Технічні науки

Myronenko Artem

(San Diego, California, USA)

ENERGY MODERNIZATION OF HISTORICAL BUILDINGS: CHALLENGES AND WAYS OF INTEGRATING ENERGY EFFICIENT SOLUTIONS

Summary. *Energy modernization of objects with historical and cultural value represents one of the most complex and multifaceted challenges in the fields of construction and restoration research. It lies at the intersection of two of modern society's priority directions — preserving the authenticity of monuments and achieving ambitious goals for reducing carbon footprint and enhancing buildings' energy efficiency. Within the framework of this study, the aim is to identify existing challenges and pathways for integrating energy-efficient solutions in the modernization of historical buildings. The methodological foundation was a comprehensive systems analysis of specialized publications addressing methods for evaluating and implementing energy-saving technologies in historical buildings, as well as a synthesis of contemporary approaches in non-destructive testing, the application of digital building information models (HBIM), and life-cycle cost assessment (LCCA). The findings obtained and the described decision-making framework are of interest to design engineers, restoration architects, heritage protection authorities, and government institutions involved in the preparation and implementation of historical renovation programs. They make it possible to devise a balanced approach whereby sustainable development requirements harmoniously coincide with the objectives of cultural heritage conservation.*

Key words: *historical buildings, energy modernization, energy efficiency, heritage conservation, HBIM, sustainable renovation, multicriteria analysis,*

non-invasive technologies, thermal protection, integration of renewable energy sources.

Introduction. Monumental architectural ensembles and individual historical structures function not only as symbols of cultural identity but also as tangible artefacts recording the chronology of societal transformations. Their value extends far beyond aesthetics: they represent key objects of collective memory and bearers of unique technological techniques developed by preceding eras.

At the same time, a significant share of the built heritage of the European Union—namely those buildings erected before the mid-20th century—accounts for approximately 40 % of total energy consumption and about 36 % of CO_2 emissions [1]. Such a disproportion poses an exceptionally complex challenge to the research and engineering community: how to integrate the requirements of the European Directive on the Energy Performance of Buildings (EPBD) without compromising the historical and cultural authenticity of these structures.

The urgency of this issue is heightened by global climate risks and the overarching strategy to achieve carbon neutrality by 2050. Any projects aimed at greening or modernising architectural heritage must balance ambitious environmental goals with the obligation to preserve the integrity of the original design solutions.

Approximately one quarter of the residential and public building stock in EU countries is classified as historic or traditional construction. The energy retrofit of these assets encounters a multilayered complex of obstacles—from the incompatibility of modern thermal insulation technologies with the material fabric of heritage structures to contradictions between international conservation standards and national legislation, as well as ethical dilemmas related to interventions in authentic volumetric and spatial configurations [2].

Within the scientific discourse, there remains an absence of a systematically developed methodological framework capable of ensuring well-balanced decision-making in the renovation of historic urban fabric. In practice, approaches often oscillate between radical engineering interventions that undermine historical authenticity and categorical refusal of any improvements for fear of damaging cultural values. Such a black-and-white perspective must be overcome through the development of multidisciplinary assessment and decision-making models that concurrently address technical, environmental and hermeneutic aspects of architectural heritage conservation.

The **objective** is the determination of existing challenges and pathways for integrating energy-efficient solutions in the modernization of historic buildings.

The **scientific novelty** of the work is manifested in the creation of a formalized multicriteria evaluation model capable of organizing and unifying the decision-making process in the field of energy renovation of architectural monuments. The model integrates heterogeneous technical, cultural, and economic parameters into a single methodological system, which enables a considered and sequential approach to the selection of design solutions.

The **author's hypothesis** is that the application of this systemic model neutralizes the traditional contradictions between heritage preservation tasks and the implementation of modern energy-efficient technologies, ensuring the adoption of well-founded, comprehensive, and sustainable design strategies.

Materials and Methods. To achieve the stated objective, a systematic analysis of contemporary scientific literature was conducted. The works can be conditionally grouped into several directions. In the context of the European strategy for the decarbonization of historical buildings, the legal and regulatory framework plays a key role in establishing strategic guidelines and boundaries for practical solutions. The Communication of the Commission Renovation Wave for Europe emphasizes the need for a coordinated approach to building renovation taking into account the preservation of cultural heritage and the creation of new jobs [1]. Similar conclusions are drawn by the analytical report of BPIE assessing the suitability of national long-term renovation strategies for the objective of climate neutrality by 2050 and indicating the gap between ambitious targets and the actual pace of implementation of energy efficiency measures [2].

Rocha G. et al. [3] propose a scan to BIM methodology for historic structures in which laser scanning is complemented by automated algorithms for converting the point cloud into a parametric BIM model. The authors demonstrate that this approach ensures accurate spatial reproduction of the complex geometry of monuments and provides a basis for subsequent analysis of thermal flows and energy auditing. La Russa F. M., Santagati C. [4], advancing the concept of digital twins, move from a static BIM model to Historical Sentient–BIM, which incorporates integration of sensor data (temperature, humidity) for management of museum collections in historic interiors.

In the field of materials science and nondestructive diagnostics, key studies emphasize the importance of a deep understanding of the properties of enclosure structures. Karasu B. et al. [5] systematize recent advances in glass science, drawing attention to new types of low-emissivity and insulating glass compatible with protected façades. Hussain A., Akhtar S. [10] provide a review of nondestructive methods (ultrasonic, thermographic, eddy-current testing) for assessing the condition of masonry and concrete elements, emphasizing the need to calibrate instruments with respect to the authenticity of materials. Sun Y., Wilson R., Wu Y. [12] focus on Transparent Insulation Materials (TIM), demonstrating that implementation of TIM in the window openings of historic buildings allows simultaneous improvement of thermal insulation and preservation of natural interior daylighting.

When analyzing energy efficiency strategies, the literature demonstrates a wide range of approaches: Lidelöw S. et al. [6] conduct a comprehensive review of passive and active measures—from wall insulation with breathable plaster systems to installation of K zonal ventilation systems with heat recovery.

D'Agostino D. et al. [8] propose a cost optimal methodology for assessing energy efficiency, combining passive strategies (orientation, insulation) with life-cycle cost analysis. Ballarini I. et al. [11] present a practical case of transforming an office building into an nZEB, noting improvements in thermal and visual comfort with an 85 % reduction in annual energy consumption. Coelho G. B. A., Silva H. E., Henriques F. M. A. [13] emphasize the significance of calibrating hygrothermal models of historic buildings, demonstrating that the use of local meteorological data and binding material parameters to on-site test results enhances the accuracy of predictions of both indoor and outdoor microclimates.

Issues of integrating renewable energy sources are addressed in the works of Cabeza L. F., De Gracia A., Pisello A. L. [9], where the authors analyze the feasibility of installing BIPV modules on the roofs and façades of monuments, noting limitations in load-bearing capacity and light transmittance. Rosa F. [15] details the technical and regulatory barriers, including requirements for reverse engineering of original architectural elements.

The adaptation of historic buildings to climate change is considered by Hao L. et al. [14], who summarize forecasts of rising temperatures and extreme weather events, proposing enhancement of foundation waterproofing and optimization of passive cooling methods to preserve structural integrity.

Finally, Rocha P., Rodrigues R. C. [7] in a literature review underscore that research on maintenance of historic built environments remains fragmented: most publications focus on the technical aspects of restoration, whereas the issue of regular monitoring and preventive maintenance remains insufficiently developed.

Thus, despite significant progress, the literature reveals a number of contradictions and gaps. On one hand, regulatory documents set high goals, but are often disconnected from the practical capabilities of local authorities and heritage owners. Digital monitoring and modeling methods are actively developing; however, their integration into standardized renovation processes remains limited due to high costs and insufficient specialist expertise. In the field of materials, there is a gap between laboratory research on innovative insulation composites and their field testing in historic buildings, taking into account long-term stability. Regarding comprehensive retrofit solutions, issues of financing, socio-cultural acceptability, and logistical constraints in dense urban environments are underestimated. Interdisciplinary strategies for evaluating trade-offs between conservation and energy modernization, as well as the adaptation of approaches to different climatic and structural characteristics of historic buildings, are insufficiently addressed.

Results and Discussion. The conceptual decision-making framework for the energy modernization of historical buildings, described on the basis of systematization and comparison of existing methodologies, relies on three interrelated clusters of criteria: the paramount preservation of cultural heritage, the attainment of high energy efficiency and the assurance of the economic and social justification of projects. Designated as the Triad of Sustainable Modernization, this model provides for the phased implementation of a multi-criteria evaluation at each level of analysis.

Stage 1. Comprehensive diagnostics of the asset. This step goes far beyond a standard energy audit and includes:

- deep-going historical-archival and architectural analysis to identify elements of the highest value;

- the assessment of their physical condition using non-destructive methods: infrared thermography to detect hidden defects and cold bridges, three-dimensionallaser scanning to construct the precise geometry of an HBIM model, as well as hygrothermal monitoring to investigate moisture indicators of the structures [4, 10].

On the basis of the data obtained, a digital twin of the building is formed, functioning as a virtual testbed for subsequent energy and microclimatic simulations.

Stage 2. Multidimensional evaluation and selection of modernization measures. In this process each proposal is scrutinized through the prism of the Triad. Thus the preservation of heritage component requires avoiding excessive invasiveness, observing reversibility and the harmonious integration of materials and visual characteristics. The classic external thermal insulation composite system ETICS on a historical structure proves unacceptable, and therefore internal thermal insulation using specialized capillary-active boards and detailed calculations of heat and moisture exchange processes to prevent condensate buildup between the enclosure and the insulation is considered [5]. In this case not only operational performance indicators but also the level of visual and physical impact on the authentic facing layer are evaluated. In Figure 1 a schematic illustrating the procedure for analyzing options from the standpoint of preserving the historical substance is presented.

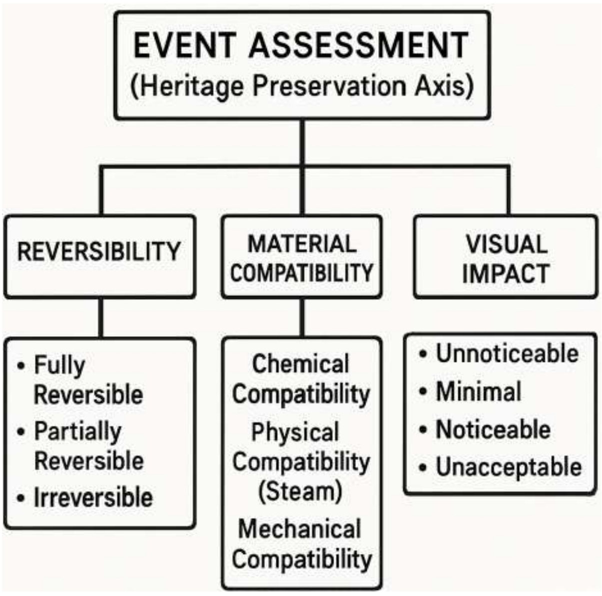

Fig. 1. Criteria for assessing activities within the framework of the principle of heritage conservation

Source: compiled by the author based on the analysis of [4; 5; 8; 10]

Within the Maximization of energy efficiency area a detailed quantitative assessment of the potential for reducing energy consumption is performed for each investigated measure or their aggregate

For this purpose dynamic energy modelling in the HBIM environment is applied, which allows the reproduction of heat flows and the evaluation of their variation depending on the selected measures

In the analysis several scenarios are developed, ranging from the baseline condition (without any interventions) to comprehensive deep renovation with a full suite of thermal insulation and engineering interventions

It should be emphasised that for cultural heritage assets achieving the requirements of the nZEB (Nearly Zero-Energy Building) standard often proves technically impossible or economically unviable [11, 13, 15]

Consequently project objectives must be formulated taking into account historical and architectural constraints and defined with respect to the unique characteristics of each individual building

Table 1 provides a comparison of the main internal insulation variants recommended for application in the constructions of historical stone and brick walls

Table 1

Comparative analysis of materials for internal insulation of historical buildings

Material	Thermal conductivity, λ (W/m·K)	Vapour permeability, μ (-)	Capillary activity	Reversibility	Approximate cost (€/m²)
Mineral wool	0.035 – 0.040	1 – 2	Low	High	40 – 70
Expanded/Extruded polystyrene (EPS/XPS)	0.030 – 0.038	40 – 200	Absent	Medium	30 – 60
Calcium silicate boards	0.060 – 0.070	5 – 10	High	High	90 – 150
Aerogel (in plasters)	0.015 – 0.028	5 – 20	Medium	High	200 – 400
Wood fibre boards	0.038 – 0.045	3 – 5	High	High	50 – 90

Source: compiled by the author based on the analysis of [3; 5; 12; 13; 14]

Third coordinate, designated socio-economic feasibility, implies a comprehensive evaluation not only of initial capital investments but also of all operational expenditures over the asset life cycle (LCCA). Calculations are based on discounting future cash flows, which makes it possible to adequately align current investments and time-deferred benefits, as well as to incorporate into the model the assessment of financial risks and the cost of capital. Within this axis, potential savings on utility and energy payments, increases in real estate market value, and the possible attraction of fiscal incentives — government subsidies and tax benefits [7] are analyzed.

In addition, within the framework of an in-depth LCCA analysis key financial and economic indicators are calculated — payback period, net present value (NPV), internal rate of return (IRR) — which makes it possible to obtain a quantitatively substantiated picture of project profitability.

The core scientific and methodological innovation of the considered model lies in the integration of three significant components within a single, nonlinear iterative scheme for design decision-making (figure 2). The process is structured according to the principle of cyclic refinement: upon identification of a package of measures that ensures the declared energy efficiency targets but at the same time leads to unacceptable degradation of historical and cultural value or proves financially impractical, the design system automatically initiates a return to the previous stage to develop an alternative set of options. Thus, instead of dismantling original window frames, whose replacement drastically alters the architectural appearance of the object, solutions such as secondary glazing or the introduction of vacuum insulated glazing units (VIG) while preserving the original frames can be proposed, enabling a balance between enhanced thermal performance and the retention of historical authenticity [6, 9].

An essential complement to this mechanism is the integration of renewable energy sources, yet the direct use of standard photovoltaic panels on the roofs of heritage monuments often proves impossible due to conservation restrictions. In this regard, a promising approach is the application of photovoltaic roof tiles styled to resemble traditional roofing materials, thereby minimizing visual impact on building facades [15].

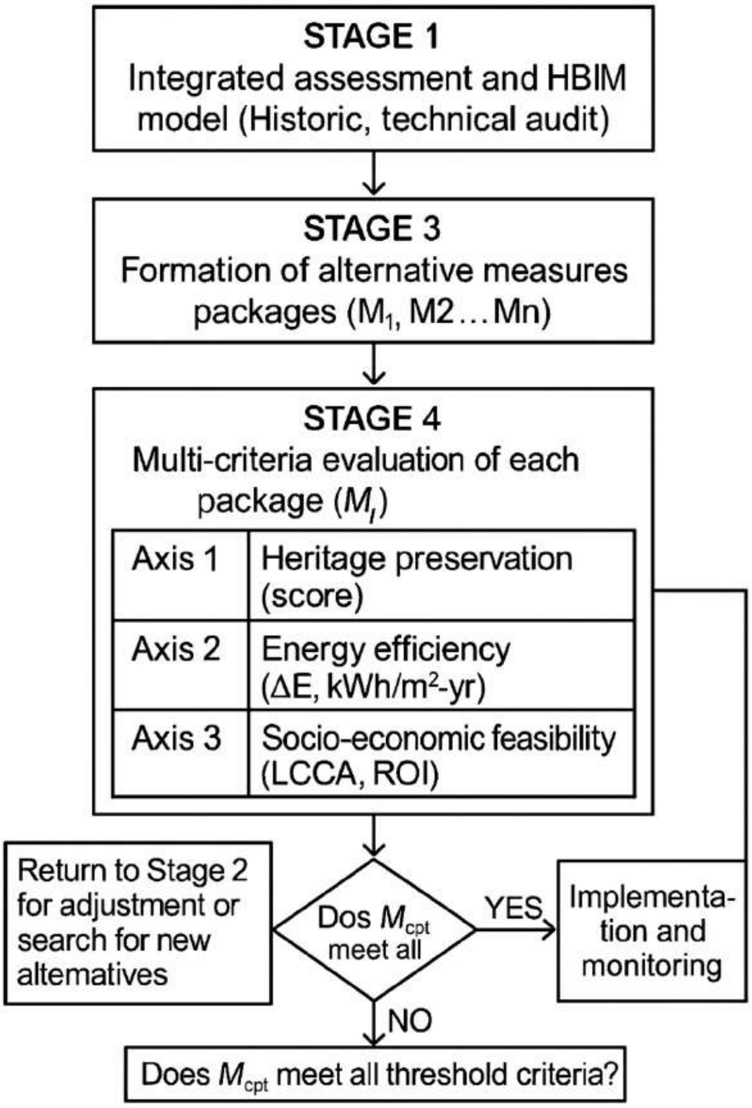

Fig. 2. Iterative model of decision-making in energy modernization of historical buildings

Source: compiled by the author based on the analysis of [6; 7; 9; 15]

The abandonment of a universalist strategy in favor of an adaptive, context-sensitive methodology represents a fundamental paradigm shift in the field of architectural heritage renovation. The model does not claim to offer exhaustive solutions but rather provides the necessary toolkit for the phased development of responses. It functions as a language of apartment-by-apartment dialogue among all participants — architects, structural engineers, conservators and clients — ensuring comprehensive consideration of both technical and value-based aspects of the project. The introduction of such a framework makes it possible to minimize risks during the modernization of historic structures, to avoid errors and to generate synergistic solutions in which the preservation of authenticity is organically combined with the objectives of improving energy efficiency. This approach shifts the discourse from a rivalry between conservation restoration and contemporary technologies to a level of integrated compromise, where both vectors reinforce one another.

Energy rehabilitation of objects of historic heritage is a multidimensional problem that requires a systemic and interdisciplinary perspective for each specific case. The mechanical transfer of techniques and technologies from new construction into the domain of heritage conservation tasks will not only fail to resolve key contradictions but also risk exacerbating them. Each object possesses a unique combination of historical and cultural value, constructive characteristics and physico-technical condition, which dictates the necessity of a detailed study of its genesis and current state. Only on the basis of such an in-depth analysis is it possible to develop an individualized program of measures that ensures the continuity of the historical continuum and long-term resilience under modern energy standards.

Conclusion. The conducted study made it possible to identify and classify the key barriers and to develop a theoretical framework for the implementation of energy-efficient technologies in historic-cultural heritage sites. It was found that the principal limiting factor in sustainable renovation is not a lack of technical means, but the absence of an integrated decision-making methodology capable of reconciling the often-contradictory objectives of preserving authenticity and enhancing the building's energy performance.

As the central achievement of the research, an iterative multicriteria model is proposed, built around three primary dimensions: protection of historical-cultural value, optimization of energy efficiency, and consideration of socio-economic realities. The model formalizes the entire workflow — from initial diagnostics using modern non-invasive techniques and HBIM modelling to the substantiated selection of a package of measures based on a comprehensive analysis of effectiveness and risks. In this way, the main objective of the study is achieved — the formulation of balanced solutions in the renovation process.

The practical significance of the model lies in its applicability as a roadmap for all stakeholders in the restoration and renovation process — from heritage protection authorities to investors and designers. The implementation of this methodology will significantly improve the quality and resilience of projects, minimize the likelihood of costly mistakes, and contribute both to the preservation of cultural heritage and to the achievement of global climate goals.

References

1. European Commission. (2020). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A renovation wave for Europe – greening our buildings, creating jobs, improving lives* (COM(2020) 662 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0662 (Accessed April 2, 2021).
2. Buildings Performance Institute Europe. (2021). *The road to climate-neutrality: Are national long-term renovation strategies fit for 2050?* https://www.bpie.eu/wp-content/uploads/2021/03/BPIE_LTRS-_10-1.pdf (Accessed April 1, 2021).
3. Rocha G. et al. A scan-to-BIM methodology applied to heritage buildings //Heritage. – 2020. – Vol. 3 (1). – pp. 47-67. https://doi.org/10.3390/heritage3010004.
4. La Russa F. M., Santagati C. Historical sentient–building information model: a digital twin for the management of museum collections in historical

architectures //The international archives of the photogrammetry, remote sensing and spatial information sciences. – 2020. – Vol. 43. – pp. 755-762.

5. Karasu B. et al. The latest developments in glass science and technology //El-Cezeri. – 2017. – Vol. 4 (2). – pp. 209-233.

6. Lidelöw S. et al. Energy-efficiency measures for heritage buildings: A literature review //Sustainable cities and society. – 2019. – Vol. 45. – pp. 231-242. https://doi.org/10.1016/j.scs.2018.09.029.

7. Rocha P., Rodrigues R. C. Bibliometric review of improvements in building maintenance //Journal of Quality in Maintenance Engineering. – 2017. – Vol. 23 (4). – pp. 437-456.

8. D'Agostino D. et al. Cost-optimal methodology and passive strategies for building energy efficiency: a case-study //Architectural Science Review. – 2018. – Vol. 61 (6). – pp. 400-409.

9. Cabeza L. F., De Gracia A., Pisello A. L. Integration of renewable technologies in historical and heritage buildings: A review //Energy and buildings. – 2018. – Vol. 177. – pp. 96-111. https://doi.org/10.1016/j.enbuild.2018.07.058.

10. Hussain A., Akhtar S. Review of non-destructive tests for evaluation of historic masonry and concrete structures //Arabian Journal for Science and Engineering. – 2017. – Vol. 42 (3). – pp. 925-940.

11. Ballarini I. et al. Transformation of an office building into a nearly zero energy building (nZEB): Implications for thermal and visual comfort and energy performance //Energies. – 2019. – Vol. 12 (5). – pp. 1-7. https://doi.org/10.3390/en12050895.

12. Sun Y., Wilson R., Wu Y. A Review of Transparent Insulation Material (TIM) for building energy saving and daylight comfort //Applied energy. – 2018. – Vol. 226. – pp. 713-729. https://doi.org/10.1016/j.apenergy.2018.05.094.

13. Coelho G. B. A., Silva H. E., Henriques F. M. A. Calibrated hygrothermal simulation models for historical buildings //Building and

Environment. – 2018. – Vol. 142. – pp. 439-450. https://doi.org/10.1016/j.buildenv.2018.06.034.

14. Hao L. et al. What are the implications of climate change for retrofitted historic buildings? A literature review //Sustainability. – 2020. – Vol. 12 (18). – pp. 2-6. https://doi.org/10.3390/su12187557.

15. Rosa F. Building-integrated photovoltaics (BIPV) in historical buildings: opportunities and constraints //Energies. – 2020. – Vol. 13 (14). – pp. 1-8. https://doi.org/10.3390/en13143628.