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Key Architectural Parameters for Optimizing energy efficiency of Building Envelopes: A Comprehensive Review

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Abstract

Energy efficiency in building design has emerged as a pivotal concern due to escalating urbanization and its associated environmental impact. This paper critically examines the architectural parameters influencing the energy performance of building envelopes, with a specific focus on passive design strategies applicable to hospital buildings in India's composite climate. Hospitals, being high energy consumers, are key to achieving substantial energy savings through optimized building envelope design. The study explores passive techniques such as building orientation, thermal insulation, shading devices, window-to-wall ratio optimization, and material selection to minimize heat transfer and enhance natural ventilation. Insights from global and Indian case studies underscore the efficacy of these strategies in reducing energy demand, operational costs, and carbon emissions. By integrating passive measures during the initial design phase, this research advocates for sustainable hospital environments that align with India's energy conservation goals and address its unique climatic challenges.

Keywords: *Building envelope, passive parameters, energy efficiency, hospitals, energy performance*

1. Introduction

1.1 Buildings and Energy Consumption

The link between building energy consumption and carbon emissions in India is a crucial research focus, especially given the nation's swift urbanization and growing population. With urbanization in India expected to rise to 40% within the next ten years, the corresponding increase in carbon emissions from buildings has become an urgent issue (Yang et al., 2023). The construction sector is a significant contributor to greenhouse gas emissions, accounting for a substantial portion of total emissions in many contexts, including India. The construction sector is a significant contributor to greenhouse gas emissions, accounting for a substantial portion of total emissions in many contexts, including India

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(Song et al., 2018). This trend is intensified by the dependence on conventional building materials, which carry high embodied carbon footprints, along with inefficient energy usage during the operational phases of buildings (Akbarnezhad & Xiao, 2017). India's rapid urbanization and economic growth have led to an increased demand for energy, particularly in the building sector, which is responsible for approximately 30-40% of the country's total energy consumption (Wang 2023). Pandey and Basu emphasize the importance of energy optimization in building structures to mitigate unnecessary energy wastage and minimize carbon emissions. The authors argue that without effective energy management, India faces a potential energy shortfall, necessitating a dual approach: increasing energy production and minimizing consumption (Pandey & Basu, 2020). This is echoed by Itoo and Ali, who found that rising population and energy consumption significantly correlate with increased pollution levels, including carbon emissions (Itoo & Ali, 2022). The interplay between energy consumption, building practices, and carbon emissions in India necessitates a multifaceted approach that includes optimizing energy use, selecting sustainable materials, and implementing robust policy measures. As urbanization continues to rise, addressing these factors will be crucial in mitigating the environmental impact of the building sector and achieving sustainable development goals. As the nation strives to meet its energy needs while addressing climate change, the potential for energy mitigation in buildings, especially hospitals, has become a focal point for researchers and policymakersalike.

The scenario of CO2 emissions in India is a critical area of research, particularly given the country's rapid economic growth and reliance on fossil fuels. As the fifth-largest emitter of CO2 globally, India faces significant challenges in balancing economic development with environmental sustainability. India's CO2 emissions have been on an upward trajectory, primarily driven by its energy sector, which is heavily reliant on coal. According to Bajpai and Mondal, coal-fired thermal power generation is a major contributor to India's greenhouse gas emissions, accounting for a significant portion of the country's total CO2 output (Bajpai & Mondal, 2013). The authors note that India's emissions are projected to increase by approximately 6%, contrasting with trends in other major economies, where emissions are stabilizing or decreasing (A, 2023). This trend is concerning, as it indicates that India's economic growth is closely tied to its carbon emissions, which could undermine global efforts to combat climate change. The role of energy consumption in shaping India's CO2 emissions cannot be overstated. Sahu and Kumar highlight that economic growth and energy consumption have a significant negative impact on environmental quality in India, suggesting that increased energy use is directly correlated with rising emissions (Sahu & Kumar, 2020). This is further supported by the findings of Nagarkatti and Kolar, who emphasize that coal-fired power plants are the largest source of anthropogenic CO2 emissions per unit of electricity generated in the country (Nagarkatti & Kolar, 2014). The reliance on coal, coupled with limited reserves of cleaner energy sources, poses a significant challenge for India in its quest to reduce emissions.

The reliance on coal, coupled with limited reserves of cleaner energy sources, poses a significant challenge for India in its quest to reduce emissions (Zioło et al., 2019). The authors argue that while coal is an abundant resource, its combustion releases substantial amounts of CO2, exacerbating climate change. The limited availability of cleaner energy sources, such as wind and solar, further complicates India's transition to a low-carbon economy. This situation necessitates the exploration of alternative energy strategies that align with India's economic and environmental realities. This suggests that India,

as a developing economy, may need to adopt unique strategies that consider its specific economic and environmental context. Moreover, the COVID-19 pandemic has had a notable impact on CO2 emissions in India. A study by Sajid and González indicates that the pandemic led to a temporary reduction in emissions due to decreased economic activity and demand shocks. While the immediate effects of the pandemic resulted in a notable decrease in emissions, the authors caution against viewing this as a sustainable solution. The rebound in economic activity post-lockdown has led to a resurgence in emissions, highlighting the need for long-term strategies that promote sustainable development. Sajid and González argue that the pandemic presents an opportunity for India to rethink its energy policies and prioritize investments in clean energy infrastructure (Sajid & Gonzalez, 2021). By adopting unique strategies tailored to its specific economic and environmental context, India can work towards achieving sustainable development while addressing the pressing challenges of climatechange.

1.2 How the Healthcare Sector Fuels Climate Change?

As per the estimates of CEA the per capita consumption in kWh for India has increased from 1181kWh in FY 2018-19 to 1255kWh in the FY 2021-22. Hospitals contribute to around 9% of India's commercial electricity in the FY 2019-20 (Prabhakaran et al., 2023). The healthcare sector, particularly hospital buildings, is a significant contributor to carbon emissions in India, primarily due to their high energy consumption. Hospitals are known to consume more energy per square meter than other types of public buildings, largely due to their continuous operation, extensive HVAC requirements, and the energy-intensive nature of medical equipment (Ji & Qu, 2019; Bawaneh et al., 2019). Studies indicate that hospitals can achieve energy savings of 24-50% by adopting green building practices compared to conventional designs (Barsbay, 2021). Also, India stands fourth in the world amongst the top ten healthcare CO2 e-emitters when compared to total top ten emitters. This high energy demand translates into substantial greenhouse gas emissions, making it imperative to focus on energy efficiency measures within this sector. A comprehensive review of energy consumption trends in hospital buildings reveals that they are responsible for a considerable share of total energy use in India, which is exacerbated by the rapid urbanization and expansion of healthcare facilities (Dandia et al., 2021). The Energy Conservation Building Code (ECBC) of India highlights the potential for hospitals to achieve significant energy savings up to 42% through the implementation of energy-efficient measures. These measures include optimizing HVAC systems, improving thermal insulation, and utilizing renewable energy sources, which are critical in reducing the operational carbon footprint of hospitals (Reddy et al., 2019).

2. Literature Review

2.1 Passive measures as important parameter in achieving energy reduction in thebuilding sector

Passive design strategies play a crucial role in enhancing energy efficiency in hospital buildings. By optimizing building orientation, maximizing natural ventilation, and using materials with low embodied energy, hospitals can significantly reduce their reliance on mechanical systems for heating and cooling. For instance, the integration of thermal mass and insulation can help maintain comfortable indoor temperatures, thereby reducing the energy demand for HVAC systems (A. Kumar et al., 2015) Furthermore, the use of daylighting strategies can minimize the need for artificial lighting, which is a

substantial contributor to energy consumption in hospitals (Maskarenj et al., 2014). The design and retrofitting of hospital buildings present substantial opportunities for energy efficiency improvements. Research has shown that optimizing the building envelope, including the use of bioclimatic facades and appropriate glazing, can significantly reduce energy demand (Bulakh, 2019; Cesari et al., 2020). For example, the adoption of wider windows with energy-efficient glazing can lower energy consumption while improving patient and staff well-being through enhanced natural lighting (Cesari et al., 2020). Additionally, the use of climate-adaptive building shells allows for dynamic responses toenvironmental changes, further minimizing energy use (Loonen et al., 2013).

Passive design techniques are increasingly recognized as vital components of building envelopes, particularly in the context of achieving energy efficiency in buildings located in the composite climate of India. The composite climate, characterized by hot summers and cool winters, presents unique challenges and opportunities for optimizing building performance through passive strategies. In regions with hot climatic conditions, the heat dissipation from the interiors and controlling solar heat gains is very important to maintain thermally comfortable indoor conditions. Hence passive cooling measures can be used in the buildings to reduce energy usage and improve the thermal performance of the building. The relevance of focusing on passive measures is underscored by the findings that energy- saving transformations in hospital buildings can lead to substantial reductions in carbon emissions. For example, studies indicate that energy-efficient renovations can save over 654 tons of CO2 annually in specific hospital settings (Wu, 2023). A study highlights that energy efficiency in public hospital buildings can be achieved through passive design, allowing for lower energy consumption without compromising comfort or productivity. By incorporating energy-efficient measures at the initial design stage, hospitals can enhance the quality of interior spaces. This approach not only optimizes energy usage but also extends the lifespan of hospital equipment and reduces waste (Muhamad et al., 2017). Additionally, the adoption of passive design principles not only contributes to energy savings but also enhances occupant comfort and well-being, which is particularly important in healthcare environments (Juan et al., 2016). In conclusion, addressing the energy consumption and carbon emissions of hospital buildings in India is critical for achieving sustainability goals. By prioritizing passive measures and energy-efficient technologies, the healthcare sector can significantly mitigate its environmental impact while improving operational efficiency. The integration of these strategies aligns with India's goal to achieve the goal of sustainable development in the built environment by reducing greenhouse gas emissions.

Heat transfer in buildings happens through three modes as mentioned in Figure 1 below. The passive techniques can be classified under three main categories as (Bhamare et.al., 2019) solar and heat protection, heat modulation techniques, heat dissipation techniques. The first two strategies aim at minimizing the heat gain in the buildings and the third one aims at rejecting the heat from the buildinginteriors to maintain low temperature inside.

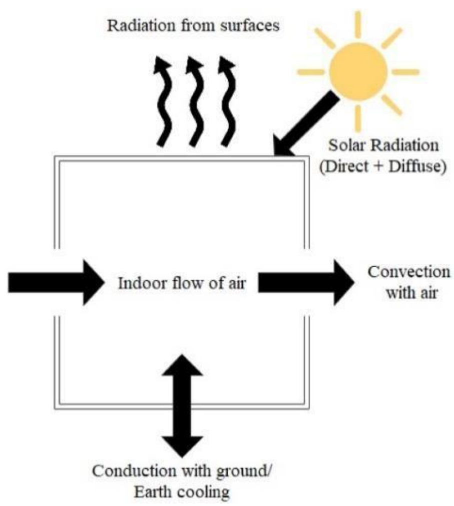

Figure 1 Modes of heat transfer in a building, source: Al-Shamkhee et al. (2022)

The flowchart of the passive cooling techniques in Figure 2 below shows the various passive cooling techniques. The building envelope plays a critical role in determining the energy performance of structures, acting as a barrier between the indoor environment and external conditions. As global energy demands rise and climate change becomes an increasingly pressing issue, the design of building envelopes has evolved significantly to enhance energy efficiency and sustainability. This article explores the current trends and strategies in building envelope design, focusing on key elements such as thermal insulation, window-to-wall ratio (WWR), and the integration of passive design strategies. Numerous studies have validated the effectiveness of passive design strategies (PDSs) in lowering energy demand in buildings. A study revealed that the design of net zero energy healthcare facilities involves three basic approaches i.e. passive design strategies, the use of energy efficient system, and renewable energy system. The passive design approach focusing on parameters like building orientation, shading devices, ventilation and thermal insulation are some of the points which need attention in the hospitals (Abdellah et al., 2017).

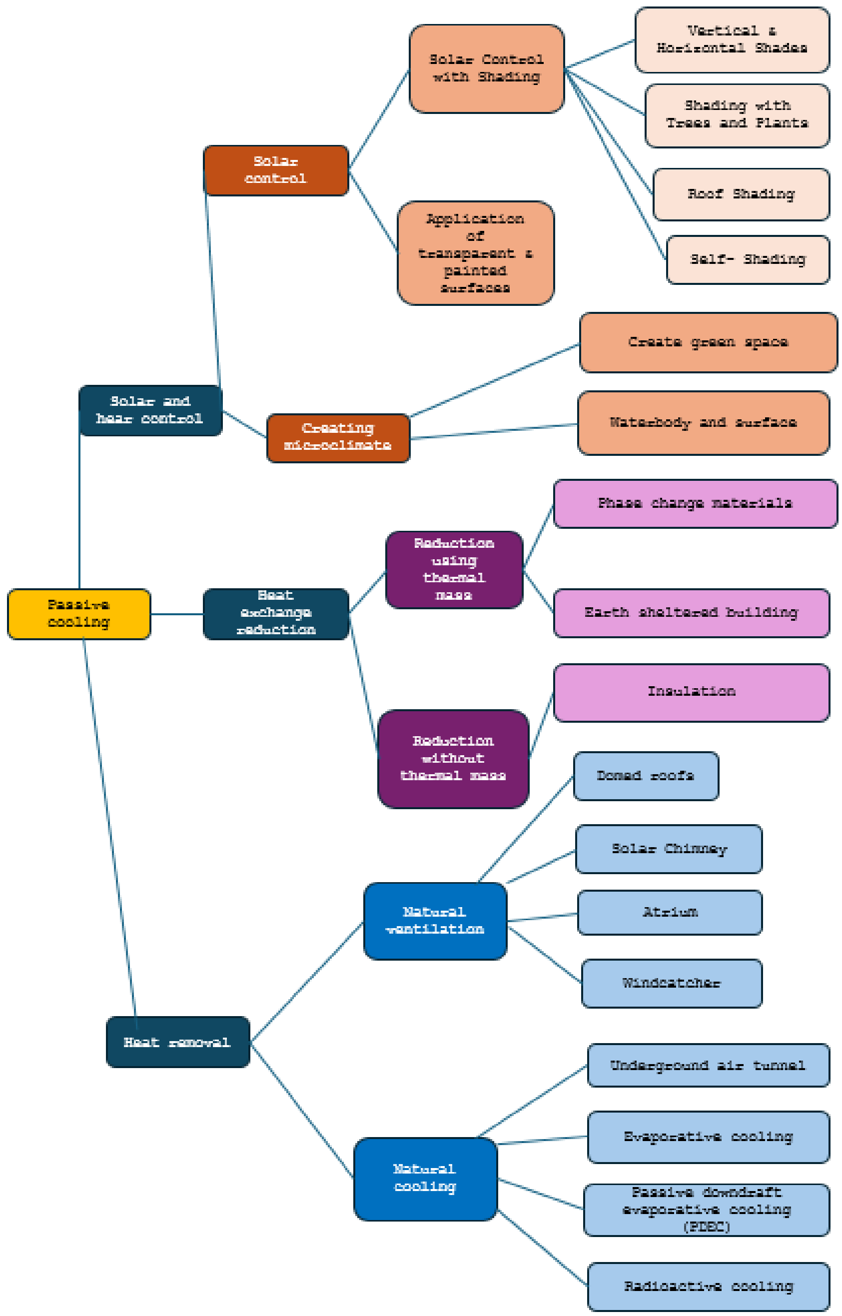

Figure 2 Passive cooling techniques

2.1.1 Building Shape and Orientation

The component of surface area exposed to the exterior in a building affects the amount of heat gains from the exterior to the interior and the heating cooling or losses in the interiors. The larger the area ratio, more will be the need for heating or cooling. Hence, the surface area is an important feature to reduce the energy demand in a building.

Building orientation plays a vital role in improving the efficiency of a building since it directly impacts how the building interacts with the climate of place throughout the year. Design of a building differs with respect to its climate and location. Proper orientation helps to maximize natural daylighting thereby reducing the need for artificial ventilation. By careful planning and placing the building as per the climatic conditions, building can capture maximum sunlight in colder climate and minimise the heat gain by the building envelope in the warmer climates (Ashmawy & Azmy, 2018). To determine the optimal building orientation, it's important to understand the sun's movement using a sun path diagram and to consider the prevailing wind directions (Figure 3). After setting the orientation, the amount of heat entering the building can be managed by adjusting the glazing area and type, as well as selecting appropriate wall and roof materials and incorporating shading strategies (Bano & Kamal,2016).

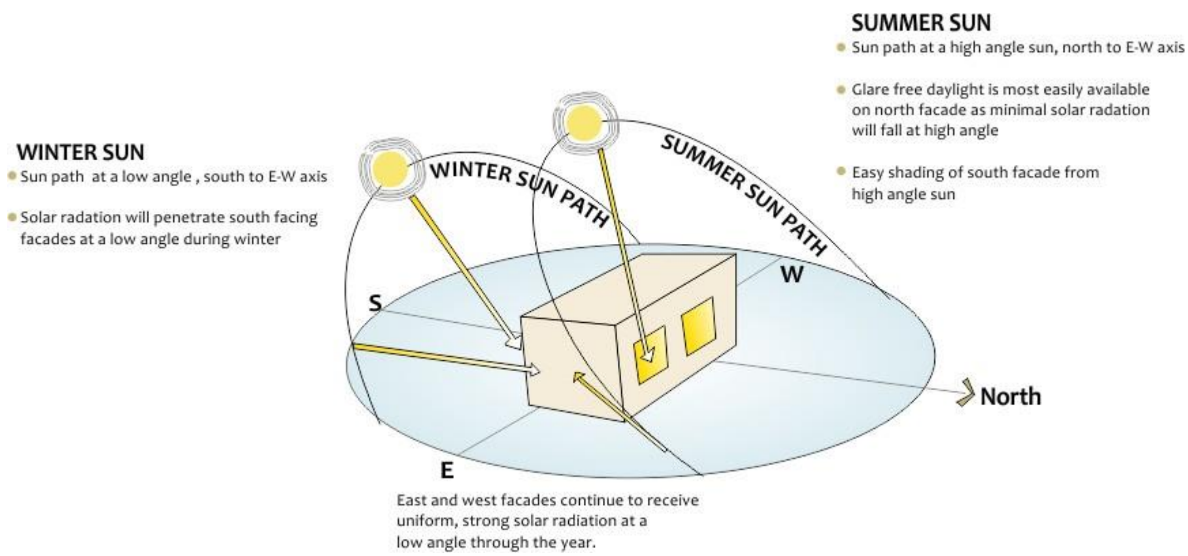

Figure 3. Building form and orientation, source: https://nzeb.in/knowledge-centre/passive-design/form-orientation/

2.1.2 Thermal Insulation of walls and roofs

The outer surfaces of the building envelope, such as the roof and walls, which are directly exposed to solar radiation, heat up to temperatures higher than the indoor temperature in India (Figure 4). This heat transfers from the building envelope to the interior surfaces of the roof and walls via thermal conduction, introducing unwanted warmth into the occupants' space. Inside the building, this heat is further distributed through radiation and convection, causing discomfort for occupants. Therefore, it's crucial to ensure good air circulation, ventilation, and cooling within the space, typically achieved by energy-powered fans and air-conditioning systems. Thermal insulation remains a cornerstone of effective building envelope design. It minimizes heat transfer between the interior and exterior, thereby reducing the energy required for heating and cooling. Recent studies have highlighted the importance of optimizing insulation thickness based on wall orientation and local climate conditions. For instance, Ramin et al. demonstrated that implementing appropriate insulation can significantly lower energy consumption in buildings, particularly in regions with extreme temperatures Ramin et al. (2015). The choice of insulation materials also plays a crucial role, as different materials exhibit varying thermal resistance properties, directly influencing the overall energy efficiency of the building (Gorantla et al., 2016). Roof and wall insulation in buildings are other Passive Design strategies(PDS) which help in reducing energy demand in buildings and save up to 35% energy (Figure 5). The cool roof technology can help to reduce temperature up to 4.7°C (Rawat & Singh, 2022). Kolokotsa et. al. revealed that cool roofs can reduce the yearly energy demand by about 17% since they reflect more sunlight as compared to the traditional roofs (Kolokotsa et al., 2018). In hot-dry, warm-humid, and composite climate zones, roofs account for approximately 50 to 60% of the total cooling load entering a building from the external environment (Rawat & Singh, 2022). The use of vertical green walls on the façade of the building can not only help to reduce energy use in buildings but also provide comfortable indoor conditions and reduce the harmful carbon emissions (Wong & Baldwin, 2016).

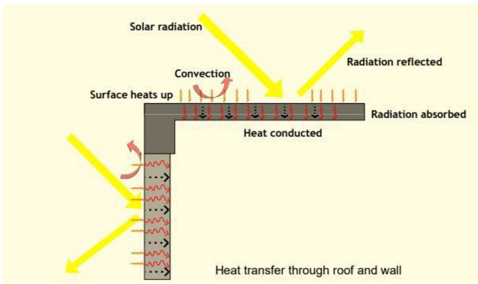

Figure 4. Thermal Insulation of buildings, source: BEEP

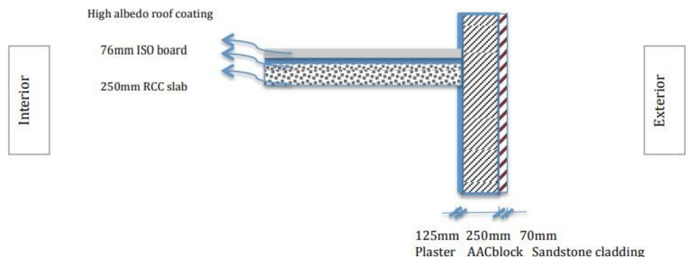

Figure 5. Cross section of wall and roof with low U-value assemblies at ITC Green Center, Gurgaon, source: escholarship.org

2.1.3 Window-to-Wall Ratio (WWR)

The window-to-wall ratio (WWR) is defined as the proportion of the glazed area relative to the total outer wall area. WWR is an important factor influencing a building's energy efficiency, as window size impacts heating and cooling loads, as well as natural daylighting within the building (Figure 6). The window-to-wall ratio (WWR) is another critical factor influencing energy performance. A well-calibrated WWR can enhance natural lighting while minimizing unwanted heat gain or loss. A study by Yang et al. indicates that optimizing WWR can lead to substantial energy savings in residential buildings, particularly in climates characterized by hot summers and cold winters (Yang et al., 2015). The balance between opaque and transparent elements in the building envelope is essential; excessive glazing can lead to increased cooling loads, while insufficient windows may compromise daylighting and occupant comfort (Uprety et al., 2021). Furthermore, studies have shown that the optimal WWR varies depending on climatic conditions, necessitating tailored approaches for different regions (Fathi & Kavoosi, 2021; Gerçek & Gucu, 2019). Many studies have shown the impact of window-to-wall ratio and their potential to save energy. Ahmed et al. (2023) in their study evaluated the impact of WWR on different orientations and different glazing materials for a office building in the hot climate of Iraq. The study revealed that even with 100% WWR on south facing windows, minimum energy consumption was achieved with the help of double clear glass. Alwetaishi (2017) studied the impact of window-wall ratio in the different climates of Saudi Arabia and revealed that east and south direction gains the highest amount of heat. The study recommended a glazing to wall ratio of 10% in the hotter regions with 20% WWR in the moderate regions of the country.

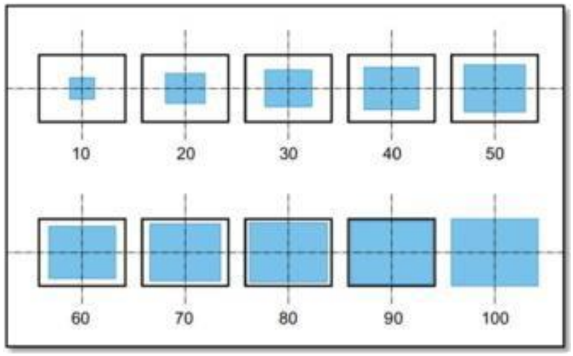

Figure 6 Impact of Window-to-wall ratio; source : Alwetaishi, 2019

2.1.4 Shading of Windows

Shading acts an important passive parameter to control the solar and wind effects. The horizontal shading devices help protect the building and its occupants from high altitude sun in summers and allows the low angle sun in winters to warm the space. (Kamal, 2010) in their study highlighted the importance of different shading devices like overhangs, louvers, awnings, roof shading and other techniques like vegetation and landscaping used as an important passive parameter in the shading of buildings. The author further emphasised the importance of shading devices which can reduce the energy needs by 10-40%.

Zhao et al. emphasize the importance of passive design in achieving low-carbon buildings, highlighting strategies such as thermal bridge-free construction and the rational arrangement of building openings to facilitate natural ventilation (Zhao et al., 2023). Additionally, the use of advanced glazing technologies, such as low-emissivity (low-E) coatings and triple glazing, can further improve the thermal performance of windows, contributing to overall energy efficiency (Shaik et al., 2021). Bui et al. in their study assessed the importance of high performance glass and revealed that it can save energyupto 60% (Bui et al., 2017).

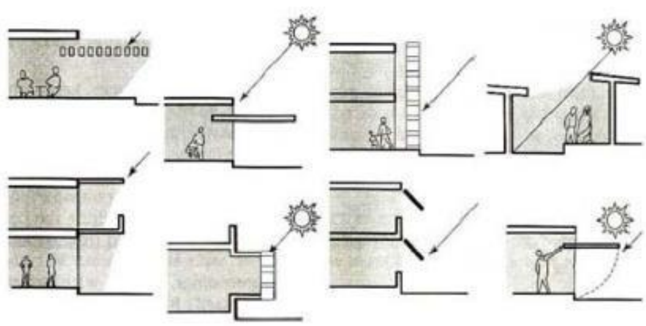

Figure 7. Different types of shading devices, source:(Maleki, 2011)

Shading devices integrated as a part of building design or used externally on the façade can help control the heat gain and provide thermal comfort to its occupants as shown in Figure 7 below.

Figure 8 Brise soleil - shading devices integrated with the building façade, Source: (Maleki, 2011)

Figure 9. Roof shading, Source: https://www.archdaily.com/964189/house-under-shadows-zero- energy-design-lab/60db830e447a92016532e0d9-house-under- shadows-zero-energy-design-lab-photo?next_project=no

2.1.5 Shading of roofs

Roof shading is a crucial method for minimizing heat gain. Roofs shading can be provided by using materials such as sheets, plants, earthen pots but at the same time should allow the heat to escape out during the night also known as nighttime cooling. Vegetated roofs, particularly those covered with deciduous plants, are effective at maintaining lower roof temperatures. Evapotranspiration from the plants' leaves cools the roof surface, keeping it lower than ambient air temperature during the day and allowing it to cool to below sky temperature at night (Kumar et al., 2005). Roof shading does more than reduce indoor temperatures; it also contributes to broader environmental sustainability. By decreasing the need for artificial cooling, roof shading lowers the overall energy consumption of a building, which in turn reduces carbon emissions. A study on the passive methods of cooling in buildings revealed that using of shades in buildings can decrease the temperature of the interior by 2.5°C to 4.5°C (R. Kumar et al., 2005). A study by Santamouris et al. highlighted the potential of efficient shading strategies to decrease cooling loads by approximately 7%, thus underscoring the importance of incorporating shading devices in building design to support environmental goals (Santamouris et al., 1994). A study on thermal performance of roof shading in the composite climate of India indicated that opaque shading could lower the hourly peak heat gain through the roof by as much as 77% on a cloudy day and 71.5% on a sunny day. Additionally, it reduced the nighttime hourly peak heat loss from the roof by up to 40% on cloudy days and 33% on sunny days (Sadevi & Agrawal,2024).

Wall shading devices play a crucial role in modern architectural design, particularly in enhancing energy efficiency and occupant comfort. Wall shading devices can be categorized into fixed, dynamic, and integrated systems. Fixed shading devices, such as overhangs and louvers, are designed to block direct sunlight while allowing diffuse daylight to penetrate. They are particularly effective in reducing cooling loads in buildings located in hot climates (Khidmat et al., 2022; Samanta et al., 2014). For instance, Khidmat et al. demonstrated that optimizing louver shading devices significantly improves daylighting performance under varying sky conditions (Khidmat et al., 2022). The effectiveness of wall shading devices is influenced by several design parameters, including orientation, geometry, and material properties. The orientation of shading devices relative to the sun's path is critical in maximizing their performance. For instance, Settino et al. conducted a multi-objective analysis of fixed solar shading systems across different climatic zones, emphasizing the importance of orientation in energy performance (Settino et al., 2020). Similarly, Lee et al. demonstrated that the azimuth orientation of shading devices significantly affects daylighting outcomes in classrooms as shown in figure 10 below (Lee et al., 2017). By carefully considering the type, design, and control of these devices, architects and engineers can create environments that not only reduce energy consumption butalso enhance the quality of life for occupants.

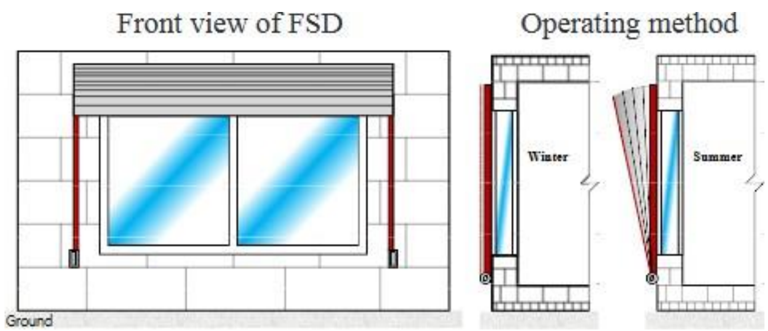

Figure 10 Concept and method of foldable shading device, source: Baek and Park (2016)

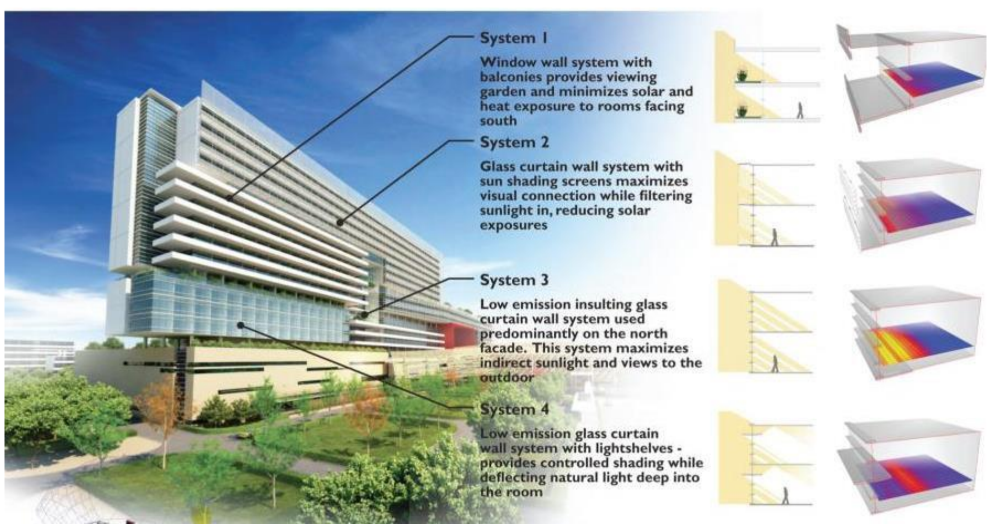

Figure 11 Facade shading elements in First People's Hospital, China, source: https://www.google.co.in/books/edition/Sustainable_Healthcare_Architecture/TIfxPU6B4t8C?hl=en&gbpv=1

3. Methodology

The methodology involves comprehensive literature review to identify key architectural parameters impacting energy efficiency such as building orientation, thermal insulation, shading devices, window-to-wall ratio (WWR) and material selection. Sources include peer reviewed journals, online case studies, government energy codes and standards such as Energy Conservation Building Code (ECBC). Case studies of hospitals from diverse climatic regions were reviewed to compare and validate the effectiveness of passive design strategies. Data were collected on energy consumption patterns, operational efficiency, and carbon emissions. In-depth analysis of successful hospital projects, both national and international, was conducted. Examples include green-rated buildings in India like Manipal Hospital and Changi General Hospital in Singapore, focusing on the application of passive measures. Metrics such as Energy Performance Index (EPI), CO2 savings, and operational costs were evaluated to draw correlations between design strategies and outcomes. This methodology provides a robust framework for assessing and advancing the energy efficiency of hospital building envelopes, leveraging both theoretical insights and practical applications.

Table 1 Summary of study based on different passive strategies used in healthcare facilities globally

Authors	Location /Climate	Passive strategy	Study	Results
Peng et al. 2014	South China	Orientation and layout	Overall layout to optimize natural ventilation, building envelope for thermal insulation, shading	Reduction in HVACcosts
Muhamad et al.2017	Tropicalclimate	Orientation, building shape, form and massing, buffer spaces, double skin facades	Combination of passive design approach and energy efficiency to achieve the aim of net zero energy buildings	Achieve Net Zero Energy Buildings NZEB and provide optimum comfort to users, improves energy efficiency
Abdellah et al. 2017	-	natural lighting, shading, insulation, and ventilation	Review of Passive approach, Energy efficiency, and Renewable energy systems	Achieve a maximum of energy efficiency
Li et al. 2017	Europe and United States	passive solutions, such as pipe-embedded envelopes (PEE) and double-skin façades	Combination of passive and activestrategies	Optimize energyefficiency
Noor Muhammad et al. 2021	tropical climates of Malaysia	Natural ventilation	Applying hybrid PV/T and heat pump systems could significantly enhance hospital energy performance	manage indoor air quality and provide thermal comfort while minimizing energy use.
Balali et al. 2021	-	Passive strategies identified placed in groups of thermal, acoustic and lighting	To identify and rank the passive strategies for using in designing of healthcare facilities	Optimizing fenestration for thermal control, using a naturally- ventilated envelope for acoustic comfort, and sun shading for lighting identifies as most important passive strategies for achieving efficiency in hospitals.

Guenther and Vittori (2013)	Marine west coast/Shunde district, China	Thermal mass, solar screens, and geothermal energy (underground air tunnels), narrow floorplate, energy responsive façade, use of local terracotta	Case study of First People's Hospital,China	Maximize daylighting and natural ventilation by narrow floorplate, onsite energy generation by use of BIPV panels, low embodied energy materials
Guenther and Vittori (2013)	Tropical	Narrow floorplate, solar shading, naturalventilation	Case study of Hospital Universitario San Vincente de Paul, Rionegro, Colombia	Shape of floorplate resulting in natural ventilation and daylighting, fixed solar shades reducing direct heat gains on façade, 70% building area naturally ventilated and passively cooled
Singapore: Changi General Hospital, Simei	Tropical rainforest	Koi ponds, palm trees and orchid murals. Hydroponic garden on the hospital roof, which grows produce for the hospital kitchen while cooling the building. Use of natural light, automatic doors to maximize cooling efficiency, energy-efficient ceiling fans, motion sensor lighting, and low-flow water fixtures.	Case study of Singapore: Changi General Hospital, Simei	Reduction in energy and water costs by US$800 000/year
Eisazadeh et al.2019	Belgium	Room geometry, type of glazing andWWR	Effect of patient room dimensions, type of glazing, WWR, WFR	Design with coated glazings have lower life cycle environmentalimpact

U.S. Department of Energy, 2010	United states	Wall and floor slab insulation, cool roof with R-30 Insulation and coating, double glazed windows	Case study of Ringgold CountyHospital	Annual electricity savings of 188,399 kWh and 23,060 therms of natural gas consumption, improved indoor air quality and thermal comfort
Latha et al. 2023	-	Building orientation, climate, building form and optimized space layout design	Systematic literature review	Proper building sizing can reduce the consumption by around 17%-35%. Correct glazing can reduce the 35–40% energy load of thebuilding.
Almarzooq et al.2022	Saudi Arabia	thermal resistance building envelope	Softwares like Revit, eQUEST and Green building studio used for simulations	Savings of 19.82% annually in the electricity
Aripin et al.	Malaysia	Building layout, orientation, natural ventilation	Case studies of 3 district hospitals inMalaysia	40% built up area of hospitals in Malaysia can be used for passive design by architects and planners
Short et al. 2009	UK	orientation, materials, glazing, passivedowndraught cooling (PDC)	Hospitals in UK under NHS considered for study	70% of net floor area of small-to-medium-sized acute hospitals could be naturally ventilated
Nematchoua et al.(2018)	-	Thermal insulation on the building facades	Case studies of six islands in the Indianocean, use of Energy-Plus software for assessing the thermal performance of hospitals	Improved thermal comfort and reduction in energy consumption
Dubey and Kamal(2022)	India/composite	Orientation, thermal insulation, cross ventilation, low energy materials like fly ash bricks	Case study of Trauma Centre, Aligarh on the basis of Energy Performance Index and peak heat gain	Assessment of GRIHA rating achieved by the hospital

Venkatasubramanian and Centre for Media Studies (CMS) (2020)	India/ Warm Humid Climate	AAC block external wall,insulated roof and double- glazed window.	Case study of Jupiter Hospital Pune, India	16% energy savings

Mathur et al. (n.d.)	India/tropical monsoon	Sustainable materials like gypsum board, mineral fibre, composite wood, fly ash bricks, double glazing, horizontal shading devices, WWR of 13% achieved.	Case study of Manipal Hospitals, Mangalore, India	EPI of 223.89 kWh/sq.m/year achieved (50%reduction)

4. Discussion

The table presents various case studies on passive design strategies and energy efficiency measures in hospitals across different climates and locations. The key passive strategies include optimizing building orientation, natural ventilation, thermal insulation, and shading systems. Advanced techniques like passive downdraught cooling (PDC), hybrid photovoltaic/thermal (PV/T) systems, and double-skin façades are applied in specific climatic contexts. In tropical climates (e.g., Malaysia, India), natural ventilation and hybrid systems enhance energy efficiency while maintaining thermal comfort. In temperate and marine climates, strategies such as thermal mass, geothermal energy, and energy- responsive façades are emphasized. Hospitals like Ringgold County Hospital (USA) achieved significant annual energy savings and improved indoor air quality through wall and roof insulation. In India, hospitals using materials like AAC blocks and fly ash bricks demonstrated substantial energy savings and improved energy performance indexes (EPI). Some hospitals, like Changi General Hospital in Singapore, integrated green roofs and hydroponic gardens, achieving dual benefits of energy efficiency and sustainable food production. The use of simulation tools like Energy Plus, Green Building Studio and eQUEST highlights the role of technology in optimizing passive designs. From Europe to Asia, these case studies showcase the adaptability of passive design principles to diverse climates and healthcare needs. The success of these initiatives demonstrates the potential for energy- efficient hospitals to reduce operational costs and environmental impact. This comprehensive set of case studies emphasizes the importance of passive strategies, locally sourced materials, and technology-driven optimization in achieving sustainable and energy-efficient hospital designs. The research conducted in the hospitals of India shows that most of the healthcare facilities have used active design strategies to achieve energy efficiency in the hospitals rather than using passive ones. Various Indian hospitals have identified opportunities to enhance energy efficiency within their facilities, achieving significant energy and cost savings. Numerous hospitals have implemented energy-saving measures tailored to their specific operational needs. The initiatives adopted by hospitals have focused on optimizing systems like HVAC, lighting, and water management to minimize waste and enhance efficiency. The Apollo Hospitals in Chennai enhanced its energy efficiency and reduced operational costs by adopting active measures like installing CFL lighting. The Jahangir Hospital in Pune installed solar water heaters, biogas plants and energy savers for AC's, again an active measure. Kovai Medical centre in Coimbatore implemented building monitoring systems and replaced electric heaters with solar heaters, installed digital meters. PGIMER, Chandigarh upgraded to screw chillers, efficient motors and boilers with economizers to reduce the power consumption. Batra hospital in New Delhi again adopted

installation of boilers with economizers, efficient AHU's and VFD's for pumps and fans for savings in monthly electricity bills (USAID ECO-III Project et al., 2009).

5. Conclusion

Optimizing the design of building envelopes, particularly for energy-intensive hospital facilities, holds immense potential for advancing sustainability in India's healthcare sector. This review demonstrates that passive design strategies, including orientation, insulation, shading, and appropriate material usage, can substantially reduce energy consumption while maintaining thermal comfort. Case studies reveal that hospitals implementing such measures achieve marked reductions in cooling loads and carbon emissions. The findings reinforce the importance of integrating energy-efficient and passive design solutions early in the design process, offering actionable insights for architects and policymakers. These strategies not only contribute to environmental sustainability but also enhance operational efficiency and occupant well-being, presenting a viable path forward for sustainable healthcare infrastructure.

6. References

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