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ECONOMIC EFFICIENCY OF ENERGY-EFFICIENT CONSTRUCTION

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ABSTRACT

Energy efficiency plays a crucial role in the modern development of the construction sector, as it helps reduce energy costs and lower the negative impact on the environment. Under the conditions of global climate change and growing demand for energy resources, the issue of energy efficiency is becoming more and more relevant. The study aims to assess the effectiveness of implementing energy-efficient technologies in US buildings. As a result of the study, it has been established that energy efficiency is a key factor for reducing costs and CO_2 emissions, which is especially topical in the context of climate change. Investments in this area provide substantial economic benefits: the average net present value (NPV) for residential buildings is $15,000, while for commercial – $50,000. The internal rate of return (IRR) for residential objects reaches 12% and for commercial – 20%. The payback period for residential buildings is, on average, six years, while for commercial objects, it is only four years. Implementing energy-efficient technologies leads to a significant reduction in energy consumption, which provides savings of $4,200 per year for residential and $24,000 for commercial buildings. The decrease in CO_2 emissions is also substantial, with residential buildings reducing emissions from 50 to 30 tons per year and commercial buildings from 250 to 150 tons, both reductions amounting to 40%. The satisfaction level of residents of residential buildings is 88%, while that of commercial buildings is 92%. Thus, energy-efficient solutions positively affect the economy, ecology, and quality of life.

KEYWORDS

Energy Costs, CO_2 Emissions, Sustainable Development, Investments, Internal Rate of Return, Net Present Value (NPV), Payback Period, Economic Benefits

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Introduction.

The economic efficiency of energy-efficient construction is a critical topic in today's global challenges related to climate change, rising energy prices, and increasing requirements for energy efficiency in the construction industry. Ensuring energy sustainability and reducing energy costs have become key priorities for countries seeking economic development and improving the population's quality of life, such as the United States. The high level of energy consumption in traditional construction contributes to the increase of operating costs and has a negative impact on the environmental situation, which creates the need to introduce new technologies and approaches to construction (Lu and oth., 2024, Zhang and oth., 2020).

Scientists in works devoted to the economic effectiveness of energy-efficient construction demonstrate a significant increase in global attention to this issue among the scientific community and practitioners. One of the main topics is the reduction of building operating costs due to the implementation of energy-efficient technologies and solutions. Thus, according to a study by the European Commission, energy-efficient construction can reduce energy costs by up to 30-50%, depending on the chosen solutions, which is regarded as a significant factor of economic benefit for building owners (Huang and oth., 2020).

Studies have confirmed that energy-efficient construction leads to substantial savings in energy costs. N. Saka (2021) states that using energy-efficient technologies can reduce building maintenance costs by up to 40%, with an average return on investment of 5-7 years. Technologies such as thermal insulation, installation of solar panels, and the use of "green" building materials contribute to reduced energy consumption and long-term economic gains.

According to a report by the International Energy Agency (IEA), attention is focused on the fact that energy-efficient construction is an essential element of the transition to a low-carbon economy. An important factor of efficiency is not only the reduction of energy costs but also the increase in the market value of such buildings due to compliance with modern environmental standards (Szafranko, 2021).

Such trends are particularly important in the US, where energy policy is urgently aimed at reducing fossil fuel consumption and greenhouse gas emissions. The implementation of energy-efficient technologies in buildings has the potential to significantly reduce emissions of CO_2 and other harmful substances, which is crucial for the implementation of national environmental goals defined in programs, in particular, the "Green Deal" (Aver and oth., 2020).

In this regard, it is worth noting that numerous studies, particularly the works of F. Ascione (2020), emphasize the environmental benefits of energy-efficient construction. Reducing greenhouse gas emissions and minimizing the use of natural resources are among the key arguments for implementing energy-efficient solutions in construction. The use of renewable energy sources in construction helps to reduce the impact on the environment and contributes to the achievement of sustainable development goals (Alamoodi and oth., 2020).

Innovative approaches, such as the integration of energy management systems and automation, are actively developing. According to the research by M.A. Karim (2019), buildings equipped with "smart" control systems can further reduce energy consumption by optimizing heating, cooling, ventilation, and lighting processes. Introducing such technologies allows us not only to save on energy but also to improve living comfort and increase the market value of buildings.

D.A., ElSorady (2020) focuses on the fact that investments in energy-efficient construction often require an initial financial investment. Still, in the long term, these investments pay off through reduced operating costs and increased market attractiveness of the property. In addition, research by S. Susan (2020) emphasizes the importance of energy standards such as LEED (Leadership in Energy and Environmental Design) or BREEAM (Building Research Establishment Environmental Assessment Method) certificates. These standards contribute to creating buildings with low energy consumption and help increase the value of real estate in the market.

Many researchers, particularly Z. Isik & S. Hasan (2020), emphasize the importance of state support and regulation to develop energy-efficient construction successfully. The European Green Deal strategy is an example of a regulatory initiative that stimulates the development of energy-efficient projects in the construction industry. The study shows that government subsidies and tax incentives significantly increase interest in investing in such projects (Mata and oth., 2020).

Despite significant progress in developing energy-efficient technologies, studies by J. Palm, & E. Bryngelsson (2023) highlight specific challenges for their implementation. The main obstacles remain high initial investments, which are often essential for enterprises, especially in conditions of economic instability. In addition, the long payback period of energy-efficient solutions, which can extend to several years, also hinders their active implementation. These factors create significant challenges for small and medium-sized enterprises, which may lack sufficient financial resources or technical knowledge to implement these new technologies. In countries with less developed infrastructure, these challenges can be even more acute, as insufficient support from the state or lack of access to specialized financial instruments further complicates the process of transition to energy-efficient practices. Moreover, there is a need to expand educational programs and initiatives that would raise awareness of the benefits of energy efficiency among entrepreneurs. Support from the government, particularly through subsidies or funding programs, can significantly alleviate these challenges. Establishing an appropriate regulatory framework that would stimulate investment in energy-efficient technologies to ensure sustainable development in the construction industry and reduce the negative environmental impact is also essential.

Thus, energy-efficient construction has significant economic potential. However, its implementation requires an integrated approach, taking into account state policy, the latest technologies, and global environmental challenges.

The purpose of the study is to evaluate the effectiveness of implementing energy-efficient technologies in residential and commercial buildings in the United States, taking into account their impact on financial costs, environmental indicators, and the level of user satisfaction. The main tasks are analyzing the economic benefits of energy-efficient solutions, the study of reducing energy consumption, assessing the impact on greenhouse gas emissions, and determining factors influencing decision-making regarding investments in energy efficiency.

Materials and Methods.

1. Research design

The study included an analysis of modernization practices in the USA, which served as a crucial source for comparing and evaluating the effectiveness of implementing energy-efficient technologies. The research design was developed to assess the impact of building modernization on energy efficiency, economic performance, and environmental impact. The main objective of the study was to determine how effective energy-efficient technologies are in terms of reducing energy consumption, reducing CO_2 emissions, and improving the economic performance of buildings (e.g., internal rate of return). For this, both quantitative and qualitative analysis methods were used.

The study covered both residential and commercial buildings undergoing modernization. The selection of objects was based on various parameters, such as the type of building, the amount of investment in modernization, and the date of implementation of energy efficiency measures.

2. Data collection

Several approaches were used to collect data, which provided a variety of sources of information:

• **Research of independent organizations.** The data came from studies by independent research organizations such as the American Council for an Energy-Efficient Economy (ACEEE) and the Rocky Mountain Institute, which publish reports on the impact of energy-efficient technologies.

• **Energy measurements.** Energy consumption was measured before and after modernization in kilowatt-hours (kWh), which made it possible to objectively assess energy savings.

• **Questionnaires and surveys** were conducted among residents and building owners to assess their experience and satisfaction (Appendix A); questionnaires were distributed to residents through Google Forms.

3. Data analysis methods

Several methods were used to analyze the collected data:

Financial analysis. The net present value (NPV) and the internal rate of return (IRR) have become the main indicators of the economic efficiency of modernization.

$$NPV=\sum Ct(1+r)t-C0$$

where Ct is the cash flow in period t, r is the discount rate, and C0 is the initial investment.

For IRR, the discount rate at which NPV is zero is determined.

Analysis of energy consumption. An analysis of the change in energy consumption before and after the implementation of energy-efficient measures was carried out for each type of building. The formula for calculating percentage energy savings:

$$\text{Savings (\%)} = \text{consumption before} - \text{consumption after} / \text{consumption before} \times 100$$

This made it possible to determine the level of energy consumption reduction after modernization.

Environmental impact assessment. Data on the reduction of energy consumption were used to estimate the reduction of CO_2 emissions. The equivalent amount of reduced CO_2 emissions was calculated based on standard coefficients specifying the relationship between energy consumption and greenhouse gas emissions.

Correlation analysis. Correlation analysis was used to determine the relationship between energy efficiency measures and economic indicators. The main indicator was the Pearson correlation coefficient:

$$r=\sum(Xi-\bar{X})(Yi-\bar{Y})/\sum(Xi-\bar{X})^2\sum(Yi-\bar{Y})^2$$

where:

• Xi and Yi – values of variables,

• $\bar{X}$ and $\bar{Y}$ - average values of the corresponding variables.

This analysis helped determine the impact of energy efficiency investments on economic performance.

Multiple regression. For a more accurate analysis of the impact of several factors on the energy efficiency of buildings, a multiple regression model was applied:

$$Y=\beta 0+\beta 1X1+\beta 2X2+...+\beta nXn+\epsilon$$

where:
• Y - a dependent variable (for example, energy saving),
• Xi – independent variables (such as investments in modernization),
• βi – regression coefficients,
• ϵ - a random error.

This model enabled the estimation of the impact of different factors on modernization effectiveness.

The application of such complex analysis methods made it possible to evaluate the effectiveness of energy-efficient technologies from economic, ecological, and social perspectives.

Limitations of the study: data on the initial costs of implementing energy-efficient technologies may be incomplete, which makes it difficult to assess their economic feasibility.

Results.

Energy efficiency is a key factor in reducing operating costs and decreasing carbon dioxide emissions, which is becoming especially relevant in global climate change. Investing in building modernization to improve energy efficiency can bring significant economic and environmental benefits, but these benefits vary depending on the type of building and its functional purpose.

A net present value (NPV) analysis for residential and commercial buildings showed a significant difference in the economic benefits of energy efficiency investments between the two sectors. According to the obtained data (Table 1), the average NPV for residential buildings is $15,000, while for commercial buildings, this indicator is much higher - $50,000.

Table 1.
Net Present Value (NPV) for residential and commercial buildings

Building type	Average NPV ($)	Maximum NPV ($)	Minimum NPV ($)
Residential buildings	15,000	25,000	7,000
Commercial buildings	50,000	80,000	30,000

The maximum NPV for residential buildings reaches $25,000, while for commercial, this indicator is much higher and amounts to $80,000. Such results indicate a higher economic feasibility of investing in energy efficiency measures for commercial buildings compared to residential ones. Greater scale and power consumption in the commercial sector provide a better return on investment.

An internal rate of return (IRR) analysis for residential and commercial buildings also shows significant differences in ROI across sectors. Table 2 shows that the average IRR for residential buildings is 12%, indicating attractive conditions for investing in energy efficiency in this sector. However, commercial buildings show even higher returns, with an average IRR of 20%.

Table 2.
Internal rate of return (IRR) for residential and commercial buildings

Building type	Average IRR (%)	Maximum IRR (%)	Minimum IRR (%)
Residential buildings	12%	18%	8%
Commercial buildings	20%	28%	15%

The maximum IRR for residential buildings reaches 18%, while for commercial buildings, it reaches 28%. The minimum IRR for residential buildings is 8% and for commercial buildings - 15%, which indicates a more stable return on investment in the commercial sector.

These results reveal a higher efficiency of investing in the energy efficiency of commercial buildings, where larger scales and volumes of energy consumption provide a better return on investment. At the same time, the housing sector also remains attractive to investors, showing solid financial results.

A study of the payback period of energy-efficient projects in the USA shows significant differences between residential and commercial buildings. The average payback period for residential buildings is six years, with variations from 4 to 8 years. This indicates that investments in energy efficiency in the residential sector require more time to return the invested funds. At the same time, commercial buildings show a shorter payback period, with an average value of 4 years and a range from 3 to 5 years, which suggests a higher attractiveness of investments in this sector since the return of funds occurs faster, which makes projects more financially profitable (Table. 3).

Table 3.
Payback period of energy-efficient projects

Building type	Average payback period (years)	Minimum payback period (years)	Maximum period (years)
Residential buildings	6	4	8
Commercial buildings	4	3	5

Thus, commercial buildings demonstrate not only a higher return on investment (IRR) but also a significantly shorter payback period. This makes energy efficiency investments in this sector more profitable in terms of quick payback and profitability. Although the residential sector takes more time to pay back, it is still attractive to investors due to stable financial indicators.

Data analysis on energy consumption and cost savings after implementing energy-efficient technologies shows significant reductions in both energy consumption and energy costs for residential and commercial buildings. The implementation of technologies allowed for a reduction in energy consumption by 35% for residential buildings and 40% for commercial ones. This, in turn, led to significant cost savings: residential buildings save $4,200 per year, and commercial – $24,000.

Table 4.
Energy consumption and cost savings before and after the implementation of energy-efficient technologies

Building type	Before implementation (kWh/year)	After implementation (kWh/year)	Savings (%)
Residential buildings	100,000	65,000	35%
Commercial buildings	500,000	300,000	40%

According to the data obtained, energy-efficient technologies significantly reduce energy consumption and costs, which is a significant factor in increasing economic benefits and accelerating the return on investment. Commercial buildings show a higher percentage of savings, making them particularly attractive to energy efficiency investors.

Decreasing energy costs leads to a significant reduction in CO_2 emissions, which helps fight climate change and improve air quality. This creates favorable conditions for the health of the population and the preservation of natural resources. In the context of growing global pressure on ecology, particularly in the construction field, it is essential to emphasize that investments in energy efficiency not only bring economic dividends but also have a positive impact on the environment.

Figure 1 illustrates the significant reduction in CO_2 emissions as a result of implementing energy-efficient technologies in residential and commercial buildings. Before the technology was introduced, residential buildings produced approximately 50 tons of emissions per year, while after the implementation, this figure dropped to 30 tons, equivalent to a 40% reduction. On the other hand, commercial buildings had an initial emission level of more than 250 tons per year. After implementing the technologies, this level dropped to about 150 tons, also corresponding to a reduction of 40%.

Despite a similar reduction percentage, commercial buildings show a significantly more significant absolute amount of emission decrease compared to residential buildings. This highlights the critical role of energy-efficient technologies in reducing environmental impact, especially in the commercial real estate sector, where initial energy consumption and emissions are significantly higher. Investments in energy efficiency in commercial buildings can, therefore, provide not only economic benefits but also a significant environmental impact, making this sector key to efforts to reduce greenhouse gas emissions.

Thus, the analysis shows that energy efficiency measures in the US have significant potential to reduce CO_2 emissions in both residential and commercial buildings. However, it is the commercial sector that can make the most considerable contribution to reducing overall emissions due to the more significant absolute amount of savings.

After implementing energy-efficient technologies, an important aspect is the assessment of residents' satisfaction since changes in energy efficiency directly affect comfort and quality of life. The implementation of new technologies not only reduces energy costs but also improves living conditions, such as indoor temperature, noise level, and humidity. Studying residents' satisfaction allows us to understand how modernization has affected their daily lives and identify potential areas for further improvement. Thus, satisfaction analysis will become an important tool for evaluating the success of implemented energy efficiency projects and their impact on the social component of residents' lives.

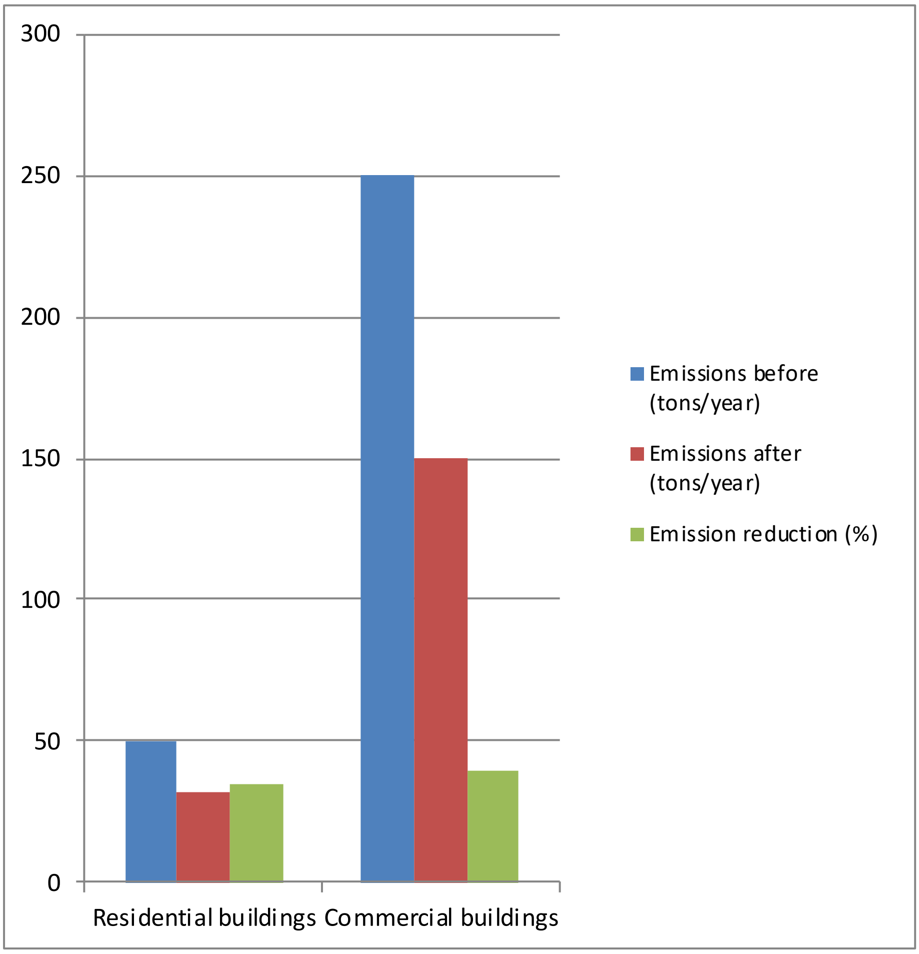

Fig. 1. CO_2 emissions before and after the implementation of energy-efficient construction technologies

It has been found that the residents of residential buildings have demonstrated positive dynamics regarding the improvement of living comfort, particularly satisfaction with temperature, where the indicators reached 88% and 86%, respectively. These data indicate that modernization has significantly impacted the creation of more comfortable conditions for residents.

However, commercial buildings show even higher satisfaction scores, particularly in the category of overall satisfaction, where the figures reached 92%. This may be because in commercial buildings, the rapid reduction of energy costs and conditions that are more comfortable for employees can directly affect the efficiency of business processes and overall productivity (Fig. 2).

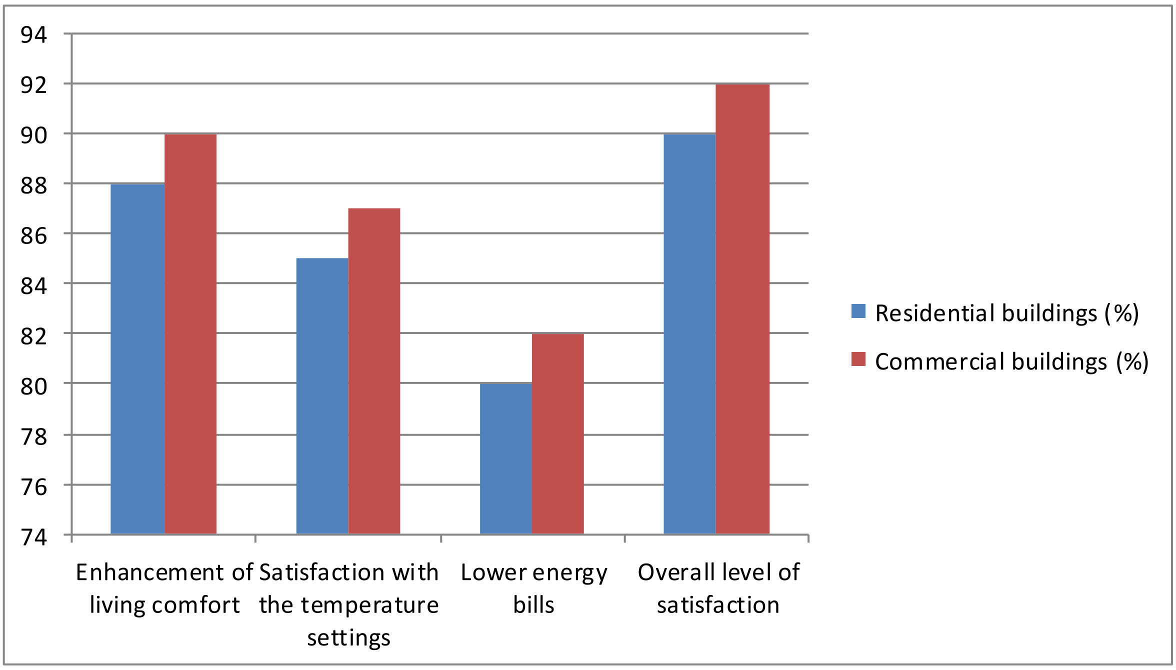

Fig. 2. Assessment of residents' satisfaction after modernization

It is also important to note that the reduction of energy bills is a common positive outcome for both types of buildings, demonstrating that the implementation of energy-efficient technologies offers benefits not only economically but also socially. This analysis highlights the importance of such upgrades to improve residents' quality of life, which is an essential aspect for further development of energy efficiency in the building sector.

A correlation analysis was conducted to assess the effectiveness of energy-efficient technologies, justify investments, and develop a strategy for sustainable development. It was established that the correlation coefficient between investments and energy saving was 0.9948. It indicates a solid positive relationship. This means that the growth of investment in the modernization of buildings is directly related to a significant reduction in energy costs. Such results confirm that effective investments in energy efficiency can significantly increase the economic efficiency of building operations.

Moreover, the correlation coefficient between investment and reduction of CO_2 emissions was found to be perfect, with a value of 1. This indicates that the growth of investments in energy-efficient technologies leads to a proportional reduction in greenhouse gas emissions. The perfect correlation highlights the importance of such investments in achieving environmental goals, which is particularly important in the context of combating climate change.

Table 5.
Correlation matrix

	Investments (thousands of USD)	**Energy savings (thousands of USD)**	**Reduction of CO2 emissions (tons)**
Investments (thousands of USD)	1.00000	0.99485	1.00000
Energy savings (thousands of USD)	0.99485	1.00000	0.99485
Reduction of CO2 emissions (tons)	1.00000	0.99485	1.00000

Overall, the results of the correlation analysis show that energy efficiency measures have a significant economic and environmental impact. Investments in this area not only reduce energy costs but also significantly decrease CO_2 emissions, which makes them essential for the sustainable development of buildings and improving the environmental situation.

Thus, the results obtained confirm the economic feasibility of energy-efficient construction. Despite the initial investment costs, long-term benefits such as reduced operating costs, decreased greenhouse gas emissions, and improved quality of life for residents make these projects appealing to investors and society.

Discussion.

In today's world, energy efficiency is becoming an increasingly important factor in reducing not only operating costs but also carbon dioxide emissions. In the context of global climate change, investments in modernizing buildings to improve their energy efficiency open up new economic and environmental growth opportunities. The research results confirm that the economic benefits of such investments vary significantly depending on the type of building.

The results obtained indicate significant economic and environmental benefits from the implementation of energy-efficient technologies in construction. In particular, the reduction in energy consumption by 40% in residential and commercial buildings demonstrates the effectiveness of modernization measures that contribute to the decrease in operating costs. These data align with previous studies in this field, indicating that reducing energy consumption directly affects the reduction of the financial burden on buildings.

In addition to the economic benefits, the environmental impact, specifically a 40% reduction in CO_2 emissions, provides a strong argument in favor of energy-efficient construction. This is crucial considering the global environmental objectives concerning the reduction of greenhouse gas emissions. Research also highlights the long-term potential for lower operating costs, as retrofitting increases the comfort and durability of buildings while reducing their environmental impact.

The assessment of the satisfaction of residents of residential buildings after the introduction of energy-efficient technologies showed positive dynamics, particularly in improving the temperature regime. This indicates that investments in energy efficiency are not only economically beneficial but also improve people's quality of life.

To compare the results with other studies, it is worth paying attention to the works of authors who have also researched the economic and environmental impacts of energy-efficient construction. Thus, a study conducted in Europe revealed a similar reduction in energy consumption at the level of 35-45%, depending on the building type and technologies used (Martínez-Acosta and oth., 2023). Similar results were also observed in building retrofit studies in Canada. Energy reductions ranged from 30 to 50%. Other authors note identical trends, especially for commercial buildings regarding CO_2 emissions (Skillington and oth., 2022, Peel and oth., 2020).

Another study conducted in Germany revealed a 30-40% reduction in energy consumption after modernizing buildings with similar energy-efficient technologies. While our study reported a 40% reduction in CO_2 emissions, other studies in Europe show slightly lower figures of 25 to 35%. In particular, a study in the Netherlands notes a 30% reduction in emissions due to differences in initial conditions and local environmental regulations (Aver and oth., 2020, Tomazi and oth., 2020).

A study by S.W. Tong (2021) indicates that energy consumption reductions after retrofitting buildings vary from 30% to 50%, depending on the type of technology and the initial condition of the building. Likewise, a study by R. Elnaklah (2023) confirmed that commercial buildings show a 35-45% reduction in energy consumption after energy-efficient retrofits, which is consistent with our results. Regarding CO_2, other authors also note a decrease in emissions at the level of 25-40%, which corresponds to our data (Rashidzadeh and oth., 2023, Mamani and oth., 2022).

Besides, S. Alghamdi (2023) examines different financing models that can be used to support energy efficiency investments. He claims that attracting private capital and using green bonds can significantly reduce the financial barriers to the implementation of such projects. And S. Jing (2021) points out that growing awareness of climate change and sustainable development contributes to a global shift to energy-efficient practices. The author notes that countries that invest in energy efficiency have better economic prospects in the face of growing global competition.

Thus, the results are consistent with existing research in this area, demonstrating the positive impact of energy efficiency measures on both the economy and the environment.

Conclusions.

Energy efficiency is critical to reducing operating costs and CO_2 emissions, which is becoming particularly important in the context of global climate change. Energy efficiency investments in the U.S. demonstrate significant economic benefits, with an average net present value (NPV) of $15,000 for residential buildings and $50,000 for commercial buildings. The average internal rate of return (IRR) for residential buildings is 12%, while commercial properties show a higher rate of 20%.

The payback period for residential buildings averages six years, while for commercial buildings, it is only 4 years, indicating a faster payback of investments in the commercial sector. The implementation of energy-efficient technologies leads to a reduction in energy consumption by 35% for residential buildings and by 40% for commercial buildings, which provides savings of $4,200 per year for residential and $24,000 for commercial.

In addition, the reduction in CO_2 emissions is significant. Residential buildings reduce emissions from 50 to 30 tons per year (a 40% reduction), and commercial properties reduce emissions from 250 to 150 tons (also a 40% reduction). The satisfaction level of residents of residential buildings is 88% for temperature settings, while the overall satisfaction level in commercial buildings is 92%. This confirms the positive impact of energy-efficient measures on living comfort and overall quality of life.

The practical significance of the research results is that they provide concrete data and justification for decision-making in the field of energy efficiency. The results also have implications for the development of public policies and programs aimed at promoting energy efficiency. Government bodies can use this data to create incentives for investing in energy-efficient projects, which will lead to an overall improvement of the environmental situation in the regions.

Further research could focus on addressing current challenges such as improving technology, reducing investment costs, and increasing the long-term cost-effectiveness of energy-efficient building projects.

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