УДК 72.02

**Olga Krivenko [1], Nataliia Kozak [2]**

[1] *Doctor of Engineering Sciences, professor*
*Professor of Department of Architectural Construction KNUCA*
knuba.o.v.k@gmail.com
orcid.org/0000-0002-8949-0944

[2] *PhD, Assoc. Prof., Department of Architectural Construction, KNUCA*
Kozak.nf@knuba.edu.ua
orcid.org/0000-0001-9387-4652

# EVOLUTION OF ENERGY-EFFICIENT SOLUTIONS IN THE FORMATION OF BIOCLIMATIC ARCHITECTURE



https://doi.org/10.32347/2519-8661.2025.34.84-90/

**Abstract:** Modern challenges of energy-efficient and environmentally friendly construction highlight the need to rethink traditional approaches to architectural design through the prism of the evolutionary development of energy-efficient technologies. This article explores the patterns of transformation of energy-saving solutions from traditional folk practices to scientifically based bioclimatic architecture.

The aim of the work is to identify the evolutionary relationships between traditional and modern energy-efficient approaches and to systematize the principles of their integration to improve the sustainability of urban settlements. The study is based on an analysis of scientific works from 2013-2025 and historical examples of traditional architecture in different climatic zones: Arctic dwellings (igloos), desert settlements of the Mozabites, traditional solutions in Northern and Southern China, Persian geothermal systems, and Italian passive cooling technologies of the 16th century. Methods of comparative analysis, typological classification, quantitative assessment of thermal characteristics, and modeling of energy characteristics of buildings were used.

The analysis confirms the high efficiency of the key principles of folk architecture: thermal inertia provides 20-30% energy savings with the potential to increase to 35-45% when integrated with phase change materials; passive cooling demonstrates 25-40% efficiency with the possibility of increasing it to 40-60% through geothermal systems; climate adaptation increases sustainability by 15-25% with the potential to expand to 30-50% thanks to smart adaptive systems.

The scientific novelty lies in establishing the evolutionary patterns of energy-efficient architectural solutions through four stages: empirical experience → scientific justification → technological integration → smart systems. The practical significance is determined by the development of a conceptual framework for the transformation of traditional energy-saving mechanisms into modern architectural and structural solutions capable of reducing energy consumption.

**Keywords:** bioclimatic architecture, evolution of energy efficiency, traditional construction, passive systems, adaptive design, architectural sustainability

**Introduction.**

The modern construction industry is responsible for about 40% of global carbon emissions, making it a key area for climate action and the transition to a low-carbon economy. Over many centuries, traditional construction practices around the world have developed in response to natural and climatic conditions, available resources, and the functional needs and cultural characteristics of local inhabitants. The development of technical progress and new technologies in construction has made it possible to create a microclimate inside buildings, regardless of natural and climatic conditions.

This has resulted in significant energy consumption, production and construction waste, and a high concentration of human waste in compact areas, which is gradually leading to the destruction of the environment. In the context of growing environmental challenges, architects and scientists are increasingly turning to the study of traditional approaches that have long demonstrated energy-saving approaches and adaptability to local climatic conditions.

Therefore, it is particularly important to study the evolutionary patterns of energy-saving solutions, from empirical folk practices to scientifically based bioclimatic technologies capable of increasing the sustainability of modern urbanized areas.

**Analysis of previous studies.**

The task of ecological architecture is to reduce the consumption of natural resources through architecture, where one of the areas of development is bioclimatic architecture. In the article, *Kryvenko O.V.* defines bioclimatic architecture as a phenomenon in ecological architecture that has ancient origins but is also a new direction in the development of energy-efficient design.

Research *by Bera M. & Nag R.* confirms the effectiveness of bioclimatic design for low-cost housing, where passive strategies provide a significant increase in thermal comfort. In particular, sunshade window shading provides 25.5% of total thermal comfort, passive solar heating with high thermal mass provides 6.2%, and natural ventilation provides 2.2% of the total energy needs of a building.

*Tang J. & Wan Ibrahim W.Y.* studied the microclimate in three traditional gardens in Suzhou, China, using GIS technologies to analyze the impact of water bodies, vegetation, and architecture on microclimatic parameters—air temperature and humidity. The results demonstrate effective microclimate regulation through the thoughtful composition of garden elements, which is an example of adaptive landscape design.

*Ferrucci M. & Peron F.* analyzed the use of natural geothermal cooling in 16th-century Italian villas in Vicenza. At an outside air temperature of 33°C, the air temperature on the first floor was 20°C thanks to the use of caves with a constant temperature of 11-12°C. The study demonstrated the effectiveness of passive cooling systems based on the use of underground channels.

*Ozarisoy B.* demonstrated the effectiveness of passive cooling strategies, which reduced temperatures from 32.1°C to 24.7°C during prolonged heat waves in Europe. *Li et al.* found that natural ventilation reduces energy consumption by 40-50% in large urban areas in Europe and North America.

*Pallin & Pilet* proved that thermal mass combined with temperature optimization provides energy savings of up to 58% in residential buildings. *Lysak* showed that geothermal cooling systems reduce electricity consumption by 90% compared to air chillers.

Problem statement: Despite numerous studies on individual aspects of traditional and modern energy-efficient construction, there is no analysis of the evolutionary patterns and interrelationships between traditional and modern energy-saving approaches for their integration into modern bioclimatic design.

**Research objective.**

To identify and scientifically substantiate the evolutionary interrelationships between traditional folk architecture solutions and modern energy-efficient technologies, developing a conceptual framework for their integration to improve the sustainability of modern buildings.

**The results of the research and their discussion.**

Folk architecture as a dynamic system has adapted to the surrounding natural environment in order to form a reliable and functional living space. Folk or traditional architecture is the beginning of the development of an energy-efficient and environmentally friendly approach, which was created empirically based on experience over thousands of years, as we will see in the examples below.

*Arctic energy-efficient technologies.* The igloo, a traditional winter dwelling of Canadian Eskimos made of ice or snow, demonstrates unique thermal properties due to the low thermal conductivity of snow ($\lambda$ = 0.05-0.15 W/(m·K)). Despite the seemingly cold building material, the igloo is quite warm and dry. Heated by breath, the snow inside begins to melt slightly, but the walls do not melt. The colder it is outside, the higher the temperature the igloo can withstand inside. The design involves spiral construction with each block supported at three points by the previous ones, ensuring structural stability and optimal load distribution.

*Desert energy-saving strategies.* The houses of the Mozabites in the Northern Sahara were built with thick (0.6-1.2 m) stone (or adobe) walls. The thermal capacity of building structures and materials protected the interior from overheating during the day, and at night, the heat accumulated in the structures warmed the rooms. Temperature fluctuations inside the rooms were no more than 5-7°C, with external daily fluctuations of 25-30°C. The high walls and narrow alleys of the Mozabite settlements were shaped and oriented in such a way as to create a cool breeze and protect the inhabitants from the scorching desert sun.

*Regional features of climate adaptation as exemplified by traditional Chinese architecture*. The conventional line of the enlarged climatic division between northern and southern China runs along the Qinling Mountains from Sichuan Province through the southern province of Shaanxi eastward along the Huaihe River to the Pacific Ocean. In northern China, traditional houses have thick walls to protect against the cold, winds in winter, and heat in summer, and have steeply sloping roofs to shed snow. Yáodong is a special form of dwelling-storage, where the earth serves as an effective heat insulator, keeping the interior warm during the cold season and cool during the hot season. The courtyards were open and faced south so that the windows and walls of the building would be as sunny as possible. In southern China, pillars and pylons were widely used to support buildings above the ground to protect them from high humidity and flooding; wide roofs with overhangs were used to protect against rain. The inner courtyards were small, limiting the amount of sunlight and removing hot air from the rooms.

*Persian passive cooling systems.* Iranians used wind towers and underground air ducts for passive cooling and ventilation as early as the fourth millennium BC. Sometimes they were integrated with underground channels for collecting water. The system provided natural circulation, as a result of which hot outside air passing through underground channels was cooled as it entered the rooms, and then heated up, rose, and was discharged outside through the upper openings of the wind towers.

*Italian geothermal systems.* In the 16th century, in the mountainous regions of Vicenza and Sicily, the construction of luxurious villas with natural cooling systems became widespread. These systems used the villas' basements, which were connected to caves by specially dug underground passages several hundred meters long. The temperature inside the caves was 11-12°C throughout the year. At an outside temperature of 33°C, the temperature of the air coming from the basements into the rooms on the first floor was 20°C.

*Systematization of evolutionary transformations of energy-efficient principles.*

A comprehensive analysis of the evolution of energy-efficient architectural solutions allows us to identify key principles that have undergone a transformation from empirical folk practices to scientifically based modern technologies through four stages of development: empirical experience → scientific justification → technological integration → smart systems. Let us conduct a quantitative assessment of the potential for integrating traditional principles into modern architectural and structural solutions with scientific justification based on a review of international research for the period 2013-2025.

*Thermal inertia*: The traditional approaches discussed above demonstrated an intuitive understanding of the heat-accumulating properties of materials. Thermal inertia as the basis for increasing energy efficiency from the traditional 20-30% to 35-45% is substantiated by research by *Pallin & Pilet*, who found that thermal mass combined with temperature optimization provides energy savings of up to 58% in residential buildings. *Ghoreishi* confirmed that the primary elements of thermal mass have the greatest impact on the energy performance of buildings.

*Passive cooling*: the expansion of potential from 25-40% to 40-60% is confirmed by research by *Ozarisoy*, who demonstrated the effectiveness of passive cooling strategies with a temperature reduction from 32.1°C to 24.7°C. Li and co-authors found a 40-50% reduction in energy consumption from natural ventilation. *Lysak* demonstrated a 90% energy saving for geothermal systems compared to air chillers.

*Climate adaptation:* the increase in efficiency from 15-25% to 30-50% is supported by research by *Correia & Amorim*, who found a 14-22% reduction in annual energy loads due to coatings with high solar reflectivity in the tropical climate of Brazil. *Alayed* investigated the variability of the thermal mass effect depending on climatic conditions.

*Local materials*: an increase in efficiency from 30-50% to 45-70% is confirmed by *Yang's* research, which found that local building materials contribute 65% to the energy efficiency standards of residential buildings. Studies of sustainable materials demonstrate minimal embodied carbon and high heat storage properties.

*Strategies for integrating traditional and modern approaches to improve the sustainability of cities.*

The integration of traditional energy-efficient principles into modern urban planning creates a synergistic effect to increase the sustainability of urban areas in key areas:

- Energy efficiency is achieved through a combination of passive and active systems, which can reduce energy consumption by integrating IoT technologies with traditional principles of natural ventilation and thermal inertia.
- Climate adaptation is implemented through the creation of microclimatic zones using traditional landscape design principles, which reduces the urban heat island effect by 3-5°C through a thoughtful composition of greenery and water elements.
- Resource autonomy is ensured through the localization of material flows and closed resource cycles, reducing dependence on external supplies through the use of local materials and the recycling of construction waste.
- Environmental sustainability is achieved through biomimicry of natural processes and the integration of green technologies, which increase the biodiversity of the urban environment and air quality through adaptive facades and natural purification systems.

It should be noted that the potential for implementing evolutionary energy efficiency principles may vary depending on the type of urban development. Public buildings have the highest potential and can serve as demonstration projects for scaling up the experience. Residential development has high potential for mass implementation thanks to standardized solutions. Commercial buildings have medium implementation potential due to the need to balance energy efficiency and economic factors. A key factor for successful integration is a phased implementation: from pilot projects to regulatory consolidation in urban planning standards. This allows for the gradual adaptation of traditional principles to modern technological capabilities and creates a sustainable foundation for the development of bioclimatic architecture in the urban environment.

**Conclusions.**

The article examines the evolutionary relationships between energy-efficient solutions in traditional and modern architecture. In order to systematize evolutionary patterns, a comprehensive analysis of the transformation of energy-efficient principles (thermal inertia, passive cooling, climate adaptation, local materials) through four stages of development was carried out: empirical experience → scientific justification → technological integration → smart systems. It has been established that traditional architecture provides a fundamental basis for modern bioclimatic solutions in architecture. Based on an analysis of scientific research from 2013-2025, it has been proven that integrating traditional principles with modern technologies increases efficiency. Four key factors of urban sustainability (energy efficiency, climate adaptation, resource autonomy, environmental sustainability) have been identified, which can be enhanced through the integration of evolutionary energy-efficient solutions . The scientific novelty of the research lies in establishing evolutionary patterns in the development of energy-efficient architectural solutions and developing a conceptual framework for the systematic integration of traditional and modern approaches. The practical significance is determined by the possibility of using the results to develop adaptive architectural strategies in the modern urban context.

**Бібліографія**

Alayed, E. (2022). Thermal mass impact on energy consumption for buildings in hot and cold conditions using Saudi Arabia as a case study climate. *Energy and Buildings*, 262, 112031. https://doi.org/10.1016/j.enbuild.2022.112031

Bera, Mahadev & Nag, Pranab. (2022). Bioclimatic Design of Low-Cost Rural Dwellings. *Frontiers in Built Environment*. 8. 773108. https://doi.org/10.3389/FBUIL.2022.773108

Correia, C. M. de A., Amorim, C. N. D., & Santamouris, M. (2024). Use of passive cooling techniques and super cool materials to minimize cooling energy and improve thermal comfort in Brazilian schools. Energy and Buildings, 307, 113947. https://doi.org/10.1016/j.enbuild.2024.114125

Ferrucci, M., & Peron, F. (2018). Ancient Use of Natural Geothermal Resources: Analysis of Natural Cooling of 16th Century Villas in Costozza (Italy) as a Reference for Modern Buildings. *Sustainability*, *10*(12), 4340. https://doi.org/10.3390/su10124340

Ghoreishi, A. (2015). Assessment of thermal mass property for energy efficiency and thermal comfort of concrete office buildings. *Portland Cement Association Research Report*. Retrieved from https://www.ideals.illinois.edu/items/79523

Li, W., Zhang, R., Liu, S., Wang, Y., & Chen, X. (2024). Natural ventilation cooling effectiveness classification for building design based on comprehensive evaluation. *Scientific Reports*, 14, 15967. https://doi.org/10.1038/s41598-024-66684-9

Lysak , O. (2025). USE OF GEOTHERMAL COOLING BY AIR CONDITIONING SYSTEMS AS A MEANS OF REDUCING THE LOAD ON POWER SUPPLY SYSTEMS IN THE WARM SEASON. *Vidnovluvana Energetika* , (1(80), 116-123. https://doi.org/10.36296/1819-8058.2025.1(80).116-123

Ozarisoy, B. (2021). Energy effectiveness of passive cooling design strategies to reduce the impact of long-term heatwaves on occupants' thermal comfort in Europe: Climate change and mitigation. *Journal of Cleaner Production*, 330, 129675. https://doi.org/10.1016/j.jclepro.2021.129675

Pallin, S. B., & Pilet, T. (2019). Variables Influenced by Thermal Mass and its Impact on Energy Performance in Buildings. *Oak Ridge National Laboratory Report*, ORNL/TM-2019/1369. Retrieved from https://www.osti.gov/servlets/purl/1649425

Tang, J., & Wan Ibrahim, W. Y. (2025). Visualization microclimate scenarios of Classical Chinese Garden in Suzhou, China. *Journal of Integrated Planning and Development*, 9(1), 10772. https://doi.org/10.24294/jipd10772

Yang, Q. (2014). Study on energy saving of local building material. *Applied Mechanics and Materials*, 539, 711-715. https://doi.org/10.4028/www.scientific.net/AMM.539.711

Кривенко, О. В. (2013). Біокліматична архітектура як явище в екологічній архітектурі. *Енергоефективність в будівництві та архітектурі*, (4), 101-105. https://repositary.knuba.edu.ua/server/api/core/bitstreams/1ae91a0a-cd5a-443c-ab02-efae4fb12f11/content

**Bibliography**


Alayed, E. (2022). Thermal mass impact on energy consumption for buildings in hot and cold conditions using Saudi Arabia as a case study climate. *Energy and Buildings*, 262, 112031. https://doi.org/10.1016/j.enbuild.2022.112031

Bera, Mahadev & Nag, Pranab. (2022). Bioclimatic Design of Low-Cost Rural Dwellings. *Frontiers in Built Environment*. 8. 773108. https://doi.org/10.3389/FBUIL.2022.773108

Correia, C. M. de A., Amorim, C. N. D., & Santamouris, M. (2024). Use of passive cooling techniques and super cool materials to minimize cooling energy and improve thermal comfort in Brazilian schools. Energy and Buildings, 307, 113947. https://doi.org/10.1016/j.enbuild.2024.114125

Ferrucci, M., & Peron, F. (2018). Ancient Use of Natural Geothermal Resources: Analysis of Natural Cooling of 16th Century Villas in Costozza (Italy) as a Reference for Modern Buildings. *Sustainability*, *10*(12), 4340. https://doi.org/10.3390/su10124340

Ghoreishi, A. (2015). Assessment of thermal mass property for energy efficiency and thermal comfort of concrete office buildings. *Portland Cement Association Research Report*. Retrieved from https://www.ideals.illinois.edu/items/79523

Li, W., Zhang, R., Liu, S., Wang, Y., & Chen, X. (2024). Natural ventilation cooling effectiveness classification for building design based on comprehensive evaluation. *Scientific Reports*, 14, 15967. https://doi.org/10.1038/s41598-024-66684-9

Lysak , O. (2025). USE OF GEOTHERMAL COOLING BY AIR CONDITIONING SYSTEMS AS A MEANS OF REDUCING THE LOAD ON POWER SUPPLY SYSTEMS IN THE WARM SEASON. *Vidnovluvana Energetika* , (1(80), 116-123. https://doi.org/10.36296/1819-8058.2025.1(80).116-123

Ozarisoy, B. (2021). Energy effectiveness of passive cooling design strategies to reduce the impact of long-term heatwaves on occupants' thermal comfort in Europe: Climate change and mitigation. *Journal of Cleaner Production*, 330, 129675. https://doi.org/10.1016/j.jclepro.2021.129675

Pallin, S. B., & Pilet, T. (2019). Variables Influenced by Thermal Mass and its Impact on Energy Performance in Buildings. *Oak Ridge National Laboratory Report*, ORNL/TM-2019/1369. Retrieved from https://www.osti.gov/servlets/purl/1649425

Tang, J., & Wan Ibrahim, W. Y. (2025). Visualization microclimate scenarios of Classical Chinese Garden in Suzhou, China. *Journal of Integrated Planning and Development*, 9(1), 10772. https://doi.org/10.24294/jipd10772

Yang, Q. (2014). Study on energy saving of local building material. *Applied Mechanics and Materials*, 539, 711-715. https://doi.org/10.4028/www.scientific.net/AMM.539.711

Kryvenko, O. V. (2013). Bioklimatychna arkhitektura yak yavyshche v ekolohichniy arkhitekturi. *Enerhoefektyvnist' v budivnytstvi ta arkhitekturi*, (4), 101-105. https://repositary.knuba.edu.ua/server/api/core/bitstreams/1ae91a0a-cd5a-443c-ab02-efae4fb12f11/content

**Кривенко О.В. [1], Козак Н.Ф. [2]**

[1] *доктор технічних наук, професор,*
*професор кафедри архітектурних конструкцій КНУБА*
knuba.o.v.k@gmail.com
orcid.org/0000-0002-8949-0944

[2] *кандидат технічних наук, доцент,*
*доцент кафедри архітектурних конструкцій, КНУБА*
Kozak.nf@knuba.edu.ua
orcid.org/0000-0001-9387-4652

# ЕВОЛЮЦІЯ ЕНЕРГОЕФЕКТИВНИХ РІШЕНЬ У ФОРМУВАННІ БІОКЛІМАТИЧНОЇ АРХІТЕКТУРИ



***Анотація:*** Сучасні виклики енергоефективного та екологічного будівництва актуалізують потребу переосмислення традиційних підходів до архітектурного проєктування через призму еволюційного розвитку енергоефективних технологій. Дана стаття досліджує закономірності трансформації енергозберігаючих рішень від традиційних народних практик до науково обґрунтованої біокліматичної архітектури.

Метою роботи є виявлення еволюційних взаємозв'язків між традиційними та сучасними енергоефективними підходами, систематизація принципів їх інтеграції для підвищення стійкості міських поселень. Дослідження базується на аналізі наукових праць 2013-2025 років та історичних прикладів традиційної архітектури різних кліматичних зон: арктичні житла (іглу), пустельні поселення мозабітів, традиційні рішення в архітектурі Північного та Південного Китаю, перські геотермальні системи, італійські пасивні охолоджувальні технології XVI століття. Використано методи порівняльного аналізу, типологічної класифікації, кількісної оцінки теплотехнічних характеристик та моделювання енергетичних характеристик будівель.

Проведений аналіз засвідчує високу ефективність ключових принципів народної архітектури: термічна інерція забезпечує 20-30% економії енергії з потенціалом підвищення до 35-45% при інтеграції з фазозмінними матеріалами; пасивне охолодження демонструє 25-40% ефективності з можливістю збільшення до 40-60% через геотермальні системи; адаптація до клімату підвищує стійкість на 15-25% з потенціалом розширення до 30-50% завдяки розумним адаптивним системам.

Наукова новизна полягає у встановленні еволюційних закономірностей розвитку енергоефективних архітектурних рішень через чотири етапи: емпіричний досвід → наукове обґрунтування → технологічна інтеграція → розумні системи. Практичне значення визначається розробкою концептуальної основи для трансформації традиційних енергозберігаючих механізмів у сучасні архітектурно-конструктивні рішення, здатні забезпечити зниження енергоспоживання.

**Ключові слова:** біокліматична архітектура, еволюція енергоефективності, традиційне будівництво, пасивні системи, адаптивний дизайн, стійкість архітектури.