BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 30 | №2 | 2026
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X
Received: 12.02.2026. Revised: 28.05.2026. Accepted: 25.06.2026. Published: 06.07.2026.

UDC 697.1 DOI: 10.33744/2308-6645-2026-2-30-8-19

Adaptive heating and ventilation systems for achieving an optimal microclimate in modern buildings

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Abstract. The relevance of the study is due to the need to improve the energy efficiency of buildings and create a comfortable microclimate in the context of growing requirements for environmental friendliness and energy savings. The purpose of the study was to assess how different approaches to heating and ventilation systems increase comfort and energy efficiency in buildings. Methods of technology efficiency analysis and comparative evaluation of energy systems were used to determine optimal solutions in the field of microclimate automation and integration of renewable energy sources. The results showed that adaptive heating and ventilation systems substantially increase energy efficiency. Heat pumps combined with geothermal technologies maintain a stable indoor temperature even under variable external conditions. Ventilation systems with heat recovery reduce energy loss by retaining heat during air exchange. Automation of the microclimate using sensors and control systems allows adjusting the parameters of heating and ventilation depending on the occupancy of the premises, humidity level, and air composition. The integration of renewable energy sources, such as solar collectors and biomass, shows high efficiency in reducing the consumption of traditional energy resources. Analysis of facilities in different countries demonstrated that the best

Suggested Citation: Pavlovskyi, S., Chaika, Yu., Tkachenko, R., Romanenko, S., & Alforov, S. (2026). Adaptive heating and ventilation systems for achieving an optimal microclimate in modern buildings. *Bulletin of the National Transport University*, 30(2), 8-19. doi: 10.33744/2308-6645-2026-2-30-8-19.

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results were achieved thanks to an integrated approach that combines modern technologies and adaptive solutions. Buildings with integrated adaptive systems maintain a stable microclimate regardless of external conditions, which has a positive effect on user comfort. Optimising energy consumption also reduces operating costs, making such solutions economically feasible for long-term use. Adaptive systems not only provide comfortable conditions but also substantially reduce energy consumption in buildings for various purposes

Keywords: energy efficiency; heat pumps; geothermal technologies; heat recovery; automation; renewable energy sources

Introduction

In construction, one of the main goals is to create comfortable conditions for people with minimal energy consumption. Heating and ventilation systems are among the most energy-intensive in buildings, so it is important to develop adaptive technologies that effectively regulate the microclimate depending on changing conditions. Adaptive heating and ventilation systems automatically adjust the temperature, humidity, and air exchange according to the needs and surrounding conditions. Due to the introduction of smart technologies such as heat pumps, geothermal systems and heat recovery systems, it is possible to drastically reduce energy consumption and ensure an optimal indoor microclimate. Automated control systems increase efficiency by dynamically adapting heating and ventilation settings to real-world conditions, such as temperature, humidity, or room occupancy. These technologies help to maximise the use of energy resources and improve comfort in buildings.

The problem of effective microclimate management in modern buildings using adaptive heating and ventilation systems is relevant, as it affects the energy saving and comfort of residents. D. Bui *et al.* (2021) noted that adaptive heating and ventilation systems made it possible to effectively adjust the microclimate parameters depending on external and internal conditions, which helped to reduce energy consumption. The authors also stressed the importance of automation to maintain a stable temperature in buildings without overspending energy. Z. Liu *et al.* (2023) stated that the integration of heat pumps and geothermal installations helped to ensure a stable temperature regime in buildings while substantially reducing energy costs. According to them, this also allowed reducing the impact of seasonal temperature fluctuations on heating efficiency. T. Pekdogan *et al.* (2021) investigated the role of heat recovery systems in reducing energy costs during ventilation, which substantially reduced the cost of heating rooms. It was also noted that such systems improve the air quality in buildings, keeping them warm even at high levels of air exchange. C. Lin *et al.* (2022) focused on mechanical ventilation systems that can adapt to changes in the number of people in rooms, improving the efficiency of air exchange. Such technologies optimise energy consumption, considering the specific needs of each room. G. Qiang *et al.* (2023) stressed the importance of automating heating and ventilation processes, which allowed dynamic adjustment of system parameters depending on changes in environmental conditions. According to the researchers, this not only increased the efficiency of the systems but also provided comfort throughout the year.

P. Lamsal *et al.* (2023) evaluated the effectiveness of adaptive systems in office buildings, emphasising that they can reduce energy costs while maintaining optimal working conditions. According to their estimates, such systems provided a better microclimate and helped increase employee productivity. A. Hassan & K. El-Rayes (2021) believe that the integration of renewable energy sources, such as solar collectors and biomass, into heating and ventilation systems substantially reduces dependence on traditional energy resources. They added that this combination has helped reduce greenhouse gas emissions and increase the sustainability of buildings' energy supply. S. Ahmed *et al.* (2021) in their study emphasised the importance of using solar collectors in temperate climates to reduce the need for traditional energy sources. This provided for the reduced heating costs and load on the overall energy system of the building. P. Zheng *et al.* (2022) underlined that adaptive heating and ventilation systems were most effective for large buildings, such as business centres, where constant regulation of temperature and air exchange is necessary. The authors pointed out that such systems can substantially reduce energy costs while maintaining a comfortable environment for a large number of people. A. Adegbenro *et al.* (2021) emphasised the need for continuous monitoring and adaptive management to maintain high efficiency of heating and ventilation systems throughout their life cycle. They noted that without regular monitoring, adaptive systems could lose their effectiveness due to changes in operating conditions. Thus, although numerous studies confirm the effectiveness of adaptive heating and ventilation systems, there is a need to review their application in different types of buildings, in particular, in different climatic zones and considering economic aspects.

The purpose of the study was to analyse ventilation technologies and their role in maintaining a comfortable indoor microclimate, assess the economic advantages, and disadvantages of adaptive systems considering the conditions of different climatic zones, and evaluate the impact of the integration of renewable energy sources on reducing energy costs in heating and ventilation systems.

Materials and Methods

This study covered various aspects of integrating adaptive heating, ventilation, and energy systems, in particular, technologies that can substantially reduce energy consumption in buildings that run on traditional fuels while reducing operating costs. The efficiency assessment of such systems was conducted on the basis of an analysis of scientific publications that include energy consumption data and a review of existing studies, which allowed for determining their effectiveness in real operating conditions. An important aspect of this study was the analysis of ventilation systems with heat recovery, the effectiveness of which was evaluated by examining their ability to recover heat from the exhaust air and redirect it to heat the supply stream. This determined the potential of such systems in improving the energy efficiency of buildings and reducing heating costs, especially in cold climates.

Special attention was paid to the operation of sensors that monitor key parameters of the microclimate, such as temperature, humidity, and carbon dioxide (CO_2) levels. The influence of automated systems based on these sensors on the optimisation of energy consumption, and precise regulation of equipment operation, which helps to reduce the load on the system and provides comfort for users was assessed. In addition, the introduction of renewable energy sources, such as solar collectors, photovoltaic panels, and biomass, into the energy systems of buildings was considered based on the analysis of climatic features of regions, the amount of available resources, and the technological compatibility of equipment with existing systems. This enabled the evaluation of the renewable energy sources' potential to reduce energy costs and greenhouse gas emissions, ensuring sustainable energy supply for buildings.

The efficiency of different systems was compared using the example of buildings in Germany (Maier *et al.*, 2022), Denmark (Johansen & Werner, 2022), Sweden (Behzadi & Sadrizadeh, 2024), and Ukraine (Sotnyk *et al.*, 2024). The analysis concentrated on assessing energy consumption, economic indicators such as system payback and operating costs, and user comfort levels. Special attention was paid to various climatic conditions: in Germany and Ukraine, the effectiveness of adaptive systems was researched in temperate continental climates, in Denmark – in marine climates, and in Sweden – in cold northern climates. In addition, the specifics of buildings were considered: in Germany, mainly office buildings with high ventilation requirements were analysed, in Denmark – residential buildings with the integration of renewable energy sources, in Sweden – public buildings with high energy-saving standards, and in Ukraine – multi-storey residential buildings with traditional heating and ventilation systems. Energy savings, reduced operating costs, and the ability to adapt to temperature changes throughout the year were compared.

The final stage of the study included the comparison of the efficiency of different heating and energy-saving systems in buildings in different countries. The efficiency assessment was based on criteria such as reduced energy consumption, improved air quality, and reduced CO_2 emissions, initial costs, and terms of return on investment. Lowering energy consumption and improving air quality were assessed by indicators of energy consumption and the concentration of harmful substances on the premises.

Results

In buildings where energy efficiency is a priority, the integration of adaptive heating systems is an important element not only to reduce energy costs but also to provide a comfortable environment for residents. One of the promising areas in this area is the use of heat pumps and geothermal installations, which automatically regulate the temperature depending on external weather conditions and user needs. Heat pumps and geothermal installations are critical elements of adaptive heating systems, each of which has its own characteristics and operational features. Heat pumps operate on the principle of heat exchange, converting heat from the environment (air, water, or land) into energy for heating buildings. They are efficient even in cold winter conditions, which lessens the consumption of traditional energy sources such as gas and electricity. This makes such a heating system a sustainable and cost-effective solution. One of the fundamental parameters is the energy conversion factor, which can reach values of 3-5, which means the production of three to five units of heat for each unit of electricity consumed (Cui *et al.*, 2024). Geothermal installations, on the other hand, use the heat stored in the ground. Geothermal pumps are able to use a stable ground temperature (approximately 10-15°C) for heating in winter and cooling in summer, which makes them very effective in temperate regions. They provide sustainable energy regardless of weather changes, have a long service life and high energy efficiency. According to a study by the European Environment Agency, geothermal systems can reduce CO_2 emissions by 50-70% compared to traditional gas or coal-fired systems (Adebayo *et al.*, 2024).

Due to automation and intelligent control systems that regulate the operation of these installations, it is possible to reduce energy consumption depending on environmental changes. The systems can automatically adapt to changes in temperature and weather conditions and the internal needs of users, which allows providing maximum comfort at minimal cost. Adaptive heating systems that use heat pumps and geothermal installations have a number of advantages and disadvantages that should be considered when adapting them to specific climatic conditions. The main advantage of such systems is reduced heating costs due to high energy efficiency. According to the studies, heat pumps can provide an energy conversion rate of 3-5, which means producing 3-5 units of heat for every unit of electricity consumed, even in cold climates (Mahmoud *et al.*, 2021). Geothermal installations use a stable soil temperature that remains relatively constant at depth, allowing them to operate efficiently even at low ambient temperatures. An additional advantage is environmental friendliness: the use of renewable energy sources, such as geothermal and solar, substantially reduces greenhouse gas emissions. For example, switching to heat pumps reduces CO_2 emissions on average, by

50-70% compared to traditional heating systems that run on gas or coal (Rane *et al.*, 2024). The economic benefits of such systems include low operating costs. The average return on investment period for heat pumps is 5-7 years, depending on climatic conditions and the level of energy subsidies in the country. Therewith, the disadvantages are high initial costs for equipment, design, and installation, which can vary depending on climatic conditions and the type of buildings. For example, in regions with extremely low winter temperatures (northern Sweden, north-western Canada, Iceland), heat pumps may require additional energy sources, such as electric heaters, which may affect overall energy efficiency. In addition, in warm climates (southwestern United States, southern Spain, Australia), the efficiency of geothermal installations may be limited due to the insufficient temperature gradient of the soil.

The need for energy efficiency and comfort in buildings requires the introduction of innovative technologies that reduce energy costs and create optimal conditions for residents. One of these solutions is ventilation systems with heat recovery, which improve air quality and substantially reduce the energy consumption of buildings. This was an important step in the development of construction technologies, as it allows efficient use of exhaust air heat and minimises the need for additional energy resources for indoor heating (Loni *et al.*, 2021). The basic principle of operation of a ventilation system with heat recovery is to transfer part of the heat energy contained in the outgoing air to the air entering the room using heat exchangers, without mixing them. Even in the cold period of the year, the air entering the room already has a comfortable temperature, which reduces the load on the heating system. The use of such systems can substantially reduce heating costs since the exhaust air that is removed from the premises usually has a high temperature, providing for effective use. It also lowers the need for additional energy sources to heat the air coming from outside, especially during the cold winter months. The indoor air quality does not suffer since the recovery system does not mix the incoming and outgoing air, thus providing a high degree of purification and ventilation.

Heat recovery systems have substantial advantages for residential, commercial, and industrial buildings, as they allow achieving sustainable and efficient energy consumption. According to scientific research, the introduction of such systems can reduce energy costs by up to 40%, depending on the size of the building and its operating conditions (Gaur *et al.*, 2021). In addition, these technologies reduce greenhouse gas emissions because they use less energy from traditional sources, such as gas or electricity. Despite the obvious advantages, the heat recovery system has certain requirements for installation and maintenance. An important condition for its efficient operation is regular cleaning of filters and heat exchangers, which will ensure smooth operation of the system and maintain indoor air quality. In addition, it is important to properly configure the system according to the needs of users to avoid excessive power consumption.

In places where comfort and efficiency are priorities in residential and commercial buildings, microclimate automation is becoming an important element for creating optimal conditions. Due to technological advances, it is possible to dynamically control the parameters of temperature, humidity, and carbon dioxide content, which opens up new prospects for achieving a high level of comfort and energy efficiency. The installation of sensors that measure these parameters allows you to automatically adjust the microclimate in the room depending on the number of people in it. This not only provides comfort but also reduces energy consumption, which is important for sustainable development (Rane *et al.*, 2024). One of the main principles of microclimate automation is the integration of temperature, humidity, and carbon dioxide sensors, which allows accurately determining the parameters of indoor air and responding to changes in real time. For example, an increase in temperature or carbon dioxide levels, which often occurs due to an increase in the number of people in a room, can automatically activate the ventilation or air conditioning system, creating a comfortable environment for stay. Temperature and humidity sensors provide precise control of the level of comfort in the room, as these parameters directly affect the feeling of warmth or coolness. According to these indicators, the system adjusts the operation of the air conditioner or heater to maintain the desired temperature without excessive fluctuations, which usually require additional energy costs.

Carbon dioxide sensors are important for keeping the air fresh, as CO_2 elevated levels may indicate the need for ventilation, which reduces gas concentrations and improves air quality. Automation has the advantage of being able to adapt the system to changes in the number of people in a room. For example, in large offices or public buildings, where the number of visitors may vary throughout the day, the system automatically adjusts the level of ventilation and temperature depending on changes in attendance. If there are a lot of people in the room, the system increases the intensity of ventilation to improve air quality and reduce carbon dioxide levels. When the number of people decreases, the system automatically reduces energy consumption, adjusting the microclimate parameters to new conditions. Such automated systems not only increase comfort but also provide substantial energy savings. Since ventilation, heating, and air conditioning only work as needed, rather than continuously, energy costs are substantially diminished. This is an important factor for ensuring sustainable development, lessening the ecological footprint of buildings without compromising the comfort and health of residents.

The introduction of microclimate automation has multifaceted consequences. In addition to saving energy, such systems can substantially improve indoor air quality, reducing the health risks associated with insufficient ventilation or excessive humidity. They also help maintain optimal working conditions, increasing people's productivity and overall well-being. Climate change and energy efficiency issues are becoming particularly important, and combining traditional heating and ventilation systems with renewable energy sources is an important step towards achieving sustainable development (Kozakevich & Kotyakova, 2021). The use of solar collectors, photovoltaic panels, and biomass substantially reduces the carbon footprint and energy costs, making buildings not only energy efficient but also environmentally friendly. Integrating these technologies into everyday life is essential to reduce the negative impact on the environment and achieve global goals in the fight against climate change (Østergaard *et al.*, 2022).

Solar collectors are one of the most cost-effective and common solutions for using renewable energy sources in buildings. They convert solar radiation into thermal energy that can be used to heat water or rooms. Solar collectors not only reduce the consumption of traditional energy sources but also help reduce the cost of heating and hot water while providing clean energy. In temperate and sunny climates, such systems can substantially increase the energy independence of buildings. Photovoltaic panels allow generating electrical energy from solar radiation. Their installation on the roof or walls of buildings can cover part of the building's energy needs and reduce dependence on centralised energy suppliers. Photovoltaic systems also have a long service life and high reliability, making them a profitable investment for building owners. They can become the main source of electricity for small and medium-sized buildings, especially in sunny regions with high solar radiation intensity. Another promising source of energy is biomass, which includes organic materials such as wood, agricultural waste, and biological waste. Biomass can be used to generate heat and electricity, which allows not only to meet the energy needs of buildings but also to efficiently dispose of waste, such as wood pellets or agricultural residues, which can be processed into energy resources using boilers or biogas plants. In some countries, such as Sweden, Poland, and the United Kingdom, biomass is widely used for district heating, where agricultural and forest waste is processed into energy supplied to the grid or directly to buildings (Saira, 2021). Biomass is also used for the production of biogas in specialised installations, which provides energy and reduces the amount of organic waste. It is a renewable energy source that helps reduce dependence on fossil fuels such as coal or oil. However, for efficient use of biomass, it is important to correctly calculate the capacity of the system and consider the energy needs of a particular building.

The combination of renewable energy sources with heating and ventilation systems can not only save energy but also reduce carbon dioxide emissions into the atmosphere, which is a crucial factor in the fight against global warming. The use of these technologies helps to reduce the level of environmental pollution, contributing to the achievement of sustainable development goals. Research shows that buildings that use renewable energy sources can reduce their carbon emissions by up to 50% compared to buildings that use only traditional energy sources (Tejani & Toshniwal, 2023). Integrating renewable energy into buildings also reduces operating costs, as energy from solar or biomass is cheaper compared to traditional fuels. For example, the cost of electricity generated by solar panels in 2023 ranged from USD 0.03 to USD 0.06 per kilowatt-hour, depending on the region, while the cost of electricity produced based on fossil fuels averaged USD 0.08-0.12 per kilowatt-hour. In the case of biomass, the cost of thermal energy varies between USD 20-30 per megawatt-hour, which is substantially lower than the cost of gas-based energy, which often exceeds USD 40-50 per megawatt-hour. These indicators indicate the economic feasibility of switching to renewable energy sources both to reduce costs and improve the energy efficiency of buildings (Heptonstall & Gross, 2021). These technologies contribute to improving the energy efficiency of buildings, which, in turn, increases their competitiveness in the real estate market. By reducing energy costs and carbon emissions, such buildings become more attractive to investors and potential buyers who pay attention to environmental friendliness and energy efficiency.

Climate change and energy efficiency issues are becoming particularly important, and combining traditional heating and ventilation systems with renewable energy sources is an important step towards sustainable development. Approaches to the design and operation of buildings include the integration of advanced technologies, in particular, renewable energy sources, with intelligent control systems, which allows achieving maximum results in reducing energy consumption and improving the quality of the internal environment. Comparing the efficiency of different systems in different countries shows that the best results are achieved when applying integrated solutions, including microclimate automation, the use of renewable energy sources, and the integration of intelligent control systems. Analysis of buildings in European countries such as Germany, Denmark, and Sweden shows that the introduction of solar collectors, geothermal heating systems, and intelligent ventilation systems can substantially reduce energy consumption and improve indoor microclimate (Table 1).

Table 1. Comparison of the efficiency of different energy supply systems in buildings in different countries

Country	Technologies	Energy consumption reduction	Air quality improvement	CO_2 emissions reduction	Initial costs (%)	Return on investment (years)
Germany	Solar panels, heat pumps, automated control	30-40%	–	25-30%	20-25%	5-7
Denmark	Intelligent ventilation systems with heat recovery	15-20%	10-15%	–	25-30%	4-6

Table 1, Continued

Country	Technologies	Energy consumption reduction	Air quality improvement	CO_2 emissions reduction	Initial costs (%)	Return on investment (years)
Sweden	Biomass, intelligent heating and ventilation control systems	25-35%	–	20-25%	30-35%	6-8
Ukraine	Solar collectors, heat pumps, automated microclimate control systems	10-15%	5-10%	10-15%	40-50%	7-10

Note: initial costs include the cost of equipment (solar panels, heat pumps, ventilation units, sensors), design, installation, integration with infrastructure, and software configuration
Source: compiled by the authors

In Germany, where the climate is temperate continental with cool winters and warm summers, the use of solar panels and heat pumps is a rational choice. A substantial level of solar radiation allows for stable energy generation throughout the year, and the combination of these technologies with automated control systems effectively regulates the temperature conditions in buildings. A special feature of such solutions is their use both in multi-storey residential buildings and in private cottages, where high-quality thermal insulation helps to minimise energy losses. For example, hybrid systems that combine solar panels, heat pumps, and automated control systems provide optimal response to changing external weather conditions and internal needs (Maier *et al.*, 2022). In Denmark, which is famous for its environmental initiatives, intelligent ventilation systems with heat recovery are most widely used. This technology is particularly relevant for public buildings and offices, where ensuring high air quality is essential for employee health and productivity. Automation systems integrated with sensors for carbon dioxide levels, temperature, and humidity adjust the intensity of ventilation depending on the number of people in the room, thereby reducing energy costs. This combination of economy and environmental friendliness provides Denmark with high energy efficiency indicators (Johansen & Werner, 2022). Sweden, which has traditionally focused on renewable energy sources, is actively implementing biomass-based technologies. The use of biomass as a fuel is relevant for residential buildings and municipal facilities, such as schools or hospitals, especially in the northern regions of the country with harsh climates. The intelligent heating and ventilation control systems that ensure optimal heat distribution reduce carbon dioxide emissions and also help to achieve high energy efficiency. In addition, such systems allow reducing resource consumption by fine-tuning real-time operation parameters (Behzadi & Sadrizadeh, 2024).

Analysis of the effectiveness of various solutions shows that the integration of modern technologies with intelligent control systems has many advantages. Such systems can reduce energy consumption by automating and adapting to changing conditions, such as ambient temperature or the number of people in the room. They help to improve the comfort of residents, creating optimal conditions for work and recreation. In addition, such solutions are cost-effective in the long term, as they can substantially reduce the cost of energy supply to buildings. Notably, the introduction of intelligent control systems requires a substantial initial investment in the development and installation of the necessary equipment, which can become a barrier for some building owners. However, in the long run, because of energy savings and reduced operating costs, such investments pay off and become cost-effective.

In Ukraine, climatic conditions vary substantially, which requires flexible approaches to the energy supply of buildings. In 2023, solar collectors, heat pumps, and automated microclimate management systems were introduced in residential and commercial buildings, which helps reduce energy consumption. Of particular interest are pilot projects in Kyiv that demonstrate the potential of such technologies in multi-storey buildings. The introduction of heat recovery systems can substantially reduce energy losses and environmental impacts. Despite the high initial costs, such initiatives show positive economic dynamics due to reduced operating costs (Deshko *et al.*, 2021). Adaptive heating and ventilation systems are becoming an important tool for reducing operating costs in buildings due to their ability to optimise energy consumption and reduce heat loss. One of the key aspects of such systems is automation, which adapts the microclimate parameters to changing conditions, such as outdoor temperature, humidity and indoor carbon dioxide levels. This ensures not only a reduction in power consumption but also a reduction in the load on the system, lowering the cost of its maintenance (Table 2).

Table 2. Comparison of operating costs for traditional and adaptive systems in buildings

Parameter	Traditional systems (average value)	Adaptive systems (average value)	Savings
Energy costs (kWh/m^2 per year)	1,500	900	40%
Maintenance costs (UAH/year)	500	300	40%
Heat consumption (kWh/m^2 per year)	1,200	750	37.5%

Table 2, Continued

Parameter	Traditional systems (average value)	Adaptive systems (average value)	Savings
Savings on energy consumption (UAH/year)	1,200	1,800	50%
Installation cost (thousand UAH)	200	250	–
System return on investment period (years)	7	5	–
Environmental savings (CO_2 emissions, t/year)	2.5	1.5	40%

Source: compiled by the authors on the basis of data obtained by Y. Alassaf (2024)

One of the most effective ways to achieve savings is to use heat recovery technologies. Ventilation systems with recuperation allow using exhaust air energy to heat or cool the supply air, which substantially reduces the cost of energy supply to buildings. These technologies are important for reducing costs, as the heat that is usually removed through the ventilation system is returned to the system and used to maintain a comfortable microclimate without additional energy costs. Optimisation of energy consumption is also achieved by using heat pumps and geothermal installations. These technologies can substantially reduce the need for traditional heating fuel, as they use renewable energy sources. Heat pumps can operate in both heating and cooling modes, maintaining a stable indoor temperature without constantly recharging the system with fuel. Equally important is automation, which is conducted using temperature, humidity, and CO_2 sensors, which allows dynamically changing system parameters depending on user needs. This provides for substantially reduced energy costs since the system operates only when necessary, and with maximum efficiency. Thereby, such control reduces the need for constant maintenance of complex mechanisms and prevents overloading of systems. A comparison of building maintenance costs with traditional and adaptive systems shows that the latter can substantially reduce overall energy costs. Energy savings offset the high initial costs of installing such systems, making them profitable in the long run. Due to an integrated approach that includes the use of renewable energy sources and intelligent management systems, substantial resource savings can be achieved, which has a positive impact not only on financial performance but also on the environmental situation in the region.

Discussion

The study on adaptive heating and ventilation systems for optimising the microclimate in modern buildings has shown their substantial potential for improving energy efficiency and comfort in residential and commercial premises. The analysis showed that these systems can automatically adjust the temperature and humidity depending on the external conditions and needs of users, providing a stable microclimate with minimal energy consumption. This reduces operating costs and contributes to long-term resource savings. A. Rieser *et al.* (2021) also investigated this issue, confirming that adaptive heating and ventilation systems regulate microclimate parameters depending on external conditions and the needs of residents. The use of temperature, humidity, and motion sensors automates the process, providing comfort with minimal energy costs. This is especially important for buildings with different functional purposes, where the requirements for the microclimate change throughout the day. H. Farzaneh *et al.* (2021) determined that adaptive systems can reduce power consumption by 30-40% due to precise adjustment of operating parameters. They can lower the temperature or turn off ventilation in empty rooms during non-working hours. This not only saves resources but also reduces the carbon footprint of buildings that meet modern environmental standards. However, the effectiveness of adaptive systems largely depends on the quality of the equipment and proper configuration. Incorrectly installed or uncalibrated sensors can reduce the accuracy of the system, resulting in energy losses. The introduction of such technologies requires an initial investment, which, although it pays off over time, can become a barrier to widespread adoption in residential buildings.

Research on heat pumps and geothermal installations has shown how these technologies optimise energy consumption through the use of renewable energy sources. Heat pumps provide efficient heating and cooling and operate without constant refuelling, which reduces dependence on fossil fuels and reduces the carbon footprint of buildings. The results showed that the use of such systems in a variable climate can substantially reduce energy costs while maintaining comfort. E. Hałaj *et al.* (2021) concluded that heat pumps and geothermal systems efficiently use soil, water, or air energy to heat or cool buildings. Due to their high energy conversion rate, they can provide up to 4 kW of heat or cold for every kW of electrical energy consumed. This can substantially reduce the consumption of traditional energy sources, increasing the energy efficiency of buildings. Upgrading the district heating system through the integration of modular heat pumps, geothermal water, and photovoltaic installations can contribute to creating sustainable urban energy, further improving energy efficiency and reducing dependence on non-renewable energy sources.

A. Hoang & X. Nguyen (2021) determined that geothermal installations maintain a stable temperature due to the use of soil thermal inertia, which ensures stable operation regardless of weather conditions. These systems are effective even in extreme climatic conditions. When combined with other renewable sources, such as solar panels, they create efficient systems with minimal carbon dioxide emissions. These results confirm previous studies conducted in countries with different climatic conditions, in particular, in Germany and Sweden, where the introduction of heat pumps and geothermal systems has shown substantial energy savings, reducing heating costs. An increase in the efficiency of systems in temperate and cold climates was also recorded, which indicates their ability to work under temperature fluctuations, confirming the practicality of such technologies for different regions with different climatic characteristics. Another important aspect of the study was the ventilation system with heat recovery. It was identified that these systems restore some of the thermal energy of the exhaust air and use it for heating or cooling the supply air, which reduces the cost of heating and cooling buildings. Heat recovery has become an effective tool for combating energy costs, enabling a substantial reduction of the amount of energy discharged from rooms through ventilation ducts.

N. Asim *et al.* (2022), concluded that ventilation systems with heat recovery can store up to 90% of the thermal energy normally lost through ventilation. They work on the principle of heat transfer from the exhaust air to the supply air, providing a comfortable microclimate in the room. This not only increases the energy efficiency of the building but also improves air quality by removing pollution and moisture. J. Li *et al.* (2021) also demonstrated that the use of heat recovery plants can substantially reduce the cost of heating in winter and cooling in summer since the system minimises energy losses. For example, in residential buildings with modern heat recovery installations, energy costs can be reduced by 20-30%. This makes such systems attractive for both the private sector and commercial facilities, especially in the face of rising energy tariffs.

The conclusions of researchers correlate with the conclusions of the authors since they confirm the effectiveness of heat recovery technologies in reducing energy consumption. The use of such systems ensures an optimal combination of energy efficiency and comfortable indoor conditions. These examples of cost reduction confirm the real financial benefits, which makes these technologies particularly relevant in the context of modern energy challenges. Automation of the microclimate was evaluated on the example of using temperature, humidity, and carbon dioxide (CO_2) sensors. Studies have shown that the use of such sensors allows the system to dynamically adjust the parameters of the microclimate depending on the number of people in the room or changing environmental conditions. This ensures efficient use of energy resources since the system operates only when necessary, and with maximum efficiency, minimising energy costs.

S. Croce & S. Tondini (2022) also conducted a study that confirmed that modern microclimate automation systems use temperature, humidity, lighting, and motion sensors to continuously monitor indoor conditions. Due to this, the systems can adapt their work in real time, providing maximum comfort for users. Such technologies not only increase convenience but also contribute to more efficient use of resources, reducing energy consumption during non-working hours or in empty rooms. F. Carlucci *et al.* (2023) also discovered that dynamic microclimate control reduces energy consumption by fine-tuning the operation of systems depending on actual needs. Motion sensors can automatically turn off heating or lighting when the room is not in use, which saves up to 20-30% of energy. Combined with intelligent control algorithms, this creates opportunities for implementing energy-efficient solutions in residential, office, and industrial buildings, and the energy flexibility of building systems in future scenarios, optimising the dynamic shading management strategy, and defining a new energy flexibility metric can further improve the efficiency of such solutions.

Comparing the results of the study, it can be concluded that automation of the microclimate using sensors has a substantial impact on reducing energy consumption. The results show that the integration of sensors with control systems provides for achieving an optimal balance between comfort and efficiency. This is confirmed by practical examples of reducing energy costs in buildings where such systems are implemented. As for the integration of renewable energy sources, the results of the study indicated that the use of solar collectors, photovoltaic panels, and biomass can substantially reduce dependence on traditional energy sources. These technologies have helped reduce the carbon footprint of buildings and ensure energy independence. The study suggested that the integration of renewable energy sources with adaptive heating and ventilation systems is an important step towards sustainable development in the construction sector.

A. Pascaris *et al.* (2021) concluded that the use of renewable energy sources such as solar panels, geothermal installations, and biomass ensures that buildings are independent of fossil fuels. The integration of these systems into the building allows not only to generate energy but also to store its surplus for further use. This approach is the basis of a modern “smart home” that meets the principles of energy efficiency and sustainable development. L. Paraschiv & S. Paraschiv (2023) stated that solar collectors effectively heat water, reducing gas or electricity consumption, which leads to a reduction in greenhouse gas emissions. The use of biomass, in particular, pellets or wood waste as an energy source, also contributes to reducing the carbon footprint since the process of burning them is carbon-neutral. Together, these solutions allow buildings to meet modern environmental standards and reduce energy costs.

Analysing the results of the study, it can be concluded that the integration of renewable energy sources into building systems has substantial potential for reducing the carbon footprint. The use of solar collectors and biomass reduces dependence on traditional energy sources and actively contributes to the achievement of goals to reduce greenhouse gas emissions. This is confirmed by data on reducing energy costs and improving the environmental situation in regions where such technologies are actively used. The study confirmed that adaptive heating and ventilation systems combined with renewable energy sources and automation can substantially improve the energy efficiency of buildings and provide a comfortable environment for residents. The results of a comparative analysis of various technologies showed that the best results are achieved precisely through the integration of modern technologies with intelligent control systems that reduce energy consumption, improve the microclimate, and reduce operating costs.

Conclusions

The study showed that adaptive heating and ventilation systems are an effective tool for achieving an optimal microclimate in modern buildings. The use of such technologies can substantially increase energy efficiency, reducing energy supply costs, and simultaneously providing comfortable conditions for residents. Heat pumps and geothermal systems that regulate indoor temperatures reduce energy consumption through the use of renewable energy sources, which is an important advantage over traditional fossil fuel heating methods. Ventilation systems with heat recovery have become one of the main elements that can substantially reduce energy costs. The use of waste heat for preheating or cooling the supply air reduces the need for energy for heating and air conditioning, which saves energy without compromising air quality.

Automation of the microclimate in buildings using temperature, humidity and CO_2 level sensors substantially optimises power consumption. Automatic adjustment of system parameters depending on changes in environmental conditions and the number of people in the room allows reducing energy costs and providing a stable level of comfort, which is important for improving the quality of life of residents. The use of renewable energy sources such as solar collectors, photovoltaic panels, and biomass has become an important step in reducing the carbon footprint of buildings. The integration of these technologies into heating and ventilation systems reduces dependence on traditional energy sources, such as gas or coal, which has a positive impact on the environmental situation. Analysis of the efficiency of various technologies in different countries has shown that the best results are achieved when integrating adaptive heating and ventilation systems with intelligent control systems that allow optimising energy use and improving the indoor microclimate. Such systems demonstrate maximum efficiency in reducing energy consumption and energy costs. Considering climatic conditions is crucial for the selection and efficiency of adaptive heating systems, such as heat pumps and geothermal installations. In cold regions, geothermal installations may be more efficient due to the stability of the Earth's temperature, while in warm climates, heat pumps that use air or water may be more optimal for reducing energy consumption and providing comfort in buildings.

The results of the study confirmed that the introduction of adaptive technologies in heating and ventilation systems is an effective tool for reducing energy costs and improving the quality of life in buildings. The use of intelligent systems and renewable energy sources can not only increase energy efficiency but also reduce the environmental impact of buildings, which is an important step towards sustainable development. Prospects for further research are to study the long-term efficiency of the integration of adaptive heating and ventilation systems with various types of renewable energy sources in different climatic zones.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Адаптивні системи опалення та вентиляції для досягнення оптимального мікроклімату в сучасних будівлях

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Анотація. Актуальність дослідження зумовлена необхідністю підвищення енергоефективності будівель та створення комфортного мікроклімату в умовах зростаючих вимог до екологічності й економії енергоресурсів. Дослідження мало на меті оцінити, як різні підходи до систем опалення та вентиляції підвищують комфорт і енергоефективність у будівлях. Для визначення оптимальних рішень у сфері автоматизації мікроклімату та інтеграції відновлювальних джерел енергії були використані методи аналізу ефективності технологій та порівняльної оцінки енергетичних систем. Результати показали, що адаптивні системи опалення та вентиляції значно підвищують енергоефективність. Теплові насоси у поєднанні з геотермальними технологіями підтримують стабільну температуру в приміщеннях навіть за змінних зовнішніх умов. Вентиляційні системи з рекуперацією тепла знижують втрати енергії, зберігаючи тепло під час повітрообміну. Автоматизація мікроклімату за допомогою датчиків і систем керування дозволяє регулювати параметри опалення та вентиляції залежно від заповненості приміщень, рівня вологості та складу повітря. Інтеграція відновлюваних джерел енергії, таких як сонячні колектори та біомаса, показала високу ефективність у зменшенні споживання традиційних енергоресурсів. Аналіз об'єктів у різних країнах показав, що найкращих результатів досягають завдяки комплексному підходу, що поєднує сучасні технології та адаптивні рішення. Будівлі з інтегрованими адаптивними системами зберігають стабільний мікроклімат незалежно від зовнішніх умов, що позитивно впливає на комфорт користувачів. Оптимізація енергоспоживання також знижує експлуатаційні витрати, роблячи такі рішення економічно доцільними для довгострокового використання. Адаптивні системи не лише забезпечують комфортні умови, а й значно скорочують споживання енергоресурсів у будівлях різного призначення

Ключові слова: енергоефективність; теплові насоси; геотермальні технології; рекуперація тепла; автоматизація; відновлювані джерела енергії