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Article

Assessing the effectiveness of building envelope materials on existing buildings in the sub-tropical climate: A case study in Kathmandu Valley, Nepal

Roshani Subedi[1], Khem N. Poudyal[1], Nawraj Bhattarai[2,*]

[1] Department of Applied Sciences and Chemical Engineering, IOE Pulchowk Campus, Tribhuvan University, Kathmandu 44618, Nepal
[2] Department of Mechanical and Aerospace Engineering, IOE Pulchowk Campus, Tribhuvan University, Kathmandu 44618, Nepal
*** Corresponding author:** Nawraj Bhattarai, bnawraj@ioe.edu.np

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Abstract: This paper is on the effect of building envelopes on thermal performance in the sub-tropical climate in Nepal. In today's urbanized world, concrete buildings are growing and therefore, the greenery is decreasing significantly. Building and construction being one of the driving engines of the worldwide economy, it has become a main concern of sustainability. The Kathmandu Valley is the most densely populated urban area of Nepal, and energy availability has been a major problem in the Valley. Energy modeling exercise was performed through a simulation tool, Ecotect software, to calculate the energy performance of a residential building in the Kathmandu Valley. To attain these objectives, the necessary features of the building site were studied. The building was simulated by creating different building envelopes as scenario cases. Overall comparison was performed to elucidate the pros and cons and show the possibilities for modification of the building to adapt to climate change. The building with materials such as double brick cavity walls and double-glazed timber windows was found to be more effective in comparison to brick walls with cement plaster. The current study has shown that the building's annual energy demand could be reduced by up to 37.5% in the best-selected scenario.

Keywords: adaptation; energy consumption; modeling; building envelope; climate change; Kathmandu Valley

1. Introduction

Building energy use has become one of the most challenging issues in the world. The Global Status Report on Buildings and Construction 2019 states that the building sector is not taking sufficient action to address climate change. The report shows that in 2018, the final energy demand for buildings increased by 1% compared to 2017 and by 7% compared to 2010 [1,2]. Buildings account for one-third of global energy consumption and one-third of direct and indirect greenhouse gas emissions [3–5]. Approximately 40% and 34% of the total energy consumption worldwide is used for space heating and cooling in commercial and residential buildings respectively [6], and it may increase by 7–40% from 2010 levels by 2050 [7]. Buildings and the construction of new buildings continue to use more energy because of increased energy access in developing nations, rising air conditioning demand in tropical regions, increased ownership and use of energy-intensive appliances, and the rapid increase in the building area around the worldwide.

According to the United Nations Department of Economic and Social Affairs

(UN-DESA), over 55% of the world's population currently resides in urban areas, and this is projected to increase to 60% by 2030 and 66.4% by 2050 [8]. This rapid urbanization is particularly significant in less developed regions, where the urban population is expected to grow by 2 billion by 2050, with a 90% increase in Asia and Africa [8, 9]. This rapid urbanization brings many challenges such as housing, transportation, environmental degradation, and social inequalities. It also creates opportunities for sustainable development by improving access to basic services and opportunities for economic growth. The topTop of FormBottom of FormKathmandu Valley, one of the fastest-growing cities in South Asia, accounts for 9% of the total population of Nepal, with a population growth rate of 4.35% [10–12]. The Valley is located at approximately latitude 27.7172° N, longitude 85.3240° E, with an average altitude of 1350 m above sea level [13]. It possesses a temperate monsoon climate with warm, wet summers and cool, dry winters, and most rainfall occurs in June to September [14]. The energy demand in the residential sector has risen day by day because of increasing urbanization and modern lifestyles, which is a crucial sign of a shift in consumption patterns through the construction of energy-efficient structures. Therefore, the study is performed on a residential building located in the Kathmandu Valley. This study determines the effectiveness of building envelopes as insulating barriers for adapting to climate change in a residential building, thereby investigating the performance of the materials in the building envelope.

Envelopes are among the crucial components for studies on energy consumption among the many parts of a building [15]. The building envelope is the primary point of contact between indoors and the outside and plays a vital role in regulating changes in the weather outside, ensuring thermal comfort for inhabitants and determining the structure's heating and cooling loads [16, 17]. The efficiency with which a building's envelope is thermally treated determines the amount of energy needed to cool or heat it, particularly in envelope-dominated buildings such as residences. The thermal properties of building materials, such as their capacity to absorb or emit solar heat, as well as the overall U-value of relevant components, such as insulation, play a significant role in determining the thermal performance of a building envelope [18,19]. The U-value measures the heat transfer through a material or assembly. It is the inverse of the R-value (thermal resistance). A lower U-value indicates better thermal performance [20]. The thermal mass of the building envelope determines the ability to slow down heat movement through the building structure over time. Thermal mass is a property of a building envelope that is related to the thickness and type of construction material used. By absorbing and gradually releasing the heat generated both internally and externally, it aids in the regulation of the interior temperature. As a result, the peak interior loads are reduced, and the mean radiant temperature is decreased [17]. Residential building sustainability performance can be evaluate by using 6D building information modelling (BIM) for integrated energy , cost, and environmental impact assessment [21].

2. Materials and methods

Building energy simulation is a tool that can be used to predict and analyze the energy performance of a building. It can be used in the design phase to evaluate the energy efficiency of different design options and identify opportunities for improvement. It can also be used during the operation and maintenance phase to monitor energy usage and identify potential issues. Ecotect does not automatically include build-in-climate data specifically for Kathmandu, thus gathering data from different secondary sources, with the lack of reliable local climate data input in the mode,l is the limitation of this study. Building energy simulation is becoming increasingly popular as a cost-effective way to support energy efficiency in buildings and to make informed decisions about energy management [22]. These simulations include assessing energy-saving techniques and architectural design [23]. Ecotect is one of the few tools that can perform a straightforward thermal performance analysis that is both reasonably accurate and extremely responsive graphically [24–26]. This program has been utilized in numerous research investigations by researchers to analyze the necessary design configurations. Shoubi et al. studied a double-story bungalow house in the warm and humid climate of Malaysia to reduce the total energy consumption in the building [27]. Al-Tamimi and Fadzil showed different passive design approaches to reduce the cooling requirement for high-rise apartments through an improved building envelope design [28]. Aldali and Moustafa used Ecotect to measure the building energy and lighting performance in one of the modern cities, Madenaty city, Egypt. They analyzed the heating and cooling loads in two duplex residential flats [29]. A similar study is performed by Eskin and Türkmen for a commercial building in Turkey [30]. Anand et al. proposed 14 different room layouts for a moderate climate in India to find the best thermal comfort conditions for nights and the day using the windows analysis [31]. Numerous studies are performed using simulation software to analyze the physical environment of the building and predict energy consumption. Based on these studies, architects and engineers attempt to provide ecological and energy-saving strategies in the earlier design process, thereby integrating the architecture into a scientific and organic component [32–35]. The framework of this study is shown in **Figure 1**.

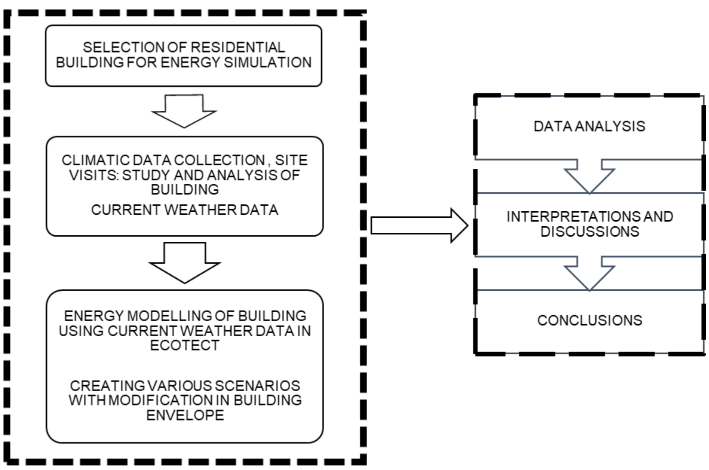

Figure 1. Framework of the study.

2.1. Study area

The Kathmandu Valley lies at an average elevation of 1300 meters above sea level and is located between latitudes 27°32′13″ and 27°49′10″ north and longitudes 85°11′31″ and 85°31′38″ east. It covers an area of 665 square kilometers and is home to the districts of Bhaktapur, Kathmandu, and Lalitpur. The Valley has a unique bowl-like shape, which has resulted in a microclimate that differs from the surrounding areas. The city lies in a sub-tropical region and experiences a relatively mild climate with an average temperature of around 24 °C. However, temperatures can vary significantly depending on the season, with warmer temperatures during the summer months and cooler temperatures in the winter. The annual humidity in Kathmandu is around 75%, which can make the climate feel more humid and uncomfortable during certain times of the year [36]. The mean annual rainfall of the Kathmandu Valley is 1600 mm, with nearly 80% occurring during the monsoon [37]. The Kathmandu Valley has an estimated population of 2.54 million and is experiencing rapid growth at a rate of 6.5% per year [38]. It is an important site for studying the effects of climate change on building envelopes due to its rapid urbanization. As the population of the Valley continues to grow and urbanization continues, buildings are being constructed at a rapid pace to accommodate the increasing population. However, many of these buildings may not be designed and constructed to withstand the effects of climate change. Therefore, it is important to study the effectiveness of building envelopes in protecting buildings and their occupants from the impacts of climate change. This research can help inform urban planners and architects in the development of more resilient and sustainable buildings in the Valley, which can ultimately improve the living conditions of the population and support sustainable urban development.

2.2. Data collection and analysis

The primary investigative approach used in this study was simulation research. Energy simulation software Ecotect is used to assess building performance. Energy modeling was performed by creating four different scenarios. The Ecotect software is used in various research to study the thermal performance of buildings [39,40]. It is compatible with BIM applications such as Autodesk Revit Architecture. Numerous studies have demonstrated that Ecotect simulations are highly accurate [3,24,25]. To attain this objective, a three and a half-story residential building is selected and studied as this is one of the most common types of building in Kathmandu. The collected documents and drawings were drafted according to site conditions and simulated. Simulation research is conducted using the Ecotect model, calibrating the software with recorded weather data for 2020 as shown in **Figure 2**. After combining the weather file in Ecotect, thermal analysis is the major concern to study the comfort level of the building. Here, a few parameters were set and calculated to study the energy performance of the building. Parameters such as the monthly load of an active system, passive gain breakdown, and annual heating loads are calculated for thermal analysis. Also, the building is simulated by creating different building envelopes as scenario cases, as shown in **Table 1**. Overall comparisons are performed to dissect the pros and cons and the possibilities of modification in building to adapt to climate change.

The floor and roof are kept the same as a typical concrete floor structure because the simulation's focus is on building envelope features.

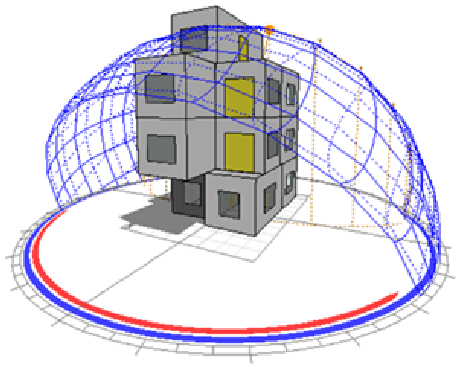

Figure 2. Energy modeling in Ecotect.

Table 1. Materials are assigned to different scenarios.

	Scenario 1: Business-as-usual (BAU)	Scenario 2	Scenario 3	Scenario 4
Door	Solid core oak timber	Hollow-core plywood	Hollow-core plywood	Hollow-core plywood
Window	single-glazed timber window	Double-glazed timber window	Double-glazed timber window	Double-glazed timber window
Wall	Brick with a cement plaster-230 mm	Double brick cavity wall	8 in. (203 mm) thick concrete block wall	Reverse brick veneer wall-R 20

3. Results and discussion

3.1. Annual heating and cooling load

Figures 3 and **4** depict the outcomes of the heating and cooling load simulations carried out using Ecotect. The maximum heating load is observed in scenario 1, which represents the business-as-usual (BAU) scenario, and then in scenario 3. Scenario 4, which features a reverse brick veneer wall, performed better in terms of heating load compared to the other wall types owing to its high R value. The insulation layer, which is usually made of a high-density material, provides an effective barrier to heat transfer, preventing heat from escaping from the building's interior. In addition, the reverse brick veneer wall construction also helps to reduce thermal bridging, which occurs when heat is conducted through the solid components of the wall, such as the studs, and is lost to the outside environment [41]. The insulation layer in reverse brick veneer construction is located outside of the thermal mass of the building, which means that the thermal mass can be used to store heat generated from the sun or heating systems during the day, releasing it slowly during the colder nighttime hours.

Nonetheless, the effectiveness of reverse brick veneer construction in providing thermal insulation is reliant on the quality of insulation and the installation methods employed. Other factors such as air leaks, thermal bridging, and moisture management can also influence a building's thermal performance. Proper construction and design approaches can ensure that reverse brick veneer construction offers adequate thermal insulation.

In terms of cooling load, scenario 2 outperformed the other scenarios. Scenario 2, featuring a double brick cavity wall, has the lowest cooling load among the tested wall types. The air gap between two layers of brick prevents the transfer of heat from the external environment to the internal environment, reducing the amount of heat that needs to be removed through cooling. During the hot summer months, the cavity acts as a barrier to the penetration of heat, thereby keeping the interior of the building cooler. Scenario 2 is followed by scenario 4. Compared to a double brick cavity wall, reverse brick veneer has a lower thermal mass, making it more susceptible to heat transfer from outside to inside, increasing cooling loads [42]. It is crucial to understand that choosing a wall material is just one of many elements that can affect a building's thermal performance. A thorough approach to building design should therefore include numerous techniques to maximize thermal performance.

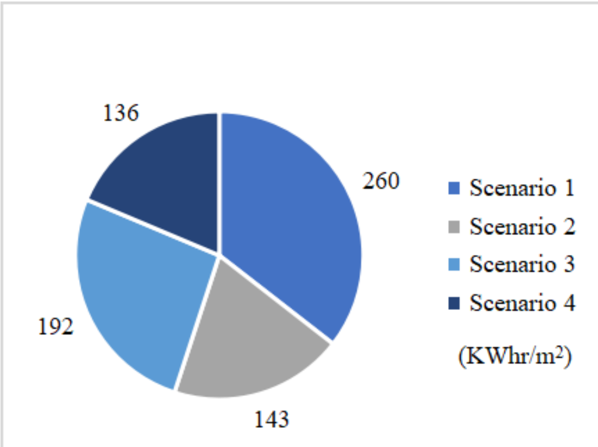

Figure 3. Total annual heating load.

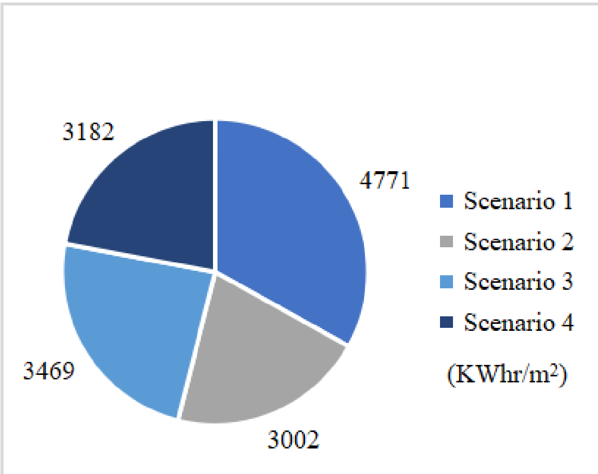

Figure 4. Total annual cooling load.

3.2. Annual energy consumption

3.2.1. Annual energy consumption—Heating loads (kWh)

Figure 5 displays that for all four scenarios, the annual energy consumption for heating is highest in January, which corresponds with the coldest time of the year in Kathmandu. Scenario 1 (business as usual) has the greatest energy consumption out of the four scenarios, whereas scenarios 2 and 4 demonstrate comparable energy consumption levels for heating. Maharjan and Uprety conducted a study on a residential building in Kathmandu, which yielded comparable findings [43].

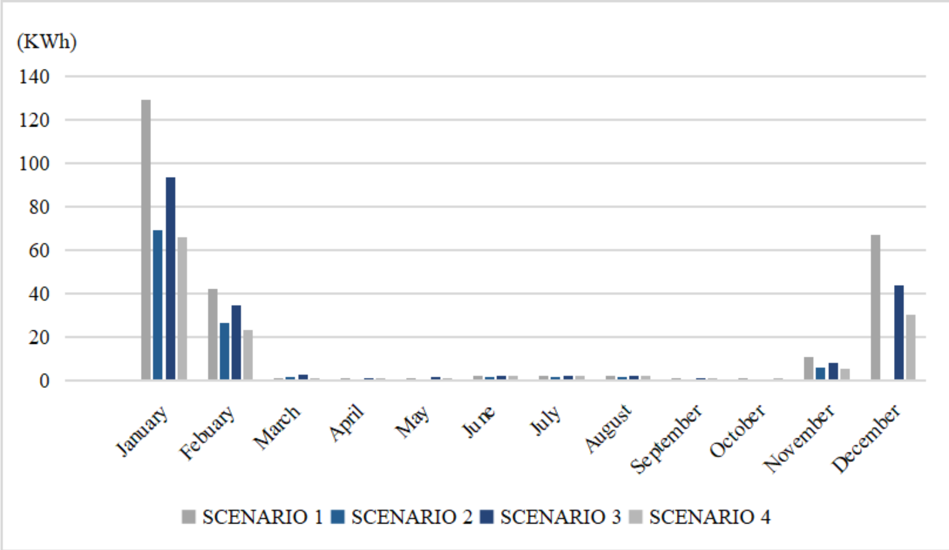

Figure 5. Annual energy consumption—Heating loads.

3.2.2. Annual energy consumption—Cooling loads (kWh)

Figure 6 illustrates that all four scenarios have the highest annual energy consumption for cooling in June, which coincides with the hottest time of the year in Kathmandu. Out of the four scenarios, it appears that scenario 1 (business as usual) has the greatest energy consumption, while scenarios 2 and 4 show similar and lower energy consumption for cooling**.** Maharjan and Uprety conducted a study on a residential building in Kathmandu, which yielded comparable findings [43].

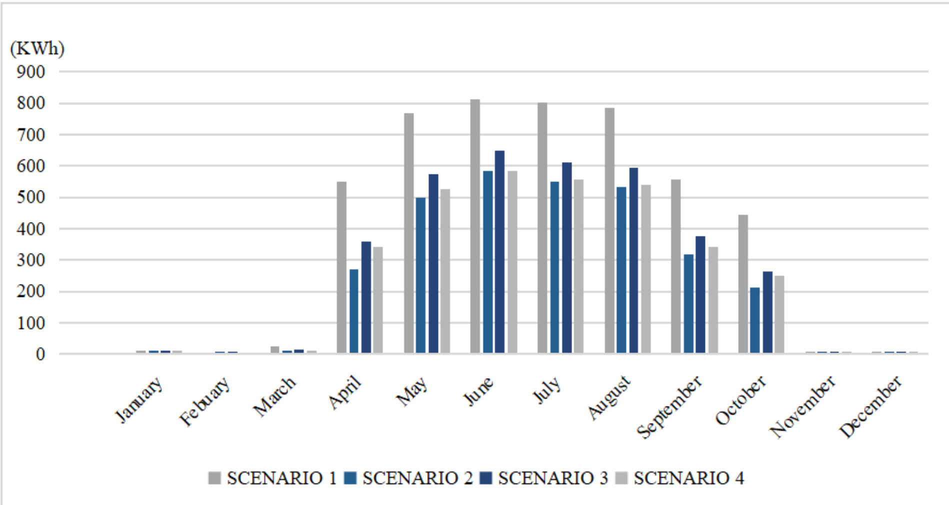

Figure 6. Annual energy consumption—Cooling loads.

3.2.3. Annual energy consumption loads (KWh)

Figure 7 illustrates that across all four scenarios, the annual energy consumption is highest in June and lowest in November in the Kathmandu Valley. Scenario 1 (business as usual) has the greatest energy consumption among the four scenarios, while scenario 2 (double brick cavity wall) consistently has the lowest annual energy consumption for each month. Additionally, the findings indicate that the cooling load is greater than the heating load, suggesting the impact of climate change in Kathmandu. This is significant because Kathmandu previously experienced cold climatic conditions [44].

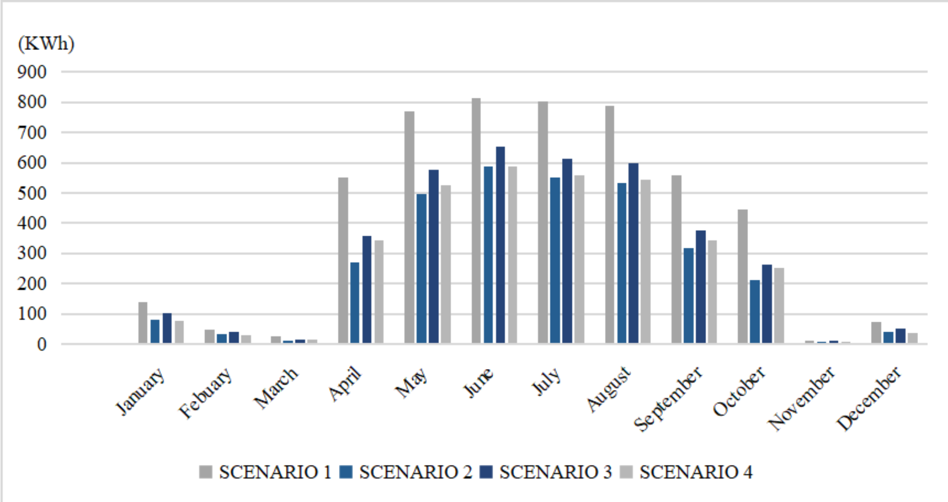

Figure 7. Annual energy consumption—Total loads.

The results of the other three scenarios were compared to scenario 1 (BAU), which showed that scenario 2 (double brick cavity wall with double glazed window) has the highest reduction at 37.5%, followed by scenario 4 at 34.05%, and scenario 3 at 27.17%. The use of materials such as double brick cavity walls and double-glazed windows was found to be a much more efficient solution than brick with cement plaster 230 mm and single-glazed glass windows, resulting in a potential annual energy consumption demand reduction of up to 37.5%. This is consistent with Bajracharya et al.'s study on energy-efficient buildings in the Kathmandu Valley, which found that cavity wall construction is 38% more energy-efficient than 9-inch-thick brick walls [45], and using Building Information Modelling (BIM) together with anorthogonal test method shows significantly lowers the energy consumption [46], which supports the results of this study. Energy-efficient residential buildings in Kathmandu Valley have higher initial construction costs, but reduce consumption over time, lowering the payback period ranging from four to ten years [47]. Thus, the scope of the current study is significant in the real world applications. Likewise, Thapa et al. studies showed a similar result in a residential building [48]. This result is also very similar to the study performed in Sydney, Australia [49]. Their research showed that cavity brick dwellings have benefited more in terms of reduction in energy consumption than weatherboard and brick veneer dwellings. However, this metric is heavily reliant on the occupant's behavior, their understanding of energy efficiency, and the cost of energy. Considering the low level of energy efficiency awareness among the local population because of vast fuel sources and considerable subsidies, appropriate legislation and societal outreach activities are required. Building envelopes are key factors for improving the energy performance of a building. The sensitivity analysis of Kathmandu residential buildings shows insulation, window size, and orientation significantly impact energy uses, thermal comfort and optimal costs [50]. The energy-efficient materials-built environment should also be considered and incorporated into buildings to achieve sustainable goals. Integrating green technologies with urban modelling improves efficiency, lowers emissions, and supports cost-effective sustainable urban construction decisions [51]. The uses of complex artificial intelligence (AI) models can accurately predict and optimize energy use in buildings, significantly improve sustainability, and reduce energy costs [52]. Therefore, it is recommended to do more analysis using the tool in the case of Kathmandu Valley's residential sector's building analysis. Energy simulation tools guide residential design for improved efficiency, sustainability and reduce energy consumption [53]. Hence, the application of the tools will provide the policy makers with the formulation of effective policies in the sector in the days to come.

4. Conclusion

The efficiency of the building envelope in terms of thermal performance is significantly influenced by the type of building. This study gives a broad overview of the performance traits, key properties, and uses of common building envelope materials in concrete building systems. The thermal performance of residential buildings was assessed by energy simulation of the typical building materials. The goal of this study is to offer comprehensive and useful knowledge for the design and construction of energy-efficient buildings. The recommendations can be summarized in the following points:

- Thermal performance can be significantly increased by properly treating building envelopes, especially for buildings with a high envelope load, such as residences. Properly treating the building envelope, including the careful selection and treatment of its parts, can significantly increase its thermal efficiency and ultimately improve the overall energy efficiency of the building.
- To create more thermally comfortable spaces and reduce energy consumption, insulation is advised for buildings in all climates. Insulation contributes to minimizing conduction losses across all building envelope elements.

The results of the study serve as a basis for developing methodological foundations for the design, construction, operation, and renovation of energy-efficient buildings. The results can provide valuable information on the thermal performance of different building envelope materials and can help guide architects, builders, and engineers in making informed decisions about which materials to use and how to properly treat the building envelope to optimize energy efficiency. The study's findings can also be used to develop policy guidelines and codes to promote the construction of energy-efficient buildings to builders and support efforts to reduce energy consumption and mitigate the impacts of climate change.

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