Impact of Building Envelope Materials on Residential Energy Consumption in the Indian Composite Climate: Insights from Gurugram

Ar. Nisha Sharma[1*] & Dr. Bandana Jha[2]
[1]PhD Scholar, SPA Delhi, India; ORCID: 0000-0001-5739-7959
[2]Professor, SPA Delhi, India; ORCID: 0000-0001-5826-8809
E-mail: nisha.phd.282.arch22@spa.ac.in[1], bandana.jha@spa.ac.in[2]

Received	Reviewed	Revised	Published
11.08.2023	14.11.2023	20.11.2023	30.11.2023

https://doi.org/10.61275/ISVSej-2023-10-11-09

Abstract

In India, the residential sector currently accounts for 26% of total electricity consumption, a figure anticipated to surge to 38% by 2030 and 39% by 2047. This escalation is primarily attributed to the growing prevalence of air conditioning systems, serving to achieve thermal comfort in both urban and rural settings. To align with Sustainable Development Goal 11 (SDG11), fostering environmentally friendly practices, integrating energy-efficient products, and employing sustainable techniques in the residential sector become imperative.

Among the various strategies, the adoption of energy-efficient building envelope designs emerges as a pivotal approach in curbing operational energy consumption. This study investigates the impact of different building envelope materials on energy consumption in residential buildings, employing an optimization study utilizing the e-Quest simulation tool. The research focuses on an existing residence in Gurugram, Haryana, situated in a composite climate. A notable aspect of the study is the exploration of the most influential building envelope component—whether walls, roofs, or fenestrations—in achieving maximal energy consumption reduction.

The findings show the significance of designing building envelope components, particularly walls, roofs, and fenestrations, to minimize heat gain and maximize energy consumption reduction. Notably, energy-efficient walls exhibit a more pronounced impact than other components. Lightweight concrete walls emerge as more energy-efficient than counterparts with cavities, AAC blocks, concrete blocks, cellular concrete, and bricks, showcasing substantial variations in energy consumption reduction. The introduction of insulation materials proves to be a crucial factor, contributing significantly to reduction in energy consumption combined with any wall material. Collectively, an energy-efficient building envelope design presents a remarkable potential to reduce operational building energy consumption by approximately 18%.

Keywords: Building envelope, Building materials, Energy efficiency, Energy consumption reduction, Residential buildings, and Composite climate.

Introduction

Global population is rising, and cities, though occupying 3% of land, consume 60-80% of energy and produce 75% of carbon emissions. With 55% currently in urban areas, expected to be 68% by 2050, swift action is vital (United Nation-HLPF, 2018). India is the world's third-largest energy consumer, with growing demand due to access, affordability, and urbanization (India energy outlook report (IEA), 2021). Enhancing energy efficiency is urgent, particularly in residential sectors, set to consume 38% by 2030 and 39% by 2047 (BEE, 2018; Ministry of Power, India, 2021). Common appliances in India include lighting, fans, TVs, refrigerators, washing machines, water heaters, and air conditioners. Air conditioning (AC) demand is set to rise fastest, becoming the major driver of energy demand for cooling in buildings by 2040 (IEA, 2021).

Ambient temperature, weather conditions, daylight hours, building design, equipment efficiency, and equipment installation impact building energy consumption (Kaja, 2018). Passive measures can reduce energy consumption by 19% while also saving money in the long run by lowering the life cycle cost by 12% (Hajare & Elwakil 2020). Design strategies can address environmental issues and reduce mechanical means for internal building comfort, lowering electrical energy use (Ibrahim and Hassan, 2023). In passive design strategies, the design of building envelope is done by orienting it according to the climatic data and solar system of the specific site, and it simply works 'on its own' (Singh et al., 2021; Khandelwal et al., 2020). If built with proper walls, openings, and roofs in warm climates, the building envelope can be one of the most effective parts in reducing energy use inside buildings. The inner layer has a significant impact on the amount of energy consumed in the dwellings (Al-nuaimi and Almadani, 2023). Combining materials with lower U-values can reduce energy usage. Assessing energy needs before construction allows for eco-friendly design exploration, focusing on walling materials (Olanrewaju, Adetunji and Ogundepo, 2019). Retrofitting existing buildings with suitable envelope materials is essential in light of changing climate scenarios (Kishore, 2022). Energy Retrofitting of buildings also contributes to environmental, economic, regulatory, and social benefits (Jha and Bhattacharjee, 2018).

India is divided into five climatic zones: cold, hot and dry, warm and humid, temperate, and composite, with all except the cold zone being cooling-dominated climates according to the Energy Conservation Building Code and National Building Code (Kumar et al., 2009; *NBC, 2016*). A data analysis using the Constellate platform revealed that the composite climate has received less research attention compared to hot and cold climates (Fig 1). Hence, the composite climate is chosen for studying the building envelope. It covers the central part of India and is characterized by high temperatures in summers, cold winters, low humidity in summers, and high direct solar radiation. Cities in this climate zone include New Delhi, Kanpur, Amritsar, Bhopal, and others (BEE, 2018; Kumar et al., 2009). In a composite climate, it's essential to design rooms that maintain indoor temperatures lower in summer and higher in winter than outdoor temperatures (Charde *et al.*, 2019).

In this context, the aim of this research is to ascertain the impact of the building envelope materials on energy consumption in residential buildings with special reference to the Indian composite climate. The objectives of the research are set as:

i. To ascertain the impact of materials in each building envelope component individually on energy consumption reduction of residential buildings in Indian composite climate.
ii. To establish the overall maximum impact of optimization of building envelope materials applied in all components on energy consumption reduction of residential buildings in Indian composite climate.

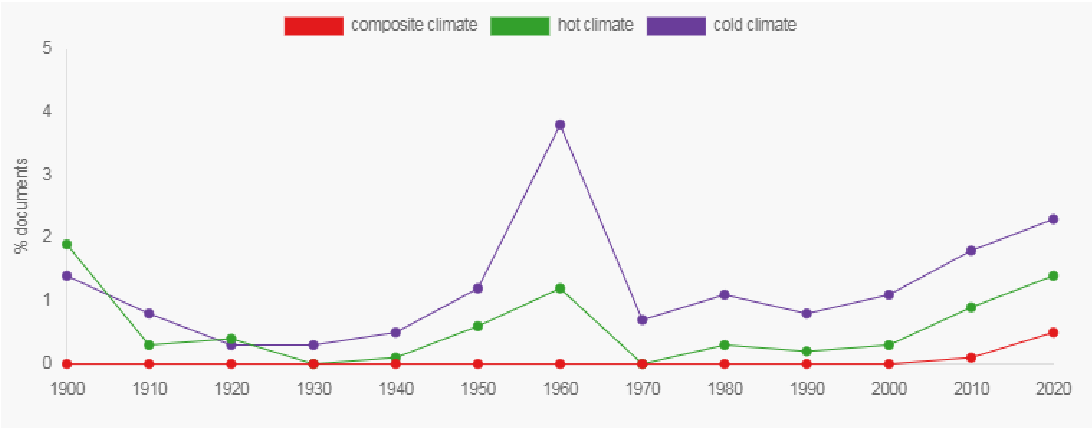


Fig. 1: Research papers conducted in composite, hot and cold climate
(Source: Author)

Review of Literature

Building Material Studies

Olanrewaju, Adetunji and Ogundepo, (2019) underscored the significance of walling material choice, highlighting that better U-values in the building envelope result in reduced energy consumption. Their research emphasizes the need for considering various design alternatives during the building design phase to achieve optimal energy savings. Khan and Baqi (2021) focused on Ferro Cellular Insulated Panel (FCIP), revealing its superior thermal performance compared to traditional brick masonry walls. Theoretical simulations demonstrated a remarkable 427% reduction in energy consumption when using FCIP, and cost-benefit analysis showed a quick payback period, positioning FCIP as an economically viable and energy-efficient material. Khan, Baqi and Talib (2021) explored Fiber-Cement Infilled Precast Aggregate (FCIPA) as a potential replacement for brick masonry walls, highlighting its equivalent mechanical strength and superior energy efficiency. Building orientation and appropriate window and door glasses were identified as crucial factors in reducing electrical energy consumption. Kumar and Suman (2013) evaluated thermal insulation materials' impact on energy savings, conforming to the Energy Conservation Building Code (ECBC) in India. They concluded that 50 mm thick Elastospray met ECBC requirements, showcasing the benefits of thermal insulation in energy savings during different seasons. Prakash and Shukla (2017) determined the Optimum Insulation Thickness (OIT) for extruded polystyrene insulation (XPS) on reinforced cement concrete roofs, emphasizing the economic and environmental benefits of selecting the appropriate insulation material and thickness for maximizing energy savings.

Gorantla et al. (2021) focus on the significance of energy-efficient triple glazing units in reducing cooling and heating costs. The research experimentally examined sixty triple glazing setups with different combinations of reflective glasses, identifying the TWG35 window glass unit in the S-E orientation as the most energy-efficient, providing substantial air-conditioning cost savings and a short payback period. Editor et al. (2019) explored the impact of cool coatings on time lag and decrement factor, emphasizing the importance of minimizing wall absorptivity for reducing cooling loads. The role of cool roofs in combating the Urban Heat Island (UHI) effect and improving thermal comfort was discussed by Rawat and Singh (2021a), highlighting potential energy savings ranging from 8.4% to 30.4% across different climatic zones in India. Additional research by Rawat and Singh (2021b) compared the effectiveness of different cool roof coatings, revealing significant heat gain reduction with the implementation of cool paints. Furthermore, the thermal performance of cool roofs in a composite climate was analyzed, demonstrating improved energy efficiency and thermal comfort by Rawat and Singh (2021c). Lastly, Rawat and Singh (2022b) conducted a techno-economic analysis of cool roof slabs, indicating their cost-effectiveness with an Internal Rate of Return (IRR) ranging from 32.55% to 36.55% and a payback period of 2 years. The studies collectively underscore the importance of thoughtful material selection, emphasizing the potential of innovative technologies and coatings to enhance energy efficiency and reduce environmental impact in the context of Indian residential buildings. Additionally, Zingre et al. (2020) delved into the limitations of existing regulations on thermal efficiency, highlighting the dynamic nature of heat transfer mechanisms and the positive impact of solar reflectance on reducing net heat gain in flat roofs.

Hasan, Khan and Uddin (2021) evaluated insulation materials and PCMs for energy performance optimization in different climatic zones. Glass wool and rock wool provided maximum energy savings, while PCM materials like Butyl stearate were effective in reducing energy consumption and peak cooling energy demand. Gandhi et al. (2020) reviewed the potential of Shape-Stabilized Phase Change Materials (SSPCMs) in hot and dry climates, highlighting their ability to reduce PCM leakage and dampen indoor temperature fluctuations. Kočí et al. (2020) investigated PCM-based plasters in European countries, showing a slight positive effect on interior climate and reduced heat flux densities during peak periods. Lakhdari et al. (2020) explored dual PCM and plaster integration for thermal comfort in different climates, revealing reduced internal wall temperature and peak heat infiltration. In New Delhi, India, Saxena et al. (2019) studied PCM integration in building envelopes, reporting potential energy conservation with PCM materials like Eicosane and OM35. Li et al. (2022) assessed PCM foamed cement walls in China's different climate zones, showing optimal phase transition temperatures and cooling load reductions of up to 37.02% in Kunming. Arumugam & Shaik (2021) evaluated the thermoeconomic performance of PCM-integrated building envelopes in Indian climates, recommending the use of OM30 PCM for optimal results Saxena et al. (2019). Moreover, Rahul Verma, Sumit Kumar and Dibakar Rakshit (2022) investigated passive design strategies, including PCM thermal storage systems, in a composite climate zone in India, highlighting the combined benefits of insulation, cool roofs, and PCM for thermal comfort and energy demand reduction. Agarwal and Prabhakar (2023) explored PCM-incorporated clay bricks for energy-saving potential and economic feasibility in Jaipur's climatic condition. Rai (2021) examined PCM integrated walls for managing cooling energy consumption in residential.

Optimization studies

In public housing projects under India's Prime Minister Awas Yojana (PMAY), Asrani et al. (2022) assessed walling assemblies and technologies' compliance with India's Residential Energy Building Code, Eco Niwas Samhita (ENS). They found that lower U-values in walling assemblies resulted in meeting ENS-prescribed thermal transmittance values, ensuring code compliance and increased thermally comfortable hours. (Dhaka, Mathur and Garg, 2012) assessed the impact of energy conservation measures (ECMs) from the Indian Energy Conservation Building Code, revealing that small buildings with ECMs achieved up to 43% energy savings. Rahul Verma, Sumit Kumar, Dibakar Rakshit (2022) conducted simulations and found that a combination of passive design strategies, including cool roofs, insulation, phase change material (PCM) thermal storage, and shading, resulted in up to 20.5% energy savings and improved thermal comfort. Chetia et al. (2016) integrated energy-efficient envelope and ventilation strategies in affordable housing projects, achieving a maximum indoor temperature of 32°C during hot summers and successfully controlled indoor temperatures through design strategies such as low U-value walls and shading. Asrani et al. (2022) mapped the design and construction practices of public housing projects, emphasizing the importance of lower U-values in walling assemblies for improved thermal comfort. In a case study, Charde et al. (2014) analyzed the impact of sunshades and brick cavity walls on indoor air temperature, emphasizing the importance of energy-efficient building technologies and design strategies. Rahul Verma, Sumit Kumar, Dibakar Rakshit (2022) evaluated passive methods for controlling heat gain by building envelopes in various Indian cities, demonstrating their potential in reducing energy consumption. Jaboyedoff et al. (2015) emphasized the significant reduction in cooling energy demand achieved through passive features in building design. Chaturvedi et al.

(2023) applied parametric optimization to high-rise residential buildings, achieving substantial reductions in cooling and operational energy demand, contributing to energy-efficient building design in composite climates. These studies collectively provide insights into effective strategies and design approaches to address energy consumption and improve thermal comfort in the unique context of India's composite climate.

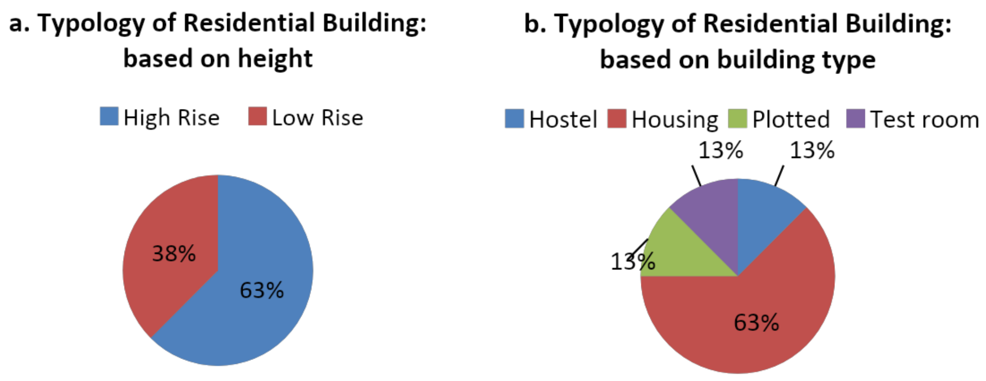


Fig. 2: Typology of residential buildings in Optimization studies
(Source: Author)

While numerous studies have delved into the examination of materials employed in walls, roofs, and fenestrations to achieve energy savings separately, a notable scarcity exists in comparative studies that effectively identify the most energy-efficient materials and their maximum impact on energy reduction in residential buildings, particularly within the context of India's composite climate. Existing optimization studies for residential buildings in this climate have predominantly centered on hostel buildings or high-rise structures, leaving a research gap concerning low-rise residential buildings (Fig. 2). Moreover, only a limited number of studies have undertaken a comprehensive comparison of building envelope components to discern which component yields the highest energy reduction. In accordance with Olanrewaju et al. (2019), maximizing energy savings necessitates considering multiple design alternatives, with a specific emphasis on the choice of walling material. Conversely, Dhaka et al. (2012) strongly advocate prioritizing roof insulation over other energy conservation measures, asserting that this measure alone can achieve up to 20% energy savings. However, these two recommendations appear to be contradictory. Consequently, the objectives of this study are formulated to resolve this contradiction and provide clarity on the most impactful building envelope component for enhancing energy efficiency in residential buildings within India's composite climate.

This study aims to meticulously analyze the impact of varying combinations of building component materials, seeking to determine the maximum achievable reduction in energy consumption for the building. Through this comprehensive process, valuable insights will be gained into the most effective strategies for enhancing the energy efficiency of residential structures in the specified climatic conditions.

Research Methodology

An optimization study was conducted in an existing residential building located in Gurugram, Haryana, situated in the composite climate of India as there is a scarcity of research focused on low-rise structures in this region.

To establish the baseline for the study, a comprehensive set of data was collected using e-Quest software. This involved analyzing monthly electricity bills spanning from January 2022 to December 2022 to compile monthly energy consumption data. Subsequently, a meticulous monthly calculation of energy consumption was undertaken by cataloging all electronic devices utilized in the building. The energy consumed by each electronic device was computed, taking into account the wattage and duration of device usage.

The optimization study on e-Quest involved the sequential application of different building materials to each building envelope component, with a careful recording of their respective impacts on energy consumption. This process unfolded in multiple cases: Case 1 entailed the application of diverse wall materials, Case 2 involved different roof materials, and Case 3 focused on various fenestration materials, as illustrated in Figure 3. The recorded values were then compared to identify the most influential building envelope materials and components. In the final phase of the study (Case 4), the most energy-efficient materials identified in Cases 1, 2, and 3 were collectively applied, and the resultant overall reduction in energy consumption was observed. Various building materials were sourced from Eco-Niwas Samhita-Residential guidelines and e-Quest building materials. The selection criteria were based on achieving a low U-value, indicating a focus on materials with enhanced thermal insulation properties.

This holistic approach aimed to determine the combined impact of optimizing various building envelope components, thereby contributing valuable insights toward enhancing the energy efficiency of the residential building in question.

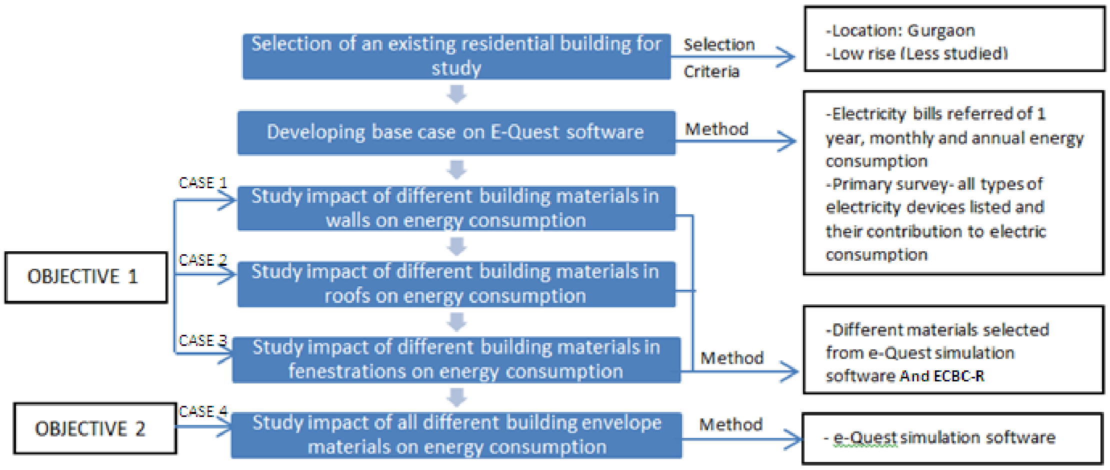


Fig. 3: Research Methodology chart
(Source: Author)

Findings & Discussion

Optimization Study

The building envelope of a G+2 house, measuring 30 x 30' (Fig. 4), situated in Gurugram, Haryana, is outlined below. The base case details have been configured using the e-Quest simulation tool (Fig. 5), aligning with the actual scenario of the structure (Table 1).

The Base case building envelope: The residential structure under consideration features a 4" concrete roof without any external finish, an 8" brick wall with both internal and external plaster, a ceiling finished with plaster, 4" concrete floors, and windows equipped with clear glass.

The Base case energy consumption: The detailed month-wise energy consumption, as per electricity bills, is presented in Table 1. These data points have been modeled using e-Quest, and the graphical representation is illustrated in Fig 5.The initial Annual Energy Consumption for this configuration is recorded at 9618 kWh. To assess and optimize energy consumption, a thorough investigation is conducted using the e-Quest simulation tool.

Table 1: Monthly Energy Consumption of residence as per electricity bills
Source: Author

Month	Energy Consumption, kWh
January	655
February	597

March	597
April	915
May	915
June	1000
July	1000
August	1095
September	1095
October	547
November	547
December	655
TOTAL	**9618**

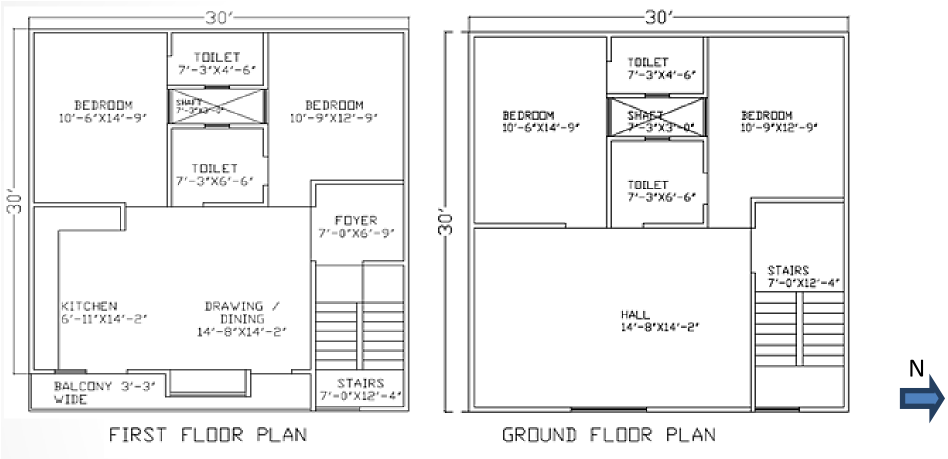
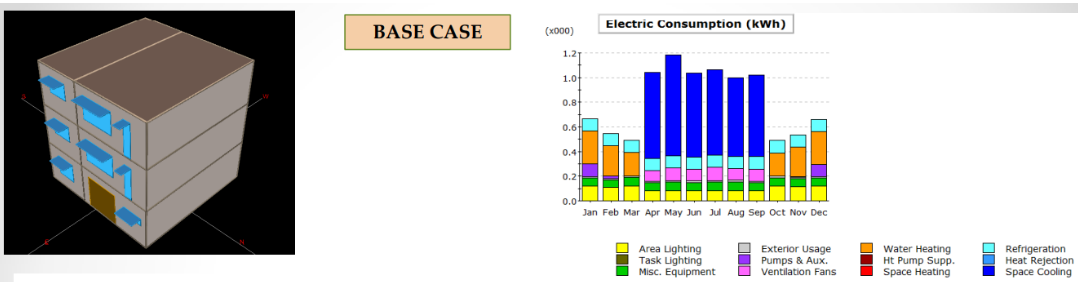


Fig. 4: Layout of residence, Gurugram, Haryana
Source: Author



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.50	0.65	0.59	0.60	0.54	0.56	-	-	-	3.44
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	0.22	0.22	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.22	0.22	1.22
Vent. Fans	-	-	-	0.05	0.06	0.05	0.06	0.05	0.06	-	-	-	0.32
Pumps & Aux.	0.07	0.01	-	-	-	-	-	-	-	-	0.00	0.06	0.14
Ext. Usage	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Misc. Equip.	0.29	0.27	0.31	0.28	0.30	0.29	0.29	0.30	0.28	0.30	0.29	0.29	3.50
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.08	0.08	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.98
Total	0.66	0.58	0.57	0.91	1.09	1.02	1.03	0.99	0.98	0.56	0.59	0.66	9.62

Fig. 5: e-Quest model of residence, Gurugram, Haryana
Source: Author

Case Study 1: The Energy Efficiency Roof (EEroof) component is subjected to thorough evaluation, assessing the impact of various roof finishes and insulation materials on energy consumption. The findings, presented in Table 2, indicate that a green roof with a 12" soil layer, coupled with 1" polyisocyanurate insulation, demonstrates the highest reduction in energy consumption when compared to alternatives such as clay tiles and stone. Additionally, it is observed that augmenting the thickness of insulation leads to a further escalation in the reduction of energy consumption along with increase in the roof thickness.

Table 2: Case Study 1: EEroof
Source: Author

Case 1: EEroof: Impact of roof components on energy consumption			
S.no	**Different roof finish material with insulations**	**Energy consumption, kWh**	**Energy consumption reduction (%) from base case**
1	clay tile 3"+ polyisocyanurate1"	9390	2.4
2	clay tile 3"+ polyisocyanurate3"	9320	3.1
3	clay tile 3"+ polyurethane 1"	9400	2.3
4	clay tile 3"+ polyurethane 3"	9350	2.8
5	stone 1"+ polyisocyanurate1"	9430	1.97
6	stone 1"+ polyisocyanurate3"	9330	3.01
7	stone 1"+ polyurethane 1"	9440	1.87
8	stone 1"+ polyurethane 3"	9350	2.8
9	soil 12"+ polyisocyanurate 1"	9280	3.5
10	soil 12"+ polyurethane 1"	9290	3.4

Case Study 2: The Energy Efficiency Fenestrations (EEfen) component undergoes a comprehensive assessment, with a specific focus on evaluating the impact of different window glazings. This evaluation maintains consistent details for the roof, walls, ceiling, and floor in comparison to the base case. The results, outlined in Table 3, highlight that double reflective glass demonstrates the most substantial reduction in energy consumption, followed by single reflective glass. Noteworthy is the observation that reflective glasses surpass the performance of lowE filled glasses, with the latter, in turn, outperforming clear glasses in terms of energy consumption reduction.

Table 3: Case Study 2: EEfen
Source: Author

Case 2: Impact of different window sizes on energy consumption			
S.no	**Different window sizes**	**Energy consumption, kWh**	**Energy consumption reduction/ addition (%) from base case**
1	single reflective: clear 1/4 in	9250	3.85
2	double clr 1/8in 1/2in air	9520	1.04
3	double reflective: 1/4in 1/2in air	9230	4.05
4	triple clr 3mm	9460	1.66
5	triple lowE (e5=.1) clr 1/8in 1/4in air	9400	2.29
6	Quad lowEfil clear 1/8in 1/3in krypton	9320	3.12

Case 3: Energy Efficiency Wall (EE wall) measures are implemented to examine the impact of diverse wall construction and insulation materials, as detailed in Table 4. This investigation involves altering wall materials while maintaining uniform details for windows, roof, ceiling, and floor in accordance with the base case. The results indicate that Concrete wall LW 30 Lb 8" outperforms Concrete wall LW 30 Lb 6", Concrete block (LW, 8", perlite filled), Cavity wall, AAC block, and cellular concrete, exhibiting a notable reduction in energy consumption. However, it is noteworthy that the variation in energy consumption becomes highly pronounced when different wall materials are utilized without an insulation layer.

Conversely, when various wall materials are coupled with an insulation layer, the variation in energy consumption diminishes significantly. This underscores the importance of insulation in optimizing energy efficiency in wall construction.

Case Study 4: In the comprehensive Energy Efficiency All (EEall) simulation, encompassing measures in all building components, including roof, fenestration, and walls (i.e., Case 1+2+3), the residence is ultimately modeled with specific specifications. These include a roof configuration with a 12" soil layer and 1" polyisocyanurate insulation, concrete walls of LW 30 Lb 8" combined with 2" polyurethane foam board (PUF) insulation, and fenestrations equipped with double reflective glass (1/4” 1/2" air). This combination results in a total energy consumption of 7890 kWh, as illustrated in Fig 6. Moreover, the annual energy consumption registers a notable reduction of 17.98%, as depicted in Fig 7. This holistic approach underscores the efficacy of integrating optimized specifications across multiple building components to achieve a significant enhancement in overall energy efficiency.

Table 4: Case Study 3
Source: Author

Impact of Each Building Envelope Component

Case 3: Impact of different wall materials on energy consumption					
S. no	**Different wall materials**	**Energy consumption, kWh**	**Thermal conductivity, W/m.K**	**R-value, Km²/W**	**Energy consumption reduction/ addition (%) from base case**
1	concrete wall LW 30 Lb 8"	8798.2	0.1299	55.232	8.5
2	concrete wall LW 30 Lb 6"	8946	0.1299	42.632	7.0
3	Cavity wall (4“ ext. brick wall+4” cavity + 4” int. brick wall with gypsum plaster)	9930	-	24.882	3.1
4	AAC block	10370	0.4200	35.835	3.4
5	concrete block LW perlite filled	8814	0.1666	44.137	8.4
6	Cellular concrete	9156.9	0.188	35.069	4.8
	Different wall insulations				
1	concrete block LW perlite filled+ polyurethane foam board PUF 2"	8624	-	46.408	10.4
2	concrete wall LW 30 Lb 8" + polyurethane foam board PUF 2"	8619.2	-	62.347	10.4
3	AAC block+ polyurethane foam board PUF 2"	8644.7	-	35.829	10.1
4	Cellular concrete+ polyurethane foam board PUF 2"	8645.4	-	35.092	10.1
5	Cavity wall (4“ ext. brick wall+ Polyurethane foam PUF 2" + 5” int. brick wall with gypsum plaster)	8668.9	-	78.246	9.9

Energy-efficient wall materials and insulations exhibit the most significant impact on energy consumption compared to other building components, namely roofs and fenestrations, as depicted in Figures 6 and 7. The influence of fenestration materials is observed to be less pronounced than that of walls but slightly more impactful than roofs, as illustrated in Figures 6 and 7.

Combined impact of all building envelope components:

Figures 6 and 7 illustrate that a residential building incorporating energy-efficient materials across all building components consumes less energy than a building where only one building envelope component is equipped with energy-efficient materials. This emphasizes the importance of a comprehensive approach to achieve maximum energy reduction in building design and construction.

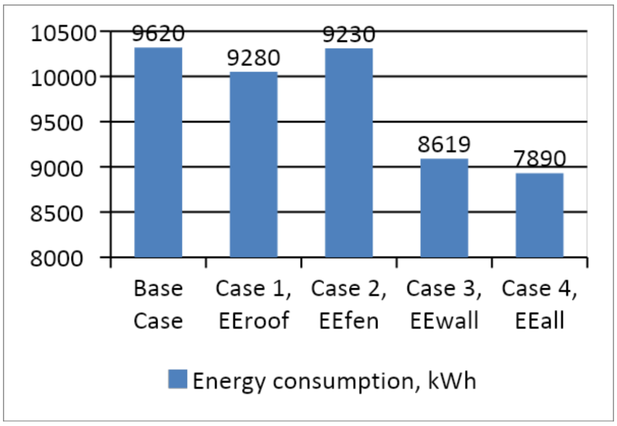


Fig. 6: Minimum Energy consumption in different cases, kWh
Source: Author

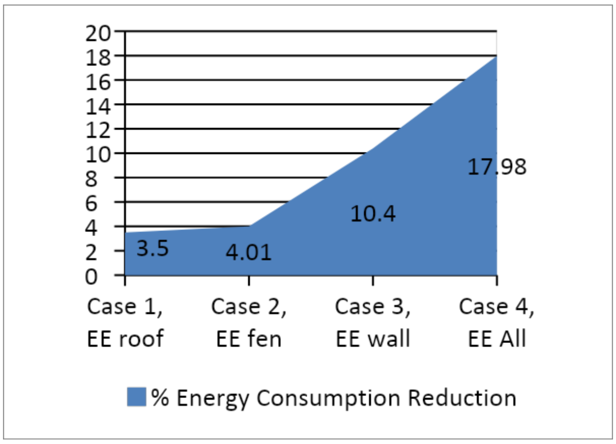


Fig. 7: Maximum Energy Consumption Reduction in different cases (%)
Source: Author

Conclusions

The urgency for enhanced energy efficiency within residential buildings is paramount. In composite climates, the key building envelope components, namely walls, roofs, and fenestrations, must be thoughtfully designed to minimize heat gain. Such a strategy ensures that indoor temperatures remain lower than the external ambient temperatures, thus promoting thermal comfort indoors. This objective can be achieved through the adoption of various strategies, including the use of building materials with low thermal conductivity (measured by U-value) and effective insulation materials. Based on the research findings, it has become evident that wall materials incorporating insulation have the most significant impact on energy consumption. This discovery runs contrary to the observations made by Dhaka (Dhaka, Mathur and Garg, 2012) who suggested that roof insulation alone could account for approximately half of the energy load reduction in comparison to other building components. One possible explanation for this disparity could be that Dhaka addressed variations in energy consumption reduction due to energy-efficient measures across buildings of different sizes. This suggests the need for further investigations into this area.

Efforts aimed at designing energy-efficient building envelopes exhibit substantial potential for curbing energy consumption during building operation, potentially achieving savings of up to 18%, as illustrated in Figure 7. The extent of these savings is heavily reliant on the specific details of the base case building envelope. Notably, the utilization of materials such as a green roof with a 12" layer of soil and 1-inch polyisocyanurate insulation in the roof, concrete walls with lightweight concrete (30 pounds per cubic foot) and an 8-inch thickness, combined with 2" polyurethane foam board insulation in walls, as well as fenestrations featuring double reflective glass and a ¼" to ½" air gap, contributes significantly to maximum energy conservation.

Different combinations of materials and energy conservation measures should be considered and simulated with the help of simulation software at the design stage of new buildings to reduce operational energy in the future. This research paper aims to provide valuable insights for researchers, shedding light on the critical role of the building envelope in enhancing energy efficiency for residential buildings situated in composite climates. The study focuses specifically on the context of India but offers a framework that can be applied to similar research endeavors in other regions.

References

Agarwal, P. & Prabhakar, A. (2023) 'Energy and thermo-economic analysis of PCM integrated brick in composite climatic condition of Jaipur - A numerical study', *Sustainable Cities and Society*, 88, pp. 104294. Available at: https://doi.org/10.1016/j.scs.2022.104294.

Al-nuaimi, S.F. & Almadani, W. (2023) 'Effects of Building Envelopes on Energy Consumption in the Domestic Buildings in Bahrain', *ISVS e-Journal*, Vol. 10, pp. 166–181. Available at: https://isvshome.com/pdf/ISVS_10-1/ISVSej10.1.11_Saad.pdf

Arumugam, C. & Shaik, S. (2021) 'Air-conditioning cost saving and CO2 emission reduction prospective of buildings designed with PCM integrated blocks and roofs', *Sustainable Energy Technologies and Assessments*, 48, pp. 101657. Available at: https://doi.org/10.1016/j.seta.2021.101657.

BEE (2018) Energy Conservation Building Code for Residential Buildings, Ministry of Power, Government of India. India: Bureau of Energy Efficiency.

Charde, M., Bhati, S., Kheterpal, A. and Gupta, R. (2014) 'COMPARATIVE THERMAL PERFORMANCE OF STATIC SUNSHADE AND BRICK CAVITY WALL FOR ENERGY EFFICIENT BUILDING', Thermal Science, 18(3), pp. 925–934. Available at: https://doi.org/10.2298/TSCI1403925C.

Charde, M., Gupta, R., Vemuri, A., Kheterpal, A. & Bhati, S. (2019) 'Passive solar design for energy efficiency in buildings in composite climate', *Journal of Physics: Conference Series*, 1276(1). Available at: https://doi.org/10.1088/1742-6596/1276/1/012080.

Chaturvedi, P.K., Kumar. N., Lamba. R. & Nirwal. V. (2023) 'A Parametric Optimization for Decision Making of Building Envelope Design: A Case Study of High-Rise Residential Building in Jaipur (India)', *Advances in Clean Energy and Sustainability*, Singapore: Springer Nature Singapore, pp. 453–465. Available at: https://doi.org/10.1007/978-981-99-2279-6_39

Chetia, S., Maithel. S., Jaboyedoff, P., Lall.A., Bhanware.P. & Gupta. A. (2016) 'A Case Study on Design of Thermally Comfortable Affordable Housing in Composite Climate: Simulation Results & Monitored Performance', *ENERGISE 2020*, (February), pp. 91–97. Available at: https://www.beepindia.org/wp-content/uploads/2013/12/Energise-2020_Smart-GHAR-Case-Study.pdf

Dhaka, S., Mathur, J. & Garg, V. (2012) 'Combined effect of energy efficiency measures and thermal adaptation on air-conditioned building in warm climatic conditions of India', *Energy and Buildings*, 55, pp. 351–360. Available at: https://doi.org/10.1016/j.enbuild.2012.09.038.

Gandhi, M., Kumar. A., Elangovan. R., Meena. S.C., Kulkarni. S.K., Kumar. A., Bhanot. G. & Kapoor. R.N. (2020) 'A Review on Shape-Stabilized Phase Change Materials for

Latent Energy Storage in Buildings', *Sustainability*, 12(22), pp. 1–17. Available at: https://doi.org/10.3390/su12229481

Gorantla, K., Shaik. S., Kontoleon. J.K., Mazzeo. D., Maduru. R. V. & Shaik. V.S. (2021) 'Sustainable reflective triple glazing design strategies: Spectral characteristics, air-conditioning cost savings, daylight factors, and payback periods', *Journal of Building Engineering*, 42(July), pp. 103089. Available at: https://doi.org/10.1016/j.jobe.2021.103089.

Hajare, A. & Elwakil, E. (2020) 'Integration of life cycle cost analysis and energy simulation for building energy-efficient strategies assessment', *Sustainable Cities and Society*, 61(June), pp. 102293. Available at: https://doi.org/10.1016/j.scs.2020.102293.

Hasan, S., Khan, S. & Uddin, S. (2021) 'Materials Today: Proceedings Impact of Phase Change Material (Butyl Stearate) and other insulation material on thermal performance of building envelope in different climates of India', *Materials Today: Proceedings*, 43, pp. 706–713. Available at: https://doi.org/10.1016/j.matpr.2020.12.764.

Ibrahim, H.K. & Hassan, S.A. (2023) 'Design Strategies Employed to Achieve Thermal Comfort in Traditional Religious Buildings in Iraq', *ISVS e-Journal,*10(2), pp. 123–135. Available at: https://isvshome.com/pdf/ISVS_10-2/ISVSej_10.2.8_Hanin.pdf

India energy outlook report (IEA) (2021) 'India Energy Outlook', *World Energy Outlook Special Report*, pp. 1–191. Available at: http://www.worldenergyoutlook.org/media/weowebsite/2015/IndiaEnergyOutlook_WEO2015.pdf.

Jaboyedoff, P., Cusack. K., Bhanware. P. & Ganesan. K. (2015) 'Parametric analysis using dynamic energy simulation tools to evaluate the performance of building envelope in the residential buildings of composite climatic region of India', *14th International Conference of IBPSA - Building Simulation 2015, BS 2015, Conference Proceedings*, (January 2019), pp. 1932–1939. Available at: https://doi.org/10.26868/25222708.2015.3098

Jha, B. & Bhattacharjee B. (2018) 'TOOL FOR ENERGY EFFICIENT BUILDING ENVELOPE RETROFITTING', *ASHRAE and IBPSA-USA Building Simulation Conference, Chicago IL*, pp. 1–8. Available at: https://www.ashrae.org/File%20Library/Conferences/Specialty%20Conferences/2018%20Building%20Performance%20Analysis%20Conference%20and%20SimBuild/Papers/C001.pdf

Khan, M.Y. & Baqi, A. (2021) 'Materials Today: Proceedings Experimental and theoretical analysis of a new kind of building envelope', *Materials Today: Proceedings*, 43, pp. 1368–1375. Available at: https://doi.org/10.1016/j.matpr.2020.09.171.

Khan, M.Y., Baqi, A. & Talib, A. (2021) 'Energy Efficiency Analysis of a Building Envelope', *Springer Proceedings in Energy*, 1691–1702. Available at: https://doi.org/10.1007/978-981-15-5955-6.

Khandelwal, R., Jain, R. & Gupta, M. (2020) 'Case Study: India's First Net-Zero Energy Building- Indira Paryavaran Bhavan', *International Journal of Scientific & Technology Research*, 9(11), pp. 353–357. Available at: https://ijcrt.org/papers/IJCRT22A6858.pdf

Kishore, N. (2022) 'Impact of climate change on future bioclimatic potential and residential building thermal and energy performance in India', *Indoor and Built Environment*, 31(2), pp. 329–354. Available at: https://doi.org/10.1177/1420326X21993919.

Kočí, J., Fořt, J. & Černý, R. (2020) 'Energy efficiency of latent heat storage systems in residential buildings: Coupled effects of wall assembly and climatic conditions', *Renewable and Sustainable Energy Reviews*, 132(March). Available at: https://doi.org/10.1016/j.rser.2020.110097.

Kumar, A. & Suman, B.M. (2013) 'Experimental evaluation of insulation materials for walls and roofs and their impact on indoor thermal comfort under composite climate', *Building and Environment*, 59, pp. 635–643. Available at: 10.1016/j.buildenv.2012.09.023.

Kumar, S. (2009) ECBC, India: Bureau of Energy Efficiency. Available at: https://beeindia.gov.in/sites/default/files/ECBC User Guide V-0.2

%28Public%29.pdf%0Ahttps://ia601000.us.archive.org/35/items/gov.in.is.3346.1980/is.3346.1980.pdf%0Ahttps://irjet.net/archives/V4/i7/IRJET-V4I7111.pdf%0Awww.irjet.net%0Ahttps://beeindia.gov.

Lakhdari, Y.A., Chikh, S. & Campo, A. (2020) 'Analysis of the Thermal Response of a Dual Phase Change Material', *Applied Thermal Engineering*, pp. 115502. Available at: https://doi.org/10.1016/j.applthermaleng.2020.115502.

Li, Q., Ju. Z., Wang. Z., Ma. L., Jiang. W., Li. D. & Jia. J. (2022) 'Thermal performance and economy of PCM foamed cement walls for buildings in different climate zones', *Energy and Buildings*, 277, pp. 112470. Available at: https://doi.org/10.1016/j.enbuild.2022.112470.

Ministry of Power, M. (2021) Annual report 2021-22, India: Government of India.

Nagaraju Kaja (2018) 'A Review of Energy Consumption in Residential Sector in India; Possibilities for Energy Conservation', *IMPACT: International Journal of Research in Humanities, Arts and Literature (IMPACT: IJRHAL)* , 6(6), pp. 375–384. Available at: http://www.impactjournals.us/journals.php?id=11&jtype=2&page=67.

BIS (2016) NBC, India: BIS. Available at: https://www.bis.gov.in/index.php/standards/technical-department/national-building-code/.

Olanrewaju, S.D., Adetunji, O.S. & Ogundepo, T.M. (2019) 'Achieving Energy Efficient Building through Energy Performance Analysis of Building Envelope in Student Housing', *Journal of Physics: Conference Series*, 1378(4). Available at: https://doi.org/10.1088/1742-6596/1378/4/042023.

Prakash, R. & Shukla, K.K. (2017) 'Economic and environmental benefits of roof insulation in composite climate of India', *Climate Change*, (March 2020), pp. 5–7. Available at: 5e60ebfd299bf182deea6a19.pdf

Rahul Verma, Sumit Kumar, Dibakar Rakshit, B.P. (2022) 'Design and Optimization of Energy Consumption for a Low-Rise Building with Seasonal Variations Under Composite Climate of India', *Sol. Energy Eng* [Preprint]. Available at: https://doi.org/10.1115/1.4054831.

Rai, A.C. (2021) 'Energy performance of phase change materials integrated into brick masonry walls for cooling load management in residential buildings', *Building and Environment*, 199(March), pp. 107930. Available at: https://doi.org/10.1016/j.buildenv.2021.107930.

Rawat, M. & Singh, R.N. (2022) 'Thermal performance of building prototype with different cool roof structures in composite climate', *International Journal of Sustainable Energy*, 41(10), pp. 1434–1465. Available at: https://doi.org/10.1080/14786451.2022.2055558.

Saxena, R., Rakshit, D. & Kaushik, S.C. (2019) 'Phase change material (PCM) incorporated bricks for energy conservation in composite climate: A sustainable building solution', *Solar Energy*, 183(March), pp. 276–284. Available at: https://doi.org/10.1016/j.solener.2019.03.035.

Singh, B., Sharma, S.K. & Syal, P. (2021) 'Net Zero Energy Building (NZEB) Design', *Journal of The Institution of Engineers (India): Series A*, 102(1), pp. 237–247. Available at: https://doi.org/10.1007/s40030-020-00500-1.

United Nation-HLPF (2018) 'Review of SDGs Implementation: SDG 11 – Make Cities and Human Settlements Inclusive, Safe, Resilient and Sustainable', *High-Level Political Forum on Sustainable Development*. Available at: https://unhabitat.org/sites/default/files/download-manager-files/SDG%2011%20Executive%20Summary.pdf

Zingre, K.T., S, K.K.D.E. V & Wan, M.P. (2020) 'Analysing the Effect of Substrate Properties on Building Envelope Thermal Performance', *Energies*, 13(19), pp. 1–8. Available at: https://doi.org/10.3390/en13195119