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Improving the Environmental and Energy Efficiency of Urbanized Areas: A Bioclimatic Approach to Sustainable Development

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ABSTRACT

The purpose of the study was to determine ways to increase the environmental and energy efficiency of high-rise buildings. The bioclimatic approach was adopted as the basis of the research approach. A content analysis of Russian norms was conducted, comparing the data with international standards. In addition, an expert survey was conducted with 25 specialists from among architects, heat engineers, and developers. The methods employed included the Likert scale, nonparametric statistics, and thematic coding of experts' responses. The research has demonstrated that Russian regulations hardly set any requirements for the optical properties of facade materials and do not stipulate the calculation of the Solar Reflectance Index (SRI). In practice, color decisions are more commonly dictated by aesthetics, customers' requests, and initial price. Energy efficiency is important mainly for engineers. Architects' awareness of the SRI remains low (8%) due to a lack of motivation (i.e., standards and incentives for implementation). The most important step to change the situation is to update the norms. Programs (courses) need to be introduced to increase knowledge of the bioclimatic approach in construction, along with economic incentives for developers. Ultimately, these measures will contribute to better environmental and energy efficiency of high-rise buildings to achieve sustainable development principles.

Keywords: *Solar reflection index, Bioclimatic competencies, Thermal bridges, Urban thermal island, Climate adaptation*

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INTRODUCTION

The construction sector is one of the largest sources of greenhouse gases and consumers of energy resources on a global scale, accounting for about 40% of the world's energy consumption and up to 30% of CO_2 emissions. In the face of climate change and natural resource depletion, the energy efficiency of buildings is becoming a pressing environmental issue (Kuanyshbayeva *et al.*, 2025). High-rise buildings, being an architectural dominant of modern megacities, hold a disproportionate share in the overall energy balance of urbanized areas due to their functional complexity, scale, and intensity of use (Ospanov *et al.*, 2024; Zakharov & Zabalueva, 2025b).

The Global Sustainable Development Goals (SDGs) adopted by the international community set the reference points for the construction industry (Lizikova, 2024). SDG 7 ("Ensure access to affordable, reliable, sustainable and modern energy for all") and SDG 11 ("Make cities and human settlements inclusive, safe, resilient and sustainable") require a fundamental revision of approaches to the design and operation of buildings (Polovchenko, 2021; Abdimomynova *et al.*, 2025). According to UN forecasts, by 2050, about 67% of the world's population will live in cities, which will create enormous pressure on urban energy systems and exacerbate environmental problems (Krasnikova *et al.*, 2024; Appassova *et al.*, 2025), including the urban heat island (UHI) effect (Oke, 1982; United Nations, Department of Economic and Social Affairs, Population Division, 2018), air pollution, and the degradation of local ecosystems (Krasnikov & Korotun, 2024; Saparov *et al*., 2024; Zhao *et al*., 2024).

The facade systems of high-rise buildings are an important element in achieving environmental sustainability, being the surface responsible for most of the energy exchange between the internal environment of the building and the external atmosphere (Larionov *et al*., 2025). The extensive facades of high-rise buildings can act as a source of undesirable incoming heat, increasing the load on cooling systems and indirectly adding to greenhouse gas emissions. At the same time, however, they can serve as a passive climate control tool that can significantly lower the environmental footprint of the building (Atyaksheva *et al*., 2022). Historical Analysis shows that the choice of architectural solutions for facades has long been dictated mainly by aesthetic considerations (Ashwin *et al*., 2024; Jin *et al*., 2024; Li *et al*., 2024; Owusu *et al*., 2024; Aksoy & Akaydin, 2025, Alves *et al*., 2025; Chen *et al*., 2025; Kunie *et al*., 2025; Romero & Campos, 2025; Watanabe & Mori, 2025). The era of black skyscrapers of the mid-20th century has exposed the environmental consequences of this approach: dark facades with high solar absorptance (SA) caused excessive heat gain, requiring continuous mechanical air-conditioning and inflating the carbon footprint of buildings (Zakharov & Zabalueva, 2025a).

The bioclimatic approach to architectural design offers an alternative paradigm in which the building is viewed as a climatically adaptive system integrated into the local ecosystem. Under this approach, the choice of color and material solutions for facades ceases to be a purely design-related task (Mikhailenko, 2024) and transforms into an engineering problem of optimizing the energy balance and minimizing environmental impact (Afanasyev & Karpova, 2024). Yet despite the growing appreciation of green construction (Logachev & Beresneva, 2024; Osipova *et al*., 2025), the large-scale adoption of bioclimatic principles is hindered by insufficient government incentive policies (Battalova & Enikeev, 2024), technological barriers, the lack of unified standards for assessing the energy efficiency of vertical facade surfaces, and the predominance of short-term economic reasoning (Yelubayeva *et al*., 2022; Abdykadyrov *et al*., 2025).

In this context, our study aimed to identify ways to improve the environmental and energy efficiency of high-rise buildings through the bioclimatic approach to achieve the principles of sustainable development. The research focused on identifying influential parameters defining the environmental and energy efficiency of facade systems and formulating practical recommendations for integrating passive climate control strategies into the practice of modern urban high-rise construction (Alhossan *et al*., 2024; Danchin *et al*., 2024; Hillman, 2024; Cuenca-Martínez *et al*., 2025; Mishra *et al*., 2025).

Literature review

The theoretical basis of bioclimatic architecture creates an interdisciplinary field of knowledge that integrates the principles of architectural design, construction physics, climatology, and ecology (Krasnikov *et al*., 2023a, 2023b; Fatkullina *et al*., 2025). In bioclimatic design, the building is adapted to local climatic conditions through the optimization of its shape and orientation, the choice of materials, and the inclusion of passive microclimate control systems (Yeang, 1997; Montayev *et al*., 2025). Approaches to the design of high-rise buildings gradually evolved from a purely aesthetic paradigm to a functional ecological one, where the criterion of energy performance stands on a par with architectural expression (Al-Kodmany, 2014). The historical experience of black skyscrapers of 1951–1973 with their high SA and excessive energy consumption underscores the fundamental contradiction between architectural fashion and climatic expediency that can only be resolved through the systematic integration of bioclimatic principles.

Modern studies on the energy efficiency of high-rise construction consistently prove the critical role of facade systems in the thermal balance and environmental profile of buildings. Passive methods such as optimized building orientation, natural ventilation, sun protection devices, and materials with optimal thermal characteristics can considerably lower both energy consumption and CO_2 emissions (Shahabian, 2015; Pietrzak, 2024). Research also suggests that bioclimatic strategies are particularly valuable for tropical and subtropical climatic zones, where high temperature and humidity render traditional approaches inadequate (Jahnkassim & Ip, 2006; Hildayanti & Wasilah, 2022).

The cornerstone engineering metric for assessing the thermodynamic efficiency of facade color solutions is the Solar Reflectance Index (SRI) (Santamouris, 2023), which combines the ability of the material to reflect solar radiation and its thermal emission. Materials with a high SRI ("cold materials") are characterized by a low surface temperature under solar irradiation, which reduces the transfer of heat inside the building and lightens the load on air conditioning systems (Kalwry & Atakara, 2025). The spectrum of SA is wide, with dark colors having coefficients of 0.92-0.98 and light, highly reflective materials having indicators below 0.30. Quantitative assessments indicate that highly reflective materials can improve energy performance by 10-20% during the cooling season, as well as help mitigate the UHI effect at the neighborhood level.

An important factor determining the actual energy efficiency of facades is the phenomenon of thermal bridges. Studies based on infrared thermography and numerical modeling reveal that unintended heat transfer paths in structural assemblies can reduce the actual thermal resistance of the facade system by 50-70% compared to design values. This phenomenon points to the need for a comprehensive approach that integrates color optimization and the minimization of thermal bridges through the use of continuous insulation (Raji, 2018).

Climate features are decisive in choosing the optimal facade design strategy (Vaslavskaya *et al*., 2025). In climatic zones with a pronounced cold season, highly reflective facades can result in a potential "heating fine," although recent studies indicate that it is often compensated by annual savings on cooling and can be minimized with high-quality thermal insulation (Lei *et al*., 2025). Thus, the optimal solution should be determined by analyzing the building's annual energy balance, considering local climatic conditions (Frost *et al*., 2024; Ismail *et al*., 2025; Laaksonen & Virtanen, 2025, Peterson & Rogers, 2025; Torres *et al*., 2025).

An additional strategy for improving the environmental and energy efficiency of high-rise buildings is the integration of vertical greening. Vertical greening systems (VGS) provide multifunctional benefits, including reduced heat gain through evaporative cooling, improved air quality, mitigation of the UHI effect, and increased biodiversity in an urbanized environment (Al-Kodmany, 2023; Grafkina *et al*., 2024; Demircan, 2025). However, the implementation of VGS faces significant practical barriers, including high installation and maintenance costs, structural risks, and the need to select plant species carefully. In the context of color solutions, VGS creates an additional level of complexity, since the choice of base color must consider the requirements of the plants for temperature conditions (Chojnacka *et al*., 2025).

In Russian scientific discourse, the problems of bioclimatic architecture of high-rise buildings have been developed over the last two decades. Researchers note that in Russian practice, "enclosing structures do not at all participate in the climatic adaptation of buildings," suggesting that bioclimatic principles are insufficiently integrated into the design process. Special emphasis is placed on the need to consider "the prevailing directions of the cold wind, the maximum glazing of the southern facades, and the minimum glazing of the northern facades, which is especially important in our harsh climate" (Larionov *et al*., 2025). Russian experts point out that double facades can reduce energy consumption by up to 65% in cold climates, but their application remains limited due to high initial costs (Atasheva *et al*., 2024) and the lack of clear regulatory requirements (Dmitrieva & Rabetz, 2024; Rusev, 2024).

A critical analysis of the available literature reveals several significant gaps. First, there are no specialized standards for measuring the SRI on vertical facade surfaces, considering the long-term aging of materials in various climatic conditions. Existing standards are intended mainly for horizontal surfaces, which creates a methodological problem when assessing the effectiveness of high-rise building facades. Second, the peculiarities of applying bioclimatic principles in a continental climate with sharp seasonal temperature fluctuations typical of a significant part of Russia have not been thoroughly studied (Krasnikov *et al*., 2024). Third, there are virtually no comprehensive studies combining the analysis of color solutions, the minimization of thermal bridges, and climatic adaptation into a single methodological framework. These exact factors became the subject of the present study.

MATERIALS AND METHODS

The current study relied on a combination of an analysis of technical documentation and an expert survey conducted in 2025.

Analysis of technical regulations

The analyzed material included Russian regulatory documents (SP 50.13330.2012 "Thermal performance of the buildings," SP 23-101-2004 "Thermal performance design of buildings," GOST R 56835-2015) and technical regulations, as well as international standards ASTM E1980 and EN 15976 on determining the SRI. Structured content analysis was conducted to establish requirements for facade color and material solutions in terms of energy efficiency, standard parameters of thermal protection, requirements for the minimization of thermal bridges, and the consideration of climatic zones. Special attention was paid to gaps in the regulatory framework, particularly the lack of standardized methods for assessing the thermodynamic characteristics of color solutions on vertical surfaces (Aslan *et al*., 2024; Bandi *et al*., 2024; Jeung, 2024; Chen *et al*., 2025; Jannath *et al*., 2025; Makoae *et al*., 2025; Salem *et al*., 2025).

Expert survey

The structured survey of specialists was conducted to explore the practice of decision-making on the color solutions of facades and barriers to the introduction of the bioclimatic approach. The experts involved included architects (n = 12), heating engineers (n = 8), and representatives of development companies (n = 5) with at least 5 years of experience working on high-rise building projects. The total sample consisted of 25 respondents from Moscow, St. Petersburg, Novosibirsk, and Kazan.

The survey consisted of three blocks: (1) factors in the choice of facade color solutions; (2) knowledge of the SRI, the bioclimatic approach, and climate adaptation; and (3) barriers to the adoption of energy-efficient solutions. The questionnaire included closed-ended questions with a 5-point Likert scale and open-ended questions. Statistical data processing was carried out with non-parametric statistics, including the calculation of medians and interquartile ranges and the Kruskal-Wallis test for inter-group comparisons. The qualitative data were processed by thematic coding.

RESULTS AND DISCUSSION

The analysis of the Russian technical regulation framework revealed significant gaps in the regulation of facade color schemes in terms of energy efficiency. **Table 1** systematizes the results of content analysis of regulatory documents on the key parameters of bioclimatic facade design.

Table 1. Requirements for facade energy efficiency parameters in Russian regulatory documents

Regulatory document	Color/optical characteristics	Thermal resistance (R-value)	Thermal bridges	Climatic differentiation	SRI calculation methods
SP 50.13330.2012	Indirect mention	Detailed requirements	General provisions	Present (4 zones)	Absent
SP 23-101-2004	Absent	Detailed requirements	Minimal	Present (3 zones)	Absent
GOST R 56835-2015	Absent	Methods of measurement	Absent	Absent	Absent
Technical Regulation	Absent	Minimal requirements	Absent	Absent	Absent
ASTM E1980 (comparison)	Detailed	Unregulated	Unregulated	Absent	Standardized
EN 15976 (comparison)	Detailed	Unregulated	Unregulated	Absent	Standardized

The comparative analysis with international standards reveals a systemic gap: in the presence of detailed requirements for the thermal resistance of enclosing structures, the Russian regulatory framework does not offer methods for assessing the thermodynamic characteristics of color solutions for vertical surfaces.

The results of the expert survey show significant differences in priorities between the specialist groups when choosing color solutions for the facades of high-rise buildings. **Table 2** shows the median estimates of the significance of various factors and the statistical significance of intergroup differences.

Table 2. Factors determining the choice of color solutions for facades (median and interquartile range)

Factor	Architects (n=12)	Heating engineers (n=8)	Developers (n=5)	Total sample (n=25)	p-value (Kruskal–Wallis)
Aesthetics	5.0 (4.0-5.0)	3.5 (3.0-4.0)	4.0 (3.5-5.0)	4.0 (4.0-5.0)	0.012*
Client's requirements	5.0 (5.0-5.0)	4.0 (3.5-4.5)	5.0 (5.0-5.0)	5.0 (4.0-5.0)	0.023*
Initial costs	4.0 (3.0-4.0)	3.0 (2.5-4.0)	5.0 (5.0-5.0)	4.0 (3.0-5.0)	0.008**
Energy efficiency	2.0 (2.0-3.0)	4.5 (4.0-5.0)	2.0 (2.0-3.0)	3.0 (2.0-4.0)	<0.001***
Normative requirements	3.0 (3.0-4.0)	4.0 (3.5-4.5)	3.0 (2.5-3.5)	3.0 (3.0-4.0)	0.156
Long-term operating costs	2.0 (2.0-3.0)	3.5 (3.0-4.0)	2.0 (1.5-2.5)	2.0 (2.0-3.0)	0.004**

*p < 0.05; **p < 0.01; ***p < 0.001

The most substantial discrepancy between the professional groups is found in their assessment of the importance of energy efficiency, which points to a fragmentation of priorities during the design process.

The analysis of experts' knowledge of the key concepts of bioclimatic design has uncovered significant gaps in professional knowledge. **Table 3** shows the distribution of the levels of familiarity with basic terms and methods.

Table 3. Experts' knowledge of bioclimatic concepts (%, n=25)

Concept/parameter	Well familiar, put into practice	Theoretically familiar, do not apply	Familiar with the term, not the details	Unfamiliar	Architects	Engineers	Developers
Solar Reflectance Index (SRI)	12%	20%	32%	36%	8% familiar	50% familiar	0% familiar
Solar Absorptance (SA)	16%	28%	24%	32%	17% familiar	63% familiar	0% familiar
Bioclimatic approach	24%	44%	20%	12%	42% familiar	75% familiar	20% familiar
Thermal bridges in facades	36%	40%	16%	8%	25% familiar	88% familiar	20% familiar
Climate adaptation of facades	20%	36%	28%	16%	25% familiar	63% familiar	0% familiar
UHI effect	28%	32%	24%	16%	33% familiar	63% familiar	0% familiar

Note: The "Architects," "Engineers," and "Developers" columns show the total percentage of respondents in each group who chose the first two categories ("Well familiar" + "Theoretically familiar")

The results demonstrate a critical gap between the technical competence of the different groups of specialists involved in decisions about facade systems.

The expert assessment of barriers to the implementation of bioclimatic principles revealed a set of institutional, economic, and professional obstacles. The ranking of the barriers by significance is presented in **Table 4**.

Table 4. Barriers to implementing energy-efficient facade colors (median and interquartile range)

Barrier	Architects (n=12)	Engineers (n=8)	Developers (n=5)	Total sample (n=25)	p-value
No normative regulation on SRI/colors	4.0 (4.0-5.0)	5.0 (4.5-5.0)	3.0 (2.5-4.0)	4.0 (4.0-5.0)	0.021*
Priority of aesthetics over energy efficiency	5.0 (4.0-5.0)	4.0 (3.5-5.0)	5.0 (4.5-5.0)	5.0 (4.0-5.0)	0.342
Lack of economic incentives (subsidies, tax breaks)	4.0 (3.0-5.0)	4.0 (3.5-4.5)	5.0 (5.0-5.0)	4.0 (4.0-5.0)	0.143
Lack of knowledge of bioclimatic principles	3.0 (2.0-4.0)	5.0 (4.0-5.0)	2.0 (2.0-3.0)	3.0 (2.0-4.5)	0.002**
Higher cost of highly reflective materials	4.0 (3.5-5.0)	3.0 (2.5-3.5)	5.0 (5.0-5.0)	4.0 (3.0-5.0)	0.009**
Clients' conservatism/preference for traditional solutions	5.0 (4.5-5.0)	4.0 (3.0-4.5)	4.0 (4.0-5.0)	4.0 (4.0-5.0)	0.178
Limited offer in the market for facade materials	3.0 (2.5-4.0)	3.0 (2.0-4.0)	4.0 (3.5-4.5)	3.0 (3.0-4.0)	0.267
Lack of economic effect calculation methods	3.0 (3.0-4.0)	4.5 (4.0-5.0)	4.0 (3.5-5.0)	4.0 (3.0-4.5)	0.067

*p < 0.05; **p < 0.01

The qualitative analysis of answers to open-ended questions discovered more thematic categories of barriers. Frequency analysis points to the following dominant topics: lack of long-term data on the actual energy efficiency of implemented projects (mentioned by 60% of respondents); the difficulty of integrating energy efficiency requirements early in the design process due to process fragmentation (44%); conflict between the requirements of architectural competitions, evaluating mainly visual expression, and sustainable development goals (36%); lack of tools to quantify the impact of color solutions on energy consumption at the draft design stage (52%).

The results of the study reveal a gap between the need to comply with the principles of environmental sustainability and the actual practice of high-rise construction design, which has direct consequences for the achievement of SDGs and deepens the environmental problems of urbanized areas.

The observed domination of aesthetic criteria over energy efficiency when choosing color solutions for facades has long-term environmental consequences. With the construction sector generating up to 30% of global CO_2 emissions, ignoring the potential of passive strategies, such as the use of highly reflective materials with optimal SRI, means losing an opportunity to reduce energy consumption by 10-20% (Aliev & Baldin, 2024; Kalwry & Atakara, 2025). For high-rise buildings with a service life of 50-75 years, this translates into tens of thousands of tons of additional greenhouse gas emissions that could have been avoided with the right choice of the facade color at the design stage.

Beyond the energy consumption of specific buildings, the Russian legislative framework's lack of criteria for the optical qualities of facade materials has an impact on the environment. With a SA coefficient of 0.92–0.98, dark facades significantly contribute to the UHI effect, raising the urban environment's temperature by 3–8°C relative to the suburbs (Zhao *et al*., 2024). This creates a cascading environmental effect: mortality increases during heat periods, energy consumption for cooling increases at the level of the entire urban area, and the concentration of ground-level ozone rises. If the color solution is chosen incorrectly, high-rise buildings with their vast facade areas can act as especially powerful sources of thermal pollution in the urban environment.

Considering international experience, the disregard for this issue in Russian practice contrasts with the development of cool city strategies in the USA, Europe, and Japan, where regulations on the SRI of facade materials are integrated into urban planning regulations precisely to mitigate the UHI effect and adapt to climate change. The barriers identified in the study, i.e., the lack of regulatory requirements, low awareness, and the dominance of short-term economic reasoning, impede the environmental transformation of Russian cities (Akhmetshin *et al*., 2024; Krokhina, 2024).

The results of the study demonstrate that the transition to bioclimatic design requires not only technical solutions but also institutional transformation. The statistically significant discrepancy in priorities between heating engineers who understand the environmental cruciality of energy efficiency and architects and developers who make the final decisions creates a systemic barrier to achieving SDG 7 (affordable and clean energy) and SDG 11 (sustainable cities). Against the background of accelerating climate change and urbanization, integrating passive climate control strategies into high-rise construction practices is not a technical option but an environmental necessity.

The limitations of the conducted study include the relatively small sample size of the expert survey (n = 25), the geographical localization of respondents in the largest cities, and the lack of analysis of actually implemented projects with the measurement of energy consumption. Future studies should focus on the quantitative assessment of the environmental effect of facade color schemes at the city block level using microclimatic modeling and satellite thermography, the development of climatically differentiated SRI standards for Russian regions, and the comprehensive analysis of the life cycle of buildings with the integration of greenhouse gas emissions estimates. Special promise can be found in the study of the potential to introduce highly reflective materials on a massive scale to mitigate the UHI effect and adapt cities to climate change, which is directly connected to environmental sustainability and the quality of the urban environment (Korotun & Goncharov, 2024).

CONCLUSION

The study has identified systemic barriers to the integration of bioclimatic principles into high-rise design practices in Russia that have critical implications for achieving SDGs and mitigating the environmental challenges of urbanized areas. The analysis of technical regulations demonstrated the lack of requirements for the optical characteristics of facade materials, particularly the SRI. In contrast with international standards, this lack of regulation deprives designers of a regulatory basis for making environmentally sound decisions. The expert survey showed a fragmentation of professional priorities: energy efficiency has minimal importance in the eyes of architects and developers who make final decisions on the color schemes of facades, despite the fact that heat engineers assess it as critical. Low awareness of the key concepts of bioclimatic design reveals significant gaps in vocational education. As a result of the priority of aesthetic expression, customers' requirements, and initial costs over long-term energy efficiency, high-rise buildings are designed without considering their contribution to the UHI effect and the generation of greenhouse gas emissions over the decades of operation. To overcome the identified barriers, a comprehensive institutional transformation has to occur. There is a need to develop a regulatory framework with the inclusion of climatically differentiated requirements for SRI, incorporate bioclimatic competencies into vocational education, and create economic incentives for the use of energy-efficient facade solutions as a prerequisite for the environmental transformation of Russian high-rise construction.

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