Energy Management in Buildings: An Integrated Energy, Economic, and Environmental Assessment – A Case Study

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Abstract **– This paper presents an applied case study evaluating the energy, economic, and environmental performance of an existing building using a structured energy management framework based on ISO 50001. By systematically assessing the current energy consumption, the study identifies opportunities for improving energy efficiency and informs the selection and implementation of appropriate technical measures. The analysis includes a baseline assessment of energy use, evaluation of potential interventions, and examination of the effects of implemented measures. The results demonstrate that the application of integrated energy efficiency measures – such as the replacement of windows and doors, wall insulation, lighting modernization, and substitution of the heating source – can lead to substantial reductions in energy consumption, operational costs, and environmental impact. The findings indicate that an integrated energy management approach can support enhancing building energy efficiency, promoting sustainable operation, and reducing the environmental footprint of energy consumption.**

Keywords **– Buildings, energy efficiency, energy management, ISO 50001, sustainability.**

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1. Introduction

The building sector is one of the largest consumers of final energy globally and contributes significantly to greenhouse gas (GHG) emissions. Buildings represent over one-third of the global energy demand and are responsible for nearly 40% of CO_2 emissions [1]. Consequently, improving energy efficiency within this sector is a crucial component in realizing both economic and environmental sustainability objectives. Moreover, improving energy efficiency in buildings via retrofitting represents a crucial approach. A thorough examination of energy retrofitting methods throughout the European Union (EU) highlights objectives including the enhancement of energy efficiency, the gradual elimination of fossil fuels, the augmentation of renewable energy sources, and the implementation of circularity, alongside evaluations of both carbon reduction and cost-saving results [2].

A wide range of studies have emphasized the importance of systematic approaches to energy management in buildings. The study by [3] highlighted that energy efficiency measures in buildings play a decisive role in achieving the United Nations Sustainable Development Goals (SDG), stressing the need for frameworks that combine economic, environmental, and social considerations. Similarly, [4] provided detailed environmental and economic datasets that underline the significance of quantifying both technical and financial aspects of building energy retrofits.

In parallel, there has been rapid advancement in digital and intelligent energy management systems. The authors in [5] proposed an (IoT)-based intelligent management system for buildings, while [6] reviewed IoT applications as promising solutions for smart building energy management, identifying both their advantages and barriers. The study by [7] further explored Artificial Neural Network (ANN) applications, demonstrating their effectiveness in predictive control and optimization of building energy use.

More recently, [8] discussed (AI)-driven energy management systems, emphasizing their potential to enable adaptive and autonomous decision-making. Another study by [9], in a comprehensive scoping review, synthesized strategies and technologies for energy management in buildings, noting the growing convergence of data-driven methods with traditional management standards.

In addition, several works have specifically focused on optimizing the selection of energy efficiency measures. The authors in [10] examined optimal selection strategies for retrofit interventions, while [11] applied a life-cycle approach to assess energy efficiency measures in the building sector. Similarly, [12] developed a simulation and optimization methodology for non-residential buildings, and [13] proposed a multi-objective optimization framework for evaluating different retrofit alternatives.

Although these contributions demonstrate substantial progress, most studies focus either on technological innovations (IoT, AI, ANN) or on conceptual frameworks, with limited evidence of systematic integration into standardized management systems. This creates a gap between advanced digital solutions and structured frameworks such as ISO 50001, which has been recognized as a robust tool for continuous energy performance improvement [14], yet practical case studies applying the framework in real buildings with quantified energy, financial, and environmental results remain relatively scarce.

This paper presents an applied case study aimed at supporting decision-making for energy efficiency retrofits in small-scale public buildings. The analysis includes baseline energy assessment, identification of technical measures, and evaluation of their implementation in terms of energy savings, cost-effectiveness, and CO_2 emission reduction. The results provide empirical evidence supporting the integration of standardized energy management systems with technical retrofits and offer insights for policymakers, practitioners, and researchers aiming to accelerate the transition toward sustainable building operations.

To the best of the authors' understanding, this case study presents documented application of ISO 50001 principles in a small public building in North Macedonia, offering a comprehensive quantitative assessment of its energy, financial, and environmental advantages.

2. Energy Management in Buildings

Energy consumption in buildings is determined by the operation of various technical systems required to satisfy user needs. The largest share of final energy demand is associated with heating and cooling, which typically account for more than half of the total consumption in buildings [15].

To ensure satisfactory energy performance throughout a building's life cycle, proper system maintenance and techno-economic evaluation of new projects are essential. Energy efficiency, defined as the effective use of energy in building systems, reduces consumption, costs, and CO_2 emissions while improving comfort and property value. Studies show that upgrades can reduce energy consumption by 20-50%, and even up to 90% with advanced technologies, with payback periods of 2-8 years [16].

An established indicator of building efficiency is the energy class, which relies on the specific annual heating energy required per square meter. Buildings are classified on a scale from A+ (most efficient) to G (least efficient), where higher classifications correspond to lower energy consumption and emissions. The energy performance certificate indicates the class and provides an overall assessment with recommendations for cost-effective improvements.

Conducting energy audits is essential for evaluating the state of buildings, identifying potential savings, and defining efficiency measures. These range from low-cost interventions to capital-intensive renovations and are typically categorized as behavioral, technical (envelope, systems, lighting, appliances, controls), or organizational. Figure 1 illustrates their typical order, while multi-objective approaches [17] support systematic prioritization and optimal ranking of retrofit strategies.

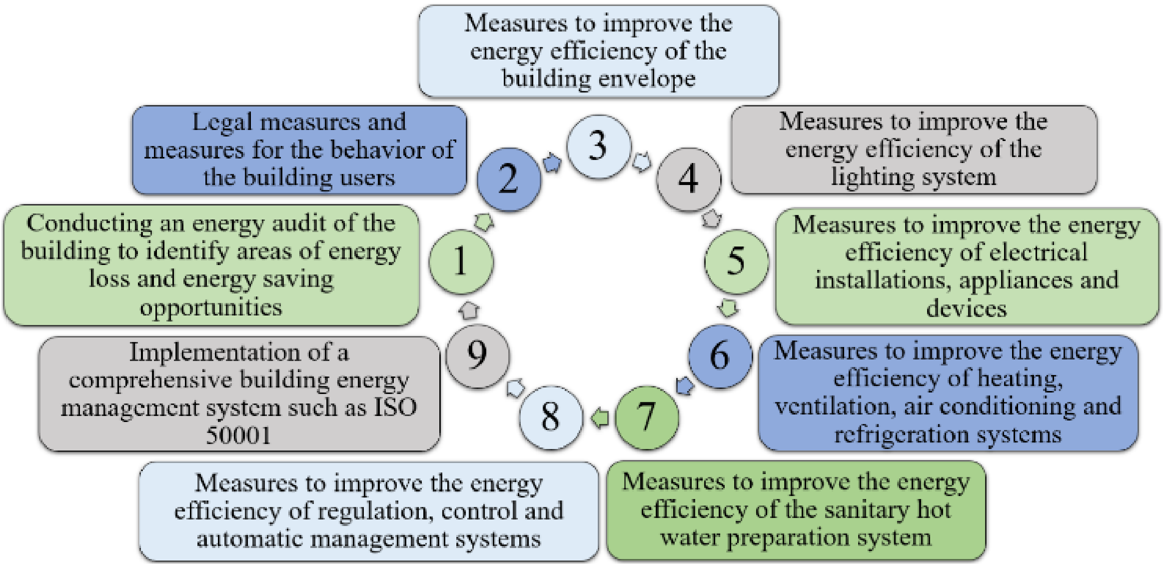

Figure 1. Sequence of implementation of energy efficiency measures for buildings

Comprehensive application of these measures can lead to nearly zero-energy buildings (nZEB), with very low demand partly met by on-site or nearby renewables. Achieving nZEB is technically possible for any building but often costly, highlighting the need for systematic and economically justified selection of efficiency measures. Recent studies confirm that integrating renewable energy technologies such as Building-Integrated Photovoltaic (BIPV) systems, together with intelligent control through hybrid renewable microgrids, can substantially reduce building emissions and improve overall energy performance. Flexible and geometrically adaptive PV systems have been shown to achieve higher annual energy outputs when optimized for surface shape and climatic conditions, providing both environmental and economic benefits. These findings emphasize that the path toward nZEB requires not only high-efficiency components but also advanced design strategies and techno-economic optimization [18].

In this context, the ISO 50001 standard [19] provides an internationally recognized framework for establishing, maintaining, and improving energy management systems. First issued in 2011 and revised in 2018, it is based on the continuous improvement cycle Plan-Do-Check-Act (PDCA). In North Macedonia, ISO 50001:2018 has been adopted as a national standard (MKS EN ISO 50001:2018). The standard defines objectives and procedures for planning, implementing, monitoring, and improving energy performance, thereby enabling organizations to integrate energy management into their long-term operational strategies. The integrated components of an energy management system (EMS) are illustrated in Figure 2.

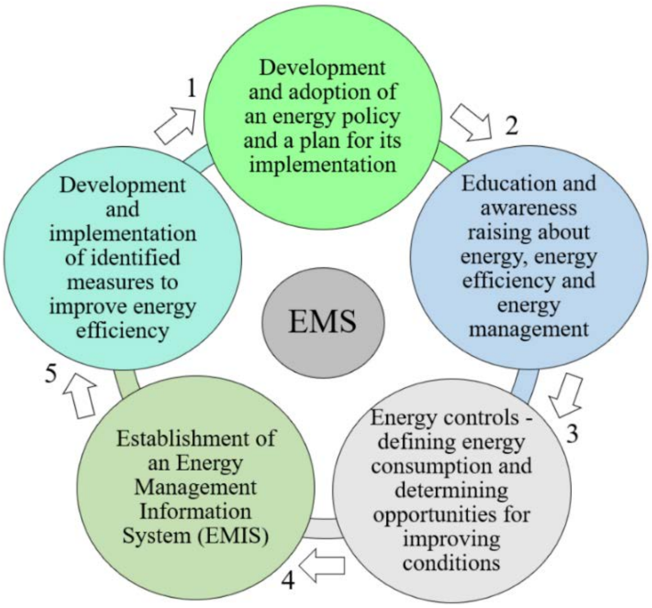

Figure 2. Integrating the components in the systematic energy management process

According to empirical findings, the application of structured energy management systems in buildings, such as ISO 50001, can achieve energy cost reductions of at least 5%, with reported cases of savings exceeding 50% depending on the initial conditions and the comprehensiveness of the measures implemented [20].

3. Case Study and Methodology

The case study was conducted on an existing public building, where a systematic approach to energy management was gradually developed and applied. The methodological framework was based on the ISO 50001:2018 standard.

The methodological approach was also informed by previous applications of ISO 50001 in different contexts. For example, [21] demonstrated the robustness of the ISO 50001 framework in industrial energy systems. By extending this structured methodology to the building sector, the present work highlights the adaptability and scalability of the standard across diverse energy-intensive domains.

Within this framework, the study was organized into three main phases:

- Baseline energy audit,
- Identification and implementation of technical measures, and
- Assessment of energy, economic, and environmental performance and further considerations.

This case study examines a single-storey public building used as a private day-care and educational center, with 139 [m^2] of conditioned floor area. It operates two shifts, 12 hours per day, five days a week, totaling 2,640 annual hours, including 124 heating-season days. Located in a temperate climate (2,635degree days; –18 [°C] winter, 35 [°C] summer), heating is facilitated by an oil-fired boiler, cooling is achieved through split air conditioning units, while domestic hot water from an electric boiler. The building represents typical small-scale public facilities in North Macedonia, with significant potential for energy efficiency improvements through systematic management.

The building consists of six rooms. Except for the storage room, where the internal design temperature in winter is 16 [ºC], the other five rooms have an internal design temperature of 20 [ºC].

The building envelope comprises the exterior walls, roof, exterior doors and windows, and the building floor. The structural and enclosing elements of the building are shown in Figure 3. The structural elements of the building are made of reinforced concrete.

The floor structure is reinforced concrete with thermal insulation made of mineral wool, applied during the construction of the building. The finishing layer in the educational and activity room and hallway is parquet, while the remaining rooms are finished with ceramic tiles.

There are two types of exterior walls used as enclosing elements. The first type consists of a solid brick wall without decorative facade bricks on the exterior side of the building. The second type consists of a solid brick wall that includes a layer of facade bricks on the exterior. The walls are not thermally insulated. The interior side of the walls is finished with a layer of interior lime plaster and paint, except in the kitchen and toilet, where the walls are finished with ceramic tiles.

The roof structure is made of wood. The roof has been renovated and insulated with high-quality materials, including a layer of mineral wool, a vapor barrier, an air layer, and a waterproofing layer, while the roof covering is made of clay tiles.

The exterior doors and windows have wooden frames with double glazing using ordinary glass and do not include any solar shading.

The initial phase was the energy audit of the building, which provided detailed insights into baseline energy consumption, system performance, and user-related factors. Following the baseline energy audit, the heating system was identified as the dominant consumer, accounting for 74.89% of total demand and representing the main source of CO_2 emissions. Lighting was the second largest contributor, responsible for 20.77% of the total annual consumption. The results of the audit serve as a reference scenario, enabling a comparative analysis of the building's performance before and after the implementation of energy efficiency measures.

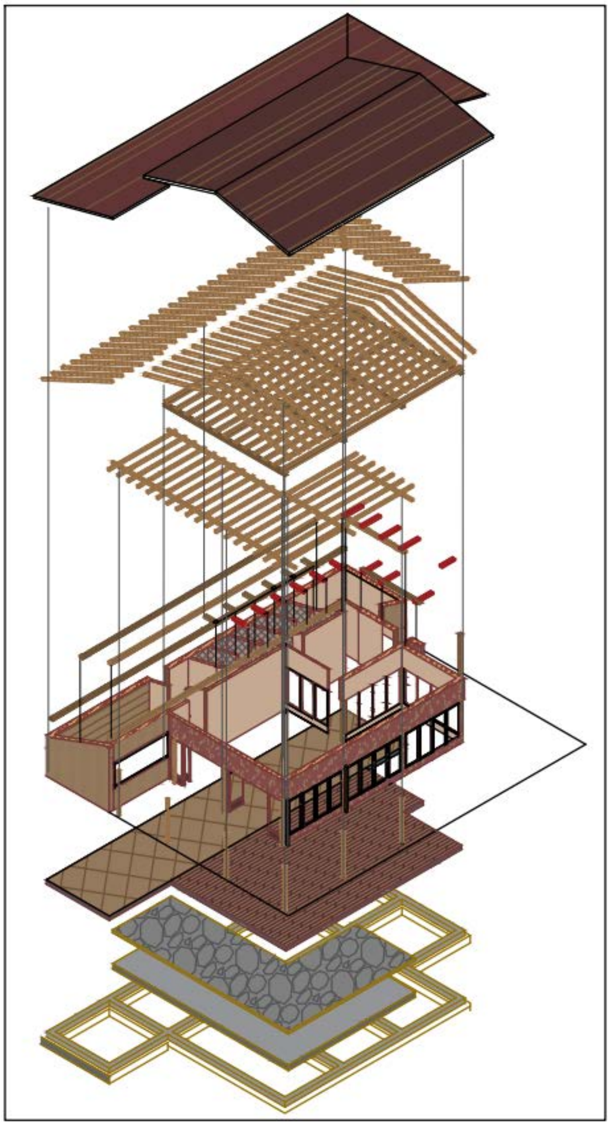

Figure 3. Building structure

In the second phase, a set of retrofit measures, as presented in Table 1, was identified and evaluated according to technical, economic, and environmental criteria, both individually and in combination. Priority was given to improvements of the building envelope. A preliminary comparative analysis of envelope improvement strategies confirmed that such measures significantly reduce transmission losses and directly influence overall energy demand.

This is consistent with recent research on advanced facade and window technologies, such as electrochromic smart windows, which have demonstrated significant potential for reducing heating and cooling loads [22]. Also, the results by [23] show that modifying the wall material or applying external wall insulation can lower energy consumption by approximately 4.9% to 13.0%. This demonstrates the significant impact that envelope improvements can have on overall building performance.

Table 1. Implementation plan for proposed measures and combinations of measures

Combination	Proposed measures	Description
	1	Replacement of the existing wooden exterior doors with double glazing with PVC doors with triple glazing with an average heat transfer coefficient U = 0.78 $Wm^{-2}K^{-1}$
	2	Replacement of the old wooden windows with PVC-framed windows with triple glazing (U = 0.94 $Wm^{-2}K^{-1}$)
I	1+2	Replacement of exterior doors and windows
	3	Installation of an ETICS (External Thermal Insulation Composite System) facade system with 180 [mm] mineral wool (λ = 0.034 $Wm^{-1}K^{-1}$) on all exterior walls
II	1+2+3	Measures to improve the building envelope
	4	Replacement of fluorescent lamps and incandescent bulbs with LED luminaires, with an efficiency of 48%
III	1+2+3+4	Measures to improve the building envelope in combination with replacement of lighting system
	5(1)	Replacement of the existing boiler using extra light fuel oil with a natural gas boiler with a capacity of 46 [kW], together with aluminum radiators and a circulation pump
IV	1+2+3+5(2)	Installation of a new natural gas boiler (24 [kW]), after the implementation of the envelope measures, together with aluminum radiators and a circulation pump
V	1+2+3+4+5(2)	Implementation of all proposed measures

(1) Replacement of the heating source was carried out according to the existing condition of the building.
(2) Replacement of the heating source was carried out according to the applied combination of measures II.

The third phase consisted of assessing the combined impacts of these measures on energy, economic, and environmental performance.

Final energy savings were quantified by comparing post-retrofit consumption, $Q_{F,after}$, with the reference annual consumption, $Q_{F,before}$, of 114,152 [kWh] by using Equation (1):

$$ES_F = Q_{F,\,before} - Q_{F,\,after} \tag{1}$$

Economic feasibility was analyzed through investment costs, annual financial savings, and simple payback periods.

The measures were categorized into:

- Low-investment actions with short payback period (e.g., lighting replacement),
- Medium-investment measures with moderate payback period (e.g., window and door replacement), and
- Combined packages with higher initial costs but significant energy and emission reductions (e.g., envelope insulation with heating system substitution).

By analyzing Figure 4, it can be concluded that the largest investments were needed to replace exterior doors, which account for 26.18% of the total investments needed for the combination of all proposed measures, while the smallest investments were needed to replace existing light bulbs with new, which account for 2.94% of the total investments.

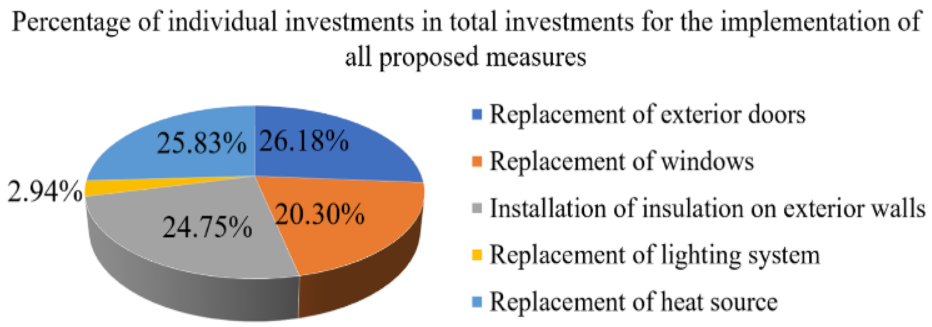

Figure 4. Share of individual investments in the total investments required for the implementation of all proposed measures

The total financial savings, in [MKD/year], were obtained according to Equation (2):

$$N = C_{before} - C_{after} \tag{2}$$

where: C_{before} and C_{after} are the annual energy costs before and after the implementation of measures.

The payback period, in years, was obtained based on the following Equation (3):

$$EPV = \frac{I}{N} \tag{3}$$

where: I, is the total investments for the implementation of the proposed measures.

From an environmental perspective, when taking into account the calculated values for total carbon dioxide emissions before and after the implementation of these measures (EM_{before} and EM_{after}), by using Equation (4) it was determined how much the reduction amounted to (in [t CO_2]):

$$ERED = EM_{before} - EM_{after} \tag{4}$$

Overall, the methodology applied in this case study ensured consistency with ISO 50001 by integrating energy auditing, systematic identification and prioritization of measures, and comprehensive evaluation of their technical, economic, and environmental impacts.

This structured approach enabled a transparent comparison of building performance before and after the implementation of measures.

4. Results and Discussion

The achieved energy, economic, and environmental improvements resulting from the implementation of individual measures and their combinations are summarized in Table 2, indicating that progressive integration of measures – particularly the addition of insulation, lighting modernization, and heating system replacement – leads to substantial cumulative benefits, ultimately resulting in the highest overall energy savings, financial gains, and emission reductions when all measures are applied.

The reduction in the values of the building's energy efficiency indicators confirms the improved energy class of the building, shifting from class F to class D, in accordance with the Rulebook on the Energy Performance of Buildings [24], representing another key benefit of applying systematic energy management in buildings.

Table 2. Recapitulation of achieved performance improvements on an annual basis

Number	Name and description	Energy savings [kWh]	Financial savings [MKD]	Required investments [MKD]	Investment return period [Year]	Emission reduction [t CO_2]
1	Replacement of exterior doors	4,189	30,088	310,200	10.3	1.272
2	Replacement of windows	7,834	56,188	240,472	4.3	2.379
I	1+2	12,023	86,276	550,672	6.4	3.651
3	Installation of insulation on exterior walls	29,986	215,108	293,206	1.4	9.106
II	1+2+3	42,095	302,035	843,878	2.8	12.784
4	Replacement of lighting system	20,511	292,077	34,800	0.12	13.538
III	1+2+3+4	62,606	594,112	878,678	1.5	26.322
5(1)	Replacement of heating source	23,016	268,185	525,629	2	11.888
IV	1+2+3+5(2)	51,912	404,661	1,149,878	2.8	17.242
V	1+2+3+4+5(2)	72,423	696,737	1,184,678	1.7	30.780
Reference energy consumption, [kWh]				114,152		
Total energy savings, [kWh]				72,423		
Reduction in energy consumption, [%]				63.44		

(1) Replacement of the heating source carried out according to the existing condition of the building envelope.
(2) Replacement of the heating source carried out according to the already applied combination of measures II.

A comparison of the building's energy efficiency indicators before and after the implementation of all proposed measures is presented in Figure 5, where a significant reduction in all key parameters can be observed. Regarding the total specific heating demand, the implementation of the measures achieved a reduction of 49.29%.

With respect to the parameter of basic energy consumption, the reduction was 63.43%. The reference indicator of energy consumption decreased by 63.64% after the implementation of the proposed measures.

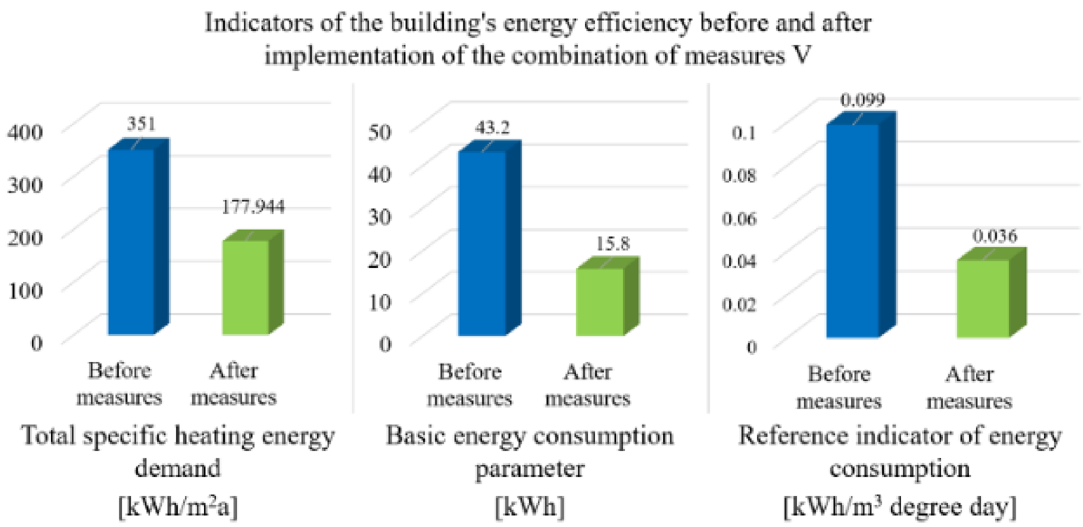

Figure 5. Improving the energy efficiency indicators of the building by implementing all proposed performance improvement measures

The trade-off between investment cost and financial return is illustrated in Figure 6, highlighting the superior cost-effectiveness of lighting modernization and combined retrofit packages. The results clearly demonstrate the economic justification of the proposed interventions, both in terms of reducing energy costs and shortening the payback period of investments.

Analysis of the payback function indicates that the higher the required investment relative to achieved financial savings, the longer the payback period.

In the first three groups of measures, the total investments were on average 80% higher than the corresponding financial savings, which explains the relatively long payback periods compared to other measures. Starting from measure 3, the payback period stabilized within the range of 1.4 to 2.8 years, except in the case of lighting modernization (measure 4). This measure is unique since the annual financial savings exceed the total investment, resulting in an extremely short payback period of 0.12 years, confirming its cost-effectiveness and high potential for integration with other measures.

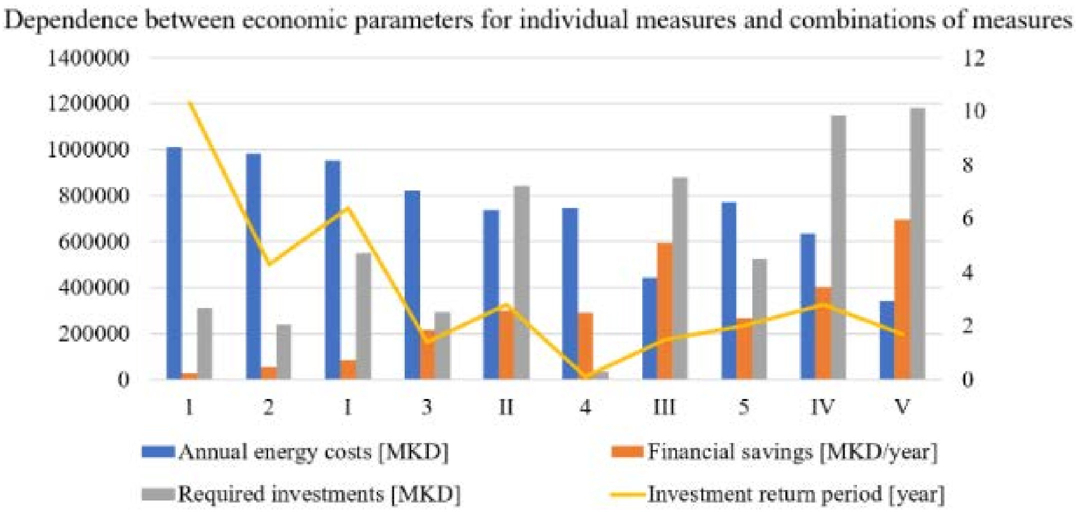

Figure 6. Analysis of economic performance for the building with gradual implementation of individual measures and combinations of measures

A comprehensive overview of the overall benefits, enabling comparison across individual and combined measures, is provided in Figure 7.

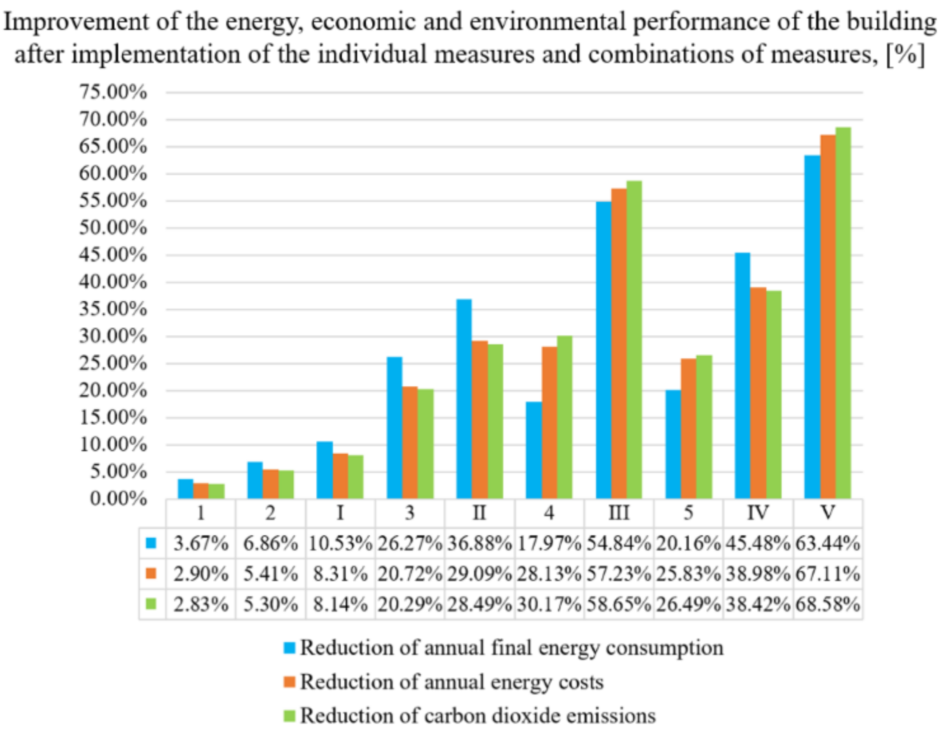

Figure 7. Recapitulation of achieved reductions for all considered variants

Energy efficiency: The insulation of exterior walls provided the most significant individual savings, underscoring the critical importance of envelope retrofits in lowering energy demand [11], [12]. The comprehensive application of all strategies (case V) resulted in the highest total savings, aligning with [13] which illustrates the collective advantages of integrated solutions.

Recent studies reinforce these findings. The authors in [25] demonstrated through a multi-objective decision optimization model based on an improved grasshopper optimization algorithm that retrofitting design guided by multi-objective optimization can reduce energy use in buildings by up to 49.6%, confirming the importance of systematic and data-driven renovation strategies. Similarly, [26] showed that intelligent HVAC control using genetic programming achieved 40.9% energy reduction while maintaining thermal comfort for 98.8% of occupied hours, further proving that algorithmic optimization can complement physical envelope improvements.

A building energy management model integrating rule-based and genetic algorithms reduced operating costs by up to 39.3%, showing how combining computational optimization with ISO 50001 management principles enhances decision-making efficiency [27]. Similarly, [28] developed a Bayesian regression and thermal inertia correction model for accurate energy prediction, achieving error reductions up to 4.4%, which supports the integration of advanced analytical tools in forecasting the outcomes of building retrofits.

Economic performance: Lighting modernization resulted in the most significant individual financial savings, whereas the comprehensive set of measures yielded the most favorable overall results, featuring a payback period of 1.7 years. This is consistent with [29], which indicated a payback period of 1.5 years for a comparable retrofit package.

Climate-adaptive and retrofit design not only enhances sustainability but also delivers substantial long-term economic benefits by lowering operational costs [30]. Policy incentives, behavioral change, and household retrofit programs significantly influence economic feasibility, while financial barriers and lack of awareness remain key obstacles [31]. These insights align with the economic rationale of ISO 50001, where structured management systems ensure that investments in efficiency measures achieve measurable cost savings and fast returns.

Environmental performance: Lighting upgrades proved to be the most significant individual intervention, while the complete package yielded the greatest benefits, achieving a reduction of 30.78 [t] of CO_2 annually. Similar outcomes were noted by [32], where residential retrofits led to a reduction of around 23.87 [t] of CO_2, thereby affirming alignment with existing literature.

The authors in [33] found that environmental awareness among school leaders and behavioral engagement with energy-saving practices strongly influence emission reductions, underscoring the importance of combining technological and organizational measures. Likewise, residential retrofits provide significant environmental gains, with energy efficiency improvements in households contributing meaningfully to national CO_2 reduction targets [31]. Furthermore, energy retrofits in residential buildings can significantly mitigate the impact of climate change by enhancing thermal comfort and reducing the carbon footprint, supporting the environmental relevance of the present study's results [30].

With reductions exceeding 60% across all three performance categories and an improvement in the building's energy class from F to D, the selection and implementation of the proposed measures are fully justified. These results align with recent findings on the cost-effectiveness of energy efficiency measures, where comparative studies confirm the importance of considering both envelope and system interventions [12], [34]. Similarly, the achieved CO_2 reductions are consistent with broader evidence on the role of building efficiency improvements in lowering emissions in combined heating, cooling, and electricity systems [35].

The reviewed studies confirm that integrating multi-objective optimization, advanced control algorithms, and behavioral engagement leads to more resilient and energy-efficient buildings. This is directly aligned with the ISO 50001 PDCA (Plan-Do-Check-Act) framework, which promotes continuous improvement and evidence-based decision-making. The inclusion of predictive models [28] and adaptive algorithms [25], [27] demonstrates the growing convergence between AI-driven optimization and structured energy management systems. Prospective actions under ISO 50001 should therefore include coupling optimized retrofits with intelligent building management, ensuring that operational data continuously feed back into decision-making to sustain performance gains over time.

In alignment with the ISO 50001 PDCA cycle principles, the focus on continuous improvement should encompass the exploration of additional opportunities. Prospective actions may include the addition of floor insulation and the substitution of the heating system with a heat pump that offers heating, cooling, and hot water capabilities. Studies reveal that when paired with enhanced building envelopes, heat pumps significantly boost efficiency and lower CO_2 emissions – up to 70% with solar-assisted systems [36], and achieving 66% savings in primary energy [37].

Considering the improved envelope in the context, such integration is thoroughly justified, although the payback period may differ from those associated with envelope or lighting measures. A recent study assessing the low-energy potential of a school building demonstrated that combining building envelope improvements with heat pump systems (supported by optimization and surrogate modeling) can lead to significant decreases in primary energy usage and operational emissions, thereby reinforcing the feasibility of these combined strategies [38]. Additional savings could be realized through the use of occupancy sensors and automated lighting, which have been shown to be cost-effective with brief payback periods [35], [39]. Finally, user behavior is a crucial element in ensuring long-term performance, highlighting the importance of awareness and compliance with the established energy management system. Behavioral and organizational dimensions are often overlooked in technical assessments, yet research indicates that without proper training and awareness programs, the longevity of savings can be significantly compromised [40].

5. Conclusion

The systematic implementation and evaluation of the proposed measures confirm that applying ISO 50001 principles significantly improves buildings' energy, economic, and environmental performance. Comparative analysis before and after implementation enabled a comprehensive assessment of cost-effectiveness and efficiency, quantifying their potential in energy savings, financial benefits, and CO_2 reduction.

The calculations and analyses were carried out for each individual measure as well as for categorized combinations, which allowed for a more precise comparison of results and facilitated the selection of the most favorable solution. This systematic approach enables the identification of optimal measures and ensures continuous performance improvement, which is the core objective of ISO 50001.

Based on the conducted analyses, the following findings can be highlighted:

- A systematic assessment of baseline conditions is essential for selecting effective measures.
- ISO 50001 establishes a framework for implementation of measures and monitoring improvements in energy, economic, and environmental performance.
- Key performance indicators include reductions in energy use, operating costs, and CO_2 emissions, enabling comparison of individual and combined measures.
- Exterior wall insulation proved the most effective single measure, reducing about one-quarter of annual demand.
- Lighting replacement achieved the highest cost and CO_2 savings with the shortest payback period, fully justifying its application.
- Combining measures improved performance more than individual actions, with the full envelope, lighting, and heating package giving optimal results.

The results of this study demonstrate that systematic energy management in buildings, in line with the ISO 50001 standard and its Plan-Do-Check-Act cycle, represents an energy-efficient, economically viable, and environmentally justified approach. The successful outcomes confirm that the adoption of properly selected and combined measures not only ensures financial and environmental benefits but also contributes to the long-term sustainability and continuous improvement of building performance.

Furthermore, the case study presented addresses a deficiency in the existing literature by offering a quantified implementation of ISO 50001 within a small public building in North Macedonia, a context rarely documented in previous research. These results strengthen the evidence base for policymakers and practitioners, showing that standardized frameworks like ISO 50001 can complement technical retrofits and advance EU energy efficiency targets.

This paper, despite its valuable contributions, has certain limitations. Firstly, the outcomes are based on a single small-scale public building, which restricts their generalizability to other building types. Additionally, the economic evaluations were conducted using fixed energy prices and investment costs, neglecting the impact of long-term market changes or life-cycle costs. Furthermore, while the study assessed CO_2 reduction, it did not take into account broader environmental and social co-benefits, and there was no implementation of digital monitoring for ongoing ISO 50001 improvement. Nevertheless, despite these constraints, the results present strong evidence supporting the effectiveness and feasibility of systematic energy management in buildings.

Subsequent research may broaden this framework to larger building categories, incorporate digital monitoring systems, and analyze synergies with renewable energy integration, thus extending the reach and significance of systematic energy management in the built environment.

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