which can pose challenges in terms of glare control and heat gain (Lim, & Sirimaneetham 2022). Balancing the entry of natural light with the need for shading and solar heat management becomes critical to maintain visual comfort and prevent excessive cooling loads.

Humidity and Moisture Control: Tropical climates are characterized by high humidity levels, which can impact the performance and durability of daylight harvesting systems. Moisture-related issues, such as condensation and mould growth, need to be addressed to ensure the long-term effectiveness and reliability of these systems.

Tropical Building Design: The architectural design of buildings in tropical regions differs from that of temperate climates. Building designs need to consider factors such as natural ventilation, thermal mass, and effective shading strategies to optimize daylight harvesting. Integrating daylight harvesting systems into existing tropical building designs may require retrofitting or redesigning, posing practical challenges.

Regional Variations: Tropical regions can have significant variations in climate, daylight availability, and building practices. Conducting region-specific research becomes essential to understand and address the specific challenges and opportunities in different tropical zones, taking into account local climate patterns, building materials, and cultural preferences.

Opportunities:

Abundant Daylight Resources: Tropical regions have a significant advantage in terms of abundant sunlight. Properly harnessing this resource through daylight harvesting systems can result in substantial energy savings and reduced reliance on artificial lighting.

Integration with Passive Design Strategies: Daylight harvesting systems can be integrated with passive design strategies, such as natural ventilation and shading devices, to optimize energy efficiency and enhance indoor comfort in tropical buildings (Litardo et al., 2021). This integration presents opportunities for holistic and sustainable building design approaches.

Environmental and Economic Benefits: Implementing daylight harvesting systems in the tropics can contribute to reducing carbon emissions, conserving energy resources, and improving the overall sustainability of buildings. Additionally, the energy savings achieved through daylight harvesting can lead to economic benefits by reducing electricity bills and operational costs (Litardo et al., 2021).

User Well-being and Productivity: Natural daylight has been linked to improved wellbeing, productivity, and occupant satisfaction. Daylight harvesting systems in the tropics offer the opportunity to create visually pleasing and comfortable indoor environments that enhance the health and well-being of building occupants (Alva et al., 2020).

Technological Advancements: Ongoing advancements in lighting technologies, sensors, and controls provide opportunities for more sophisticated and efficient daylight harvesting systems. Integration with smart building technologies and the Internet of Things (IoT) can enable real-time monitoring and adaptive control of lighting systems, further optimizing energy efficiency in tropical buildings (Asongu, Le Roux & Biekpe, 2018).

Conclusion

In conclusion, this study underscores the critical importance of addressing energy consumption in tropical regions, particularly within the building sector. By examining the potential of daylight harvesting systems, we have identified a promising avenue for achieving significant energy efficiency gains while simultaneously enhancing indoor comfort and well-being.

Moving forward, it is imperative to embark on region-specific research endeavours to gain a deeper understanding of the diverse climate conditions, architectural practices, and cultural considerations prevalent in tropical areas. This nuanced understanding will inform the development of tailored daylight harvesting strategies that are finely attuned to the unique characteristics of each locale. Furthermore, embracing an integrated design approach that involves close collaboration among architects, engineers, policymakers, and other stakeholders from the outset of building projects is paramount. By prioritizing daylight harvesting in the design phase, we can ensure the seamless integration of energy-efficient technologies and passive design strategies, thereby optimizing both environmental performance and occupant comfort.

Continuous monitoring and evaluation of daylight harvesting installations are essential to gauge their effectiveness over time and identify opportunities for refinement. Establishing robust data collection mechanisms will provide valuable insights into system performance, energy savings, user satisfaction, and any challenges encountered, enabling iterative improvements and ongoing optimization.

Moreover, raising awareness among building owners, developers, and occupants about the benefits of daylight harvesting systems is crucial for driving widespread adoption. Educational initiatives and outreach programs can empower stakeholders with the knowledge and tools needed to embrace sustainable building practices and make informed decisions about energy-efficient technologies. Policy support, including the integration of daylight harvesting requirements or incentives in building codes and green building certification programs, is essential for creating an enabling environment for sustainable development. By aligning regulatory frameworks with sustainability goals, policymakers can incentivize the adoption of energy-efficient technologies and catalyze market transformation towards greener building practices.

Furthermore, fostering innovation and technological advancements in daylight harvesting systems through research and development initiatives is key to unlocking their full potential. Collaborative partnerships between academia, industry, and government can accelerate the pace of innovation and drive continuous improvement in sustainable building technologies.

Lastly, facilitating knowledge-sharing and collaboration platforms among stakeholders will promote the exchange of ideas, best practices, and lessons learned. By harnessing collective expertise and leveraging collaborative networks, we can accelerate progress towards sustainable development goals and create a more resilient and environmentally responsible built environment in tropical regions.

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