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Improving thermal comfort and energy saving in buildings using advanced optimal configuration approaches for heating structures and panels

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Abstract

The study aims to address advanced approaches to the optimal settings of heating structures and panels to improve thermal comfort and energy efficiency in buildings. The study analysed various materials for thermal insulation, different heating systems and energy-efficient windows, using common formulas to calculate their thermal performance and efficiency. The study analysed various modern methods of optimising heating systems to improve thermal comfort and energy efficiency in buildings. As such, the study determined that the use of intelligent heating control systems, such as smart thermostats and sensors, can significantly reduce energy consumption. The study also determined that heat pumps, especially geothermal and air source heat pumps, are effective solutions for sustainable heating. The study results confirmed that three-chamber windows with a third gap between the glass panes can maximise energy savings by significantly reducing heat loss and providing high thermal insulation. The study also determined that condensing gas boilers and heat pumps are optimal for efficient energy savings. Low-temperature heating systems, such as underfloor heating and efficient radiators, contribute to even heat distribution and energy savings. The use of renewable energy sources, such as solar collectors and wind turbines, was also determined to be an effective means of reducing dependence on traditional energy resources. The study also showed that the integration of various technologies and systems into a single climate control system allows for maximum efficiency and comfort. As a result, the combined use of innovative methods and materials not only significantly reduces energy consumption but also improves living conditions in modern buildings.

Keywords

energy efficiency; smart thermostats; sensors; heat pumps; insulation materials; heat-reflective coatings.

1. Introduction

Improvement of thermal comfort and energy efficiency in buildings is crucial in the context of increasing demand for efficient use of resources and reduced environmental impact. Traditional heating systems were often inefficient, resulting in significant heat loss and high energy costs. They usually did enable precise temperature control, which often resulted in overheating or insufficient heating of the premises. This, in turn, caused discomfort for the occupants or employees of the buildings. In addition, outdated structures and insufficient insulation led to heat loss through walls, windows and other building elements (Cho et al., 2022). Innovative approaches to the optimal settings of heating structures and panels have the potential to significantly increase the energy efficiency of buildings and improve living conditions. The use of advanced technologies, such as intelligent control systems, heat pumps, the latest insulation materials and renewable energy sources, reduces energy consumption and increases thermal comfort.

The research relevance is determined by the identified shortcomings of traditional heating systems, which often cause significant heat loss and irrational energy use. It is known that such systems cannot effectively adapt to changing conditions, which leads to overheating or underheating of the premises (Osterman and Stritih, 2021). At the same time, there is great potential in using modern technologies to optimise heating systems, but the lack of comprehensive analysis and clear recommendations for their integration limits the implementation of these solutions.

The problem of improving thermal comfort and energy efficiency in buildings is a topical issue in architecture and construction. Existing heating systems are often inefficient, resulting in significant heat loss and high energy costs. This topic has already been studied by several authors, including one by Zhang et al. (2022), who determined that traditional heating systems do not provide an adequate level of energy efficiency, which leads to significant heat losses. Merabet et al. (2021) investigated intelligent control systems, such as smart thermostats, which can automatically regulate the temperature in rooms, which can significantly reduce energy consumption. Hałaj et al. (2021) addressed the efficiency of heat pumps, especially geothermal ones, in reducing energy consumption and ensuring sustainable heating.

Lamy-Mendes et al. (2021) investigated the latest insulation materials, such as aerogels, which significantly reduce heat loss through walls, floors and roofs of buildings. Zhang et al. (2023) confirmed that heat-reflective coatings for windows and facades can significantly reduce heat loss. Yang et al. (2022) highlighted the benefits of low-temperature heating systems, in particular underfloor heating, which contribute to even heat distribution and energy saving. Kalair et al. (2021) investigated the use of renewable energy sources such as solar collectors and wind turbines to reduce dependence on fossil fuels. Erdiwansyah et al. (2021) addressed the integration of various technologies into a single climate control system that provides maximum efficiency and comfort.

Zhao et al. (2022) highlighted the importance of the combined use of innovative methods and materials to ensure a significant reduction in energy consumption and improve living conditions. Himeur et al. (2021) outlined recommendations for the introduction of advanced technologies in building heating systems, emphasising their potential to significantly improve energy efficiency and thermal comfort. Despite significant achievements in this area, there are still gaps that need to be addressed. It is necessary to investigate the best ways to integrate different technologies into a single system, addressing the specifics of individual buildings and climatic conditions. More research is also needed on the cost-effectiveness and long-term reliability of new heating solutions.

The study aimed to explore advanced approaches to the optimal settings of heating structures and panels to improve thermal comfort and energy efficiency in buildings. The objectives of this study included identifying the main disadvantages of traditional heating systems, analysing modern technologies and their potential for improving the energy efficiency of buildings, and developing practical recommendations for integrating the latest technologies into heating systems.

2. Materials and Methods

The study included a detailed comparative analysis of different types of thermal insulation materials, heating systems and types of windows. The following materials were addressed in the study: mineral wool from Rockwool (Denmark), expanded polystyrene from BASF (Germany), XPS from Dow Chemical (USA) and polyurethane foam from Huntsman (USA). The study of heating systems included the analysis of such components as a gas boiler from Vaillant (Germany), a condensing gas boiler from Buderus (Germany), a heat pump from Daikin (Japan), an electric boiler from Elnur (Spain), and solar panels from SolarWorld (Germany). Regarding windows, the assessment focused on energy-efficient windows with single-chamber, double-chamber, and triple-chamber double-glazed windows from Veka (Germany).

To calculate the thermal characteristics of materials, the general formulas for thermal resistance (R) and thermal conductivity (λ) were used.

(1) $$R = \frac{d}{\lambda},$$

where: d – thickness of the material (m); λ – thermal conductivity of the material (W/(m·K)).

(2) $$\lambda = \frac{\Delta T}{R \cdot A},$$

where: ΔT – temperature gradient (°C); R – thermal resistance (m²·K/W); A – surface area (m²).

The efficiency of a gas condensing boiler:

(3) $$\eta_{kond} = \frac{Q_{inpd}}{Q_{inpd}} \times 100\%,$$

where: – boiler efficiency; – the amount of useful heat received from the boiler; – the amount of energy consumed by the boiler.

Energy saving of a gas condensing boiler:

(4) $$E_{saved} = \left(1 - \eta_{standard}\right) \times \frac{Q_{in}}{Q_{outp}},$$

where: – efficiency of a standard gas boiler (usually 70-80%).

Heat pump performance factor (HPF):

(5) $$HPF = \frac{Q_{outp}}{W},$$

where: – the amount of useful heat received from the heat pump; W – the amount of electricity consumed.

The efficiency of the heat pump:

(6) $$\eta_{tn} = HPF \times \eta_{electricity},$$

where: – efficiency of electricity use (can be around 35-45%).

The efficiency of an electric boiler:

(7) $$\eta_{power} = \frac{Q_{outp}}{W} \times 100\%,$$

where: – the boiler efficiency.

Amount of electricity generated from solar panels:

(8) $$E_{solar\ panels} = A \times H \times PR,$$

where: H – amount of solar radiation (kWh/m²); PR – performance factor (usually 0.75-0.85).

Savings from the use of solar panels:

(9) $$E_{saving} = E_{solar\ panels} \times \eta_{systems},$$

where: – heating system efficiency, which is replaced by solar panels.

The materials were evaluated for their thermal conductivity coefficients, layer thickness to achieve a certain thermal resistance, and the advantages and disadvantages of their use. The heating systems were assessed by their efficiency and cost, which determined their effectiveness and efficiency. The windows were compared in terms of thermal conductivity, thermal and noise insulation benefits, and cost.

The study analysed the following methods and technologies: intelligent heating control systems, which included smart thermostats and sensors with climate control systems. The possibility of using renewable energy sources, such as solar collectors and wind generators, was studied. Heat pumps were analysed, including geothermal and air source heat pumps. Geothermal heat pumps use the heat from the ground to heat buildings, which is extremely efficient and could significantly reduce energy consumption compared to traditional heating systems. The air source heat pumps extract heat from the outside air and transfer it to the heating system of the building. They were effective in temperate climates and could be used for both heating and cooling.

Advanced insulation materials, such as aerogels or vacuum insulation panels, were investigated, which could significantly reduce heat loss through the walls, windows and roof of the building. Heat-reflective coatings for windows and facades that help keep heat inside the building in winter and reflect it in summer, which reduces heating and air conditioning costs, were analysed. Underfloor heating was analysed, which ensured even heat distribution throughout the room, which reduced the temperature of the heat carrier and, accordingly, reduced heating costs. The company also researched radiators that operate efficiently at low coolant temperatures, which increases the energy efficiency of the heating system and reduces energy costs.

3. Results

Improvement of thermal comfort and energy efficiency in buildings is crucial in modern conditions. Advanced approaches to the optimal settings of heating structures and panels can significantly contribute to achieving these goals. Smart thermostats are one of the most promising technological innovations in the field of indoor climate control. Their main function is to automatically adjust the temperature based on the presence of people, time of day and other factors. This not only increases the comfort level for users but also significantly reduces energy consumption, making buildings more energy efficient. One of the key advantages of smart thermostats is their ability to learn user habits (Stopps and Touchie, 2021). They analyse the behaviour of residents of a house or office workers, determining the optimal operating modes of the heating system. For instance, the thermostat can automatically lower the temperature at night or when people are not in the room and raise it to a comfortable level when they return. This avoids unnecessary heating of the premises, which saves energy and reduces heating costs.

Smart thermostats can also cover other factors such as weather conditions, the quality of the insulation of the building, and the amount of heat coming from sunlight. Using this data, the thermostat can regulate the temperature even more precisely, ensuring a stable indoor climate. An additional advantage is the ability to remotely control it via mobile applications. Thus, users can change the thermostat settings even remotely, for example, when returning from work to an already warmed house or vice versa, to lower the temperature when no one is home. In addition, many modern models of smart thermostats can be integrated with other smart home systems, which can be used to create a comprehensive building management system. The introduction of smart thermostats in buildings not only improves comfort but also has a positive impact on the environment. Reduced energy consumption means less pressure on energy resources and reduced greenhouse gas emissions. This makes smart thermostats an important element in a sustainable development strategy. Smart thermostats are effective in achieving thermal comfort and energy efficiency in modern buildings. They not only save energy and reduce costs but also improve the overall quality of life of users by making homes smarter, more comfortable and environmentally friendly.

The integration of temperature, humidity and motion sensors with heating systems is an innovative approach to climate control in modern buildings. This approach allows for precise control of the climate conditions in each room, which not only improves comfort but also contributes to significant energy savings. Temperature sensors are the main components of these systems. They constantly measure the air temperature in the room and transmit this data to the central controller, which in turn regulates the operation of the heating devices. This helps to avoid overheating or underheating the premises, maintaining a stable comfortable temperature level. In addition, such systems can account for external weather conditions, adjusting the heating operation depending on changes in the temperature outside. Air humidity is another important indicator that affects the comfort and health of building occupants. Humidity sensors allow the climate control system to maintain the optimum humidity level in the room. This is especially important in winter when heating can dry out the air, which has a negative impact on respiratory tract and skin. Humidity control provides more comfortable living conditions and helps to preserve furniture and other interior items.

Motion sensors add another layer of optimisation to heating systems. They detect whether there are people in the room and adjust the temperature based on this data. For instance, if there is no one in the room, the system can automatically lower the temperature to save energy and raise it to a comfortable level when the occupants return. This approach significantly reduces energy consumption without compromising comfort. The integration of all these sensors into a single climate control system opens new opportunities for creating intelligent buildings. The central controller can analyse data from all sensors, covering various factors such as time of day, weather conditions, and the presence of people. This ensures maximum efficiency of the heating operation, providing an ideal microclimate in every room. Remote control via mobile applications provides more convenience for users. Users can change the climate control settings even from a distance, which is particularly useful for scheduling the system to operate according to their schedule. It also improves security by allowing one to check the status of the system at any time and respond to any malfunctions promptly. The introduction of sensors and climate control systems not only improves comfort but also has a significant positive impact on the environment. Reducing energy consumption leads to lower greenhouse gas emissions, which is an important step in the fight against climate change.

Integrating temperature, humidity and motion sensors with heating systems is an effective way to create energy-efficient, comfortable and environmentally friendly buildings. This approach optimises the operation of heating systems, providing precise control of the microclimate in each room and contributing to sustainable development. Geothermal heat pumps are an excellent example of advanced technologies aimed at optimising energy use in construction (Saeidi et al., 2024). These systems use an internal heat exchange unit to extract heat from the ground, which ensures efficient heating of the premises during the cold season. Geothermal heat pumps operate on the principle of a heat pump, which uses the low-potential heat of the ground as a source to generate the high-potential heat required for space heating. This process takes place through a cycle of compression and deflation, which converts low-temperature energy into a higher temperature suitable for use in heating systems. One of the key advantages of geothermal heat pumps is their high efficiency. Since ground heat is a stable and reasonably affordable source, these systems can operate efficiently in any weather and in any region where there are suitable technical conditions for installing ground collectors or vertical boreholes.

Another significant advantage is the reduction in energy consumption compared to traditional heating systems. Geothermal heat pumps use minimal amounts of electrical energy to run the compressors compared to generation output in the form of heat redistributed through the building. This significantly reduces the amount of energy required to maintain comfortable conditions in the building and, accordingly, a reduction in energy costs. However, there are certain challenges and limitations to the use of geothermal heat pumps. These include the high costs of installing and maintaining the systems, especially if vertical boreholes are required to access the deep ground heat. In addition, the effectiveness of such systems may depend on the depth of the water table and the geological conditions of a particular region. Geothermal heat pumps are an advanced solution for ensuring efficient energy use and reducing greenhouse gas emissions in the building sector. Their high efficiency and stable operation make them the ideal choice for building owners seeking to achieve sustainable development and reduce their environmental impact.

Air source heat pumps are an important component of modern heating and air conditioning systems, offering efficient use of heat from the outside air to heat buildings. These systems are particularly useful in temperate climates where the air temperature does not usually drop to very low levels, which ensures stable operation of heat pumps throughout most of the year. Air source heat pumps operate by extracting heat from the ambient air using a special compressor that raises the temperature of this heat to the level required for heating the premises. One of the main advantages of these systems is their versatility: they not only provide heating during the cold season but can also be used to cool rooms in summer by reversing the process and using the cold air to remove heat from the building. The efficiency of air-source heat pumps is demonstrated by their ability to generate more energy than they use for operation. This ensures high efficiency, which in turn leads to energy savings and reduced CO_2 emissions compared to traditional heating methods. However, air-source heat pumps also have their limitations. They can be less efficient at very low temperatures when the energy consumption for heat production becomes higher due to reduced compressor efficiency. In addition, their efficiency may depend on the condition and quality of the air used as a heat source. Air source heat pumps are a substantial innovative solution for heating and cooling buildings that can ensure efficient energy use and improve the environmental performance of building systems. Their versatility and high efficiency make them a favourable choice for modern construction projects aimed at reducing environmental impact and saving energy.

The use of advanced insulation materials, such as aerogels or vacuum insulation panels, is a critical element in reducing heat loss in buildings through walls, windows and roofs (Güler et al., 2021). These materials have high thermal resistance, which helps maintain a stable indoor temperature and reduces the need for energy for heating or air conditioning. Aerogels are one of the lightest insulating materials created. They consist of gel-like structures made using nanotechnology, which provides them with high porosity and minimal thermal conductivity. This allows the aerogel to effectively retain heat inside the building, even with thin layers of material. These properties make them ideal for use in wall and roof insulation, where every extra centimetre can reduce energy losses significantly. Vacuum insulation panels provide another approach to energy efficiency. They consist of vacuum-filled panels filled with porous materials that are completely absent from the gas. This creates a vacuum that insulates the building from the outside environment, ensuring minimal heat loss through the building structure.

Material	Thermal conductivity (W/(m×K))	Layer thickness to achieve R=3 $m^2 \cdot K/W$	Advantages	Disadvantages
Mineral wool	0.035-0.045	100-130 mm	Non-flammable, deformation-resistant, environmentally friendly	Can absorb moisture, requires waterproofing
Expanded polystyrene	0.038-0.042	80-120 mm	Low cost, easy installation	Combustible, not environmentally friendly, can release toxic substances when heated
Extruded polystyrene foam	0.032-0.035	60-90 mm	High durability, resistance to moisture	More expensive than other foams
Polyurethane foam	0.027-0.03	50-70 mm	Best thermal insulation capacity, resistance to moisture	The most expensive, complex installation

Table 1. Comparison of different types of thermal insulation materials. Source: compiled by the authors based on study by Malewska et al. (2022).

The use of such advanced insulation materials not only reduces the energy consumption of buildings but also increases the comfort of living and working in them (Table 1). They allow optimal temperature conditions to be maintained without significant energy consumption, which is a step towards sustainable construction and reducing the carbon footprint of the construction sector.

For walls and roofs, mineral wool or XPS should be used, accounting for budget and environmental considerations. Rockwool mineral wool with a thickness of 15 cm (0.15 m) covers a surface area of 100 m² at a temperature gradient of ΔT=20°C. Formulas (1-2) were calculated:

$$R = \frac{0.15\ m}{0.04 W/(m \times K)} = 3.75\ m^2 \times K/W,$$

$$\lambda = \frac{20°C}{3.75\ m^2 \times K/W \times 100\ m^2} = 0.0533\ W/(mK).$$

This shows that mineral wool provides good thermal insulation and is an environmentally friendly material. If the thickness of BASF expanded polystyrene is 10 cm (0.1 m), covering a surface area of A=100 m² at a temperature gradient of ΔT=20°C.

$$R = \frac{0.1\ m}{0.35 W/(m \times K)} = 2.86\ m^2 \times K/W,$$

$$\lambda = \frac{20°C}{2.86\ m^2 \times K/W \times 100\ m^2} = 0.07\ W/(m \times K).$$

Expanded polystyrene has high thermal insulation characteristics and is resistant to moisture, making it an excellent choice for use in roofing and wall construction. Dow Chemical's extruded polystyrene foam is 8 cm (0.08 m) thick, covering a surface area of A=100 m² at a temperature gradient of ΔT=20°C.

$$R = \frac{0.08\ m}{0.030 W/(m \times K)} = 2.67\ m^2 \times K/W,$$

$$\lambda = \frac{20°C}{2.67\ m^2 \times K/W \times 100\ m^2} = 0.0749\ W/(m \times K).$$

Extruded polystyrene foam can be a better choice for floors where moisture resistance is important. This material is highly load-bearing and highly resistant to condensation, making it ideal for use in flooring systems. Suppose that Huntsman polyurethane foam is 12 cm (0.12 m) thick, covering a surface area of A=100 m² at a temperature gradient of ΔT=20°C.

$$R = \frac{0.12\ m}{0.025 W/(m \times K)} = 4.8\ m^2 \times K/W,$$

$$\lambda = \frac{20°C}{4.8\ m^2 \times K/W \times 100\ m^2} = 0.0417\ W/(m \times K).$$

Polyurethane foam is recommended for complex geometries or to ensure maximum airtightness. This material adapts perfectly to all shapes and sizes, creating effective insulation systems without creating heat bridges. Thus, each of these materials has its advantages: mineral wool provides high thermal insulation and environmental friendliness, expanded polystyrene is resistant to moisture and has good thermal insulation properties, extruded polystyrene is well load-bearing and ideal for flooring systems, and polyurethane foam adapts to any shape and size, ensuring maximum airtightness. Insulation materials such as aerogels and vacuum panels play an important role in ensuring the energy efficiency of buildings and have great potential in the future when energy efficiency standards become even more stringent.

Heat-reflective coatings for windows and facades are an important element in ensuring the energy efficiency of buildings in a changing climate. These innovative materials play a significant role in reducing heat loss and lowering heating and air conditioning costs, which is critical in modern construction. Heat-reflective coatings are used to keep heat inside the room in winter, preventing it from escaping through windows or walls. They reflect heat radiation into the room, maintaining a comfortable temperature and reducing the need for heating systems. This is especially significant in the context of rapidly rising energy prices and the need to reduce greenhouse gas emissions. In addition, heat-reflective coatings are also useful in summer, as they reflect sun rays from the building facades, which keep the room cool and reduce the need for air conditioning. This allows for efficient energy use and reduces the environmental impact.

For instance, the use of high-performance window coatings with heat-reflecting properties can significantly reduce heat loss through glass structures, which translates into lower heating costs in winter. Such technologies contribute to the creation of a stable microclimate in buildings and pave the way for more efficient energy use in construction. Heat-reflective coatings are an important tool for achieving energy efficiency in buildings, providing optimal living and working conditions while reducing environmental impact. Their role in modern architecture and construction is inextricably linked to the rapid development of environmental and energy efficiency.

Underfloor heating is one of the most advanced heating technologies that is actively used in modern buildings to improve comfort and reduce energy costs. This method differs from traditional radiator systems in that heat is supplied through special systems located under the floor of the building. One of the main advantages of underfloor heating is the even distribution of heat throughout the room. This ensures the same temperature throughout the room, which leads to a comfortable microclimate without hot or cold zones. This heat distribution is particularly useful in rooms with large windows (Table 2) or high ceilings, where traditional radiators may not distribute heat efficiently.

For maximum energy savings, it is recommended to use triple-glazed windows (Figure 1), as they have a third gap between the glass panes, which significantly reduces heat loss and provides high thermal insulation. This is especially important in cold regions or where there are large temperature fluctuations. Double-glazed windows can be a compromise solution in terms of price and energy efficiency, as they have two gaps between the glass panes, which provides a moderate level of thermal insulation. This type of window can be effective in moderate climates where maximum energy efficiency is not required.

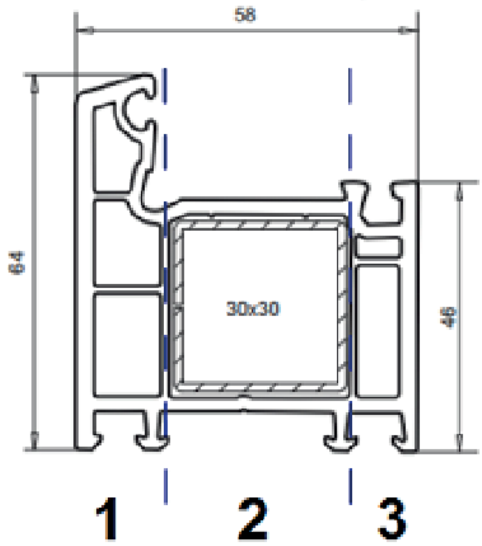

Figure 1. Diagram of a three-chamber window. Source: compiled by the authors based on OPEN TECK profile systems (2024).

Window type	Thermal conductivity (W/(m²×K))	Advantages	Disadvantages
Single-glazed window	2.8-3	Low cost	Low thermal insulation
Double-glazes window	1-1.2	Better thermal insulation	Higher cost
Triple-glazed window	0.7-0.8	The best thermal insulation	Most expensive
Energy-saving window	0.5-0.6	Best thermal insulation, noise insulation	Very high cost

Table 2. Comparison of different types of windows.
Source: compiled by the authors based on study by Heydari et al. (2021).

One of the most important technical features of underfloor heating is the lower temperature of the heat carrier compared to traditional systems. This effect can significantly reduce energy losses, as the low temperature of the heat transfer medium requires less energy to maintain a comfortable room temperature. This also helps reduce heating costs and improves the energy efficiency of the building. Underfloor heating is ideal for use with modern energy-efficient technologies such as heat pumps and solar collectors, as these systems can effectively use low heat transfer temperatures to heat buildings. Underfloor heating is an effective engineering solution that helps to improve the energy efficiency of buildings and provides maximum comfort for users. Its use in modern construction reflects a strategic approach to reducing environmental impact and ensuring sustainable development in urban and rural areas.

Radiator systems are one of the most common heating methods in many buildings, and their efficiency is significantly improved using low-temperature coolant (Cholewa et al., 2022). This approach not only provides convenience and comfort for users but also helps to reduce energy consumption and heating costs. The main advantage of low-temperature radiator systems is their ability to operate efficiently at lower coolant temperatures, which are typically less than 55-60°C. Under such conditions, radiators work more efficiently, as less energy is spent on maintaining high temperatures, which reduces the overall cost of heating the building. One of the key advantages of using low-temperature radiators is the compatibility with modern energy-efficient technology such as heat pumps and solar collectors. These systems can effectively use low heat transfer temperatures to heat a building, which is an additional step in reducing the environmental impact and increasing the sustainability of energy systems. In addition, the use of low-temperature radiators helps to improve indoor comfort. Thanks to the more even distribution of heat throughout the room, users can enjoy a stable microclimate without sudden temperature fluctuations. Low-temperature radiator systems are an effective engineering solution for modern buildings that strive for energy efficiency and sustainable development. Their use helps to reduce energy consumption, reduce heating costs and improve the overall comfort of building users.

The efficiency of heating systems is a key aspect in the design and operation of buildings, as it directly affects energy consumption, occupant comfort and overall building maintenance costs. In modern environment, there are several main heating systems, each with its advantages and disadvantages. The main types of heating systems (Table 3): are gas boilers, condensing gas boilers, heat pumps, electric boilers and solar panels.

Heating system	Efficiency factor	Approximate cost
Gas boiler	90-95%	Average
Condensing gas boiler	105-110%	High
Heat pump	300-400%	Very high
Electric boiler	99%	Average
Solar panels	20-25%	Very high

Table 3. Comparison of different types of windows. Source: compiled by the authors based on study by Lund et al. (2021).

Gas boilers are one of the most common heating options due to their high efficiency of 90-95%. Gas boilers are of medium cost and are quite efficient in temperate climates. The main advantage of gas boilers is their reliability and ability to provide stable heating. However, they depend on the availability of gas supply and have a certain environmental impact due to greenhouse gas emissions. Condensing gas boilers are more efficient than traditional gas boilers, as their efficiency can reach 105-110%. They use the heat released during the condensation of water vapour generated during gas combustion. This significantly reduces heating costs and harmful substance emissions into the atmosphere. However, condensing boilers are more expensive to install and maintain. Heat pumps are one of the most energy-efficient solutions for heating buildings, as their efficiency can reach 300-400%. Heat pumps use heat from the environment (air, ground or water) to heat rooms. They are very efficient and can significantly reduce energy consumption. The main disadvantage of heat pumps is their high installation cost and the dependence of efficiency on climatic conditions. Electric boilers have a high efficiency of around 99% and are easy to install and maintain. They do not require a gas supply or a chimney, which makes them suitable for use in buildings without a gas connection. However, electric boilers have a high cost of operation due to their high electricity consumption, which may not be economically viable in the long run. Solar panels use the energy of the sun to generate electricity, which can be used for heating. Their efficiency is 20-25%, which is lower than other heating systems. However, solar panels are an environmentally friendly and renewable source of energy, which helps reduce dependence on fossil fuels. The main disadvantages of solar panels are the high cost of installation and dependence on weather conditions.

The choice of the optimal heating system depends on many factors, including climatic conditions, resource availability, economic opportunities and environmental priorities. Each of these systems has its advantages and disadvantages, and it is important to find a balance between efficiency, cost and environmental safety. Ultimately, improving the energy efficiency of heating systems will help reduce energy consumption, lower heating costs and improve living conditions in buildings. For better energy savings, a condensing gas boiler, heat pump, electric boiler and solar panels can be used. Condensing gas boilers use the energy from the gas to maximum efficiency, thanks to condensation technology to reduce heat loss. For example, let us use formula (3) to calculate the efficiency of a condensing gas boiler that produces 20,000 kWh of useful heat while consuming 21,500 kWh of energy:

$$\eta_{kond} = \frac{20000}{21500} \times 100\% = 93\%.$$

As such, the boiler uses 93% of the energy it consumes to produce heat. If a standard gas boiler has an efficiency of 75%, the energy savings can be calculated using the formula (4):

$$\mathrm{E}_{saved} = (1 - 0.75) \times \frac{20000}{0.93} = 5376.35\ kWh \times year.$$

Heat pumps use renewable energy sources such as air, soil or water, which reduces energy costs and increases the energy efficiency of the system. If a heat pump produces 20,000 kWh of heat while consuming 5,000 kWh of electricity. The coefficient of performance (COP) of a heat pump can be calculated using the formula (5):

$$HPF = \frac{20000}{5000} = 4.$$

The heat pump efficiency , accounting for the efficiency of electricity use (40%), was calculated using formula (6):

$$\eta_{tn} = 4 \times 0.4 = 1.6 = 160\%.$$

An electric boiler may be a better choice as a backup heat source. If an electric boiler produces 20,000 kWh of heat while consuming 22,000 kWh of electricity. The efficiency of an electric boiler can be calculated using formula (7):

$$\eta_{power} = \frac{20000}{22000} \times 100\% = 90.91\%.$$

It is recommended to use solar panels in combination with other energy sources. If the area of the panels is 50 m², the amount of solar radiation is 1,500 kWh/m², and the performance factor is 0.8. The amount of electricity generated can be calculated using formula (8):

$$E_{solar\ panels} = 50 \times 1500 \times 0.8 = 60000\ kWh \times year.$$

If the efficiency of the heating system is 90%, the savings from using solar panels according to formula (9) will be:

$$E_{saving} = 60000 \times 0.9 = 50000\ kWh \times year.$$

Thus, these calculations show the efficiency and energy savings of different heating systems, addressing environmental and financial aspects. Solar collectors are an important element of modern heating systems aimed at reducing the use of traditional energy resources and improving the sustainability of building energy systems (Jasim et al., 2023). These technologies use solar energy to heat water, which can then be used to heat rooms. The main advantage of solar collectors is their ability to convert solar radiation into thermal energy with minimal electricity consumption. This significantly reduces the use of conventional energy sources such as gas or electricity, which helps to save costs and reduce CO_2 emissions. Solar collectors are effectively used in heating systems that not only heat water but also transport it through heat exchange systems to radiators or floor systems. This ensures a consistent temperature in the house and provides comfort to users throughout the heating season. The use of solar collectors in heating systems is not only a cost-effective but also an environmentally friendly solution aimed at reducing the responsibility for greenhouse gas emissions and reducing the carbon footprint of the construction sector. Solar collectors are a key component of modern energy-efficient building strategies, helping to reduce heating costs and ensuring the sustainability of an energy balance of a building in a changing climate.

The use of wind energy to generate electricity is becoming increasingly relevant in the modern world, especially in the context of reducing dependence on traditional, carbon-based energy sources to power heating systems in buildings. Wind generators operate on the principle of converting the kinetic energy of the wind into electrical energy, which can be used to power any electrical system, including heating systems. This technological solution contributes to a significant reduction in greenhouse gas emissions and other pollutants, which are negative consequences of using traditional energy sources such as coal or oil. One of the key advantages of wind turbines is that they are a sustainable source of energy, as wind is an infinite resource available all over the planet. This makes them an option that competes with traditional energy sources, particularly in the context of energy-efficient solutions for building systems.

The use of wind generators to power heating systems reduces energy dependence and stabilises electricity prices, which is an important factor in the planning and operation of construction projects. It also reduces costs and ensures a sustainable energy mix in the context of increasing demands for environmental sustainability. The use of wind turbines is a step towards sustainable development and reducing environmental impact, which contributes to energy efficiency and helps to reduce the use of fossil fuels in the construction sector. The introduction of advanced approaches to the configuration of heating structures and panels can significantly improve thermal comfort and reduce energy consumption in buildings. This requires a comprehensive approach that includes the use of intelligent control systems, efficient heat pumps, advanced insulation materials, low-temperature heating systems and renewable energy sources.

4. Discussion

Improving thermal comfort and energy efficiency in buildings is an extremely important issue in the context of growing energy needs and the need to reduce environmental impact. The use of advanced approaches to the optimal settings of heating structures and panels can play a key role in achieving these goals.

One of the main technologies contributing to energy efficiency is intelligent heating control systems. They can automatically adjust the temperature in rooms based on various parameters such as the presence of people, time of day and external weather conditions. This not only reduces energy consumption but also increases the comfort of living. Smart thermostats and integrated temperature, humidity and motion sensors are important elements of these systems. They provide precise control of the microclimate in each room, avoiding overheating or underheating. This was also investigated by Farzaneh et al. (2021), confirming that intelligent heating control systems use machine learning algorithms to adapt to user habits and provide optimal conditions at all times. This approach not only reduces heating costs but also helps to reduce carbon emissions, which is important for the environment. Bae et al. (2021) also determined that temperature and humidity sensors help maintain optimal comfort levels by preventing condensation and mould, while motion sensors allow for maximum energy efficiency by adapting heating to actual room use. This not only increases energy efficiency but also creates a more comfortable living and working environment. It is worth noting that intelligent heating control systems reduce energy consumption and integrate with other smart systems, ensuring efficient resource management and increased comfort. Although they require an initial outlay, the long-term savings render them worthwhile. These technologies also contribute to environmental sustainability by reducing greenhouse gas emissions and maintaining a healthy environment in buildings, improving the well-being of occupants.

Heat pumps, including geothermal and air source heat pumps, are another effective solution. They use natural heat sources to heat buildings. Geothermal pumps use the stable temperature of the ground, which makes them extremely efficient even in low outdoor temperatures. Air source heat pumps, although less efficient in extremely cold conditions, are still a cost-effective solution for temperate climates. This aspect was addressed by many scholars, including Wang et al. (2021), emphasising that geothermal pumps are highly efficient in using the stable ground temperature to heat buildings, making them effective even in low outdoor temperatures such as winter. They provide stable room heat and relatively low energy costs, making them an attractive choice for energy-efficient building projects. Violante et al. (2022) concluded that air source heat pumps use heat from the outside air and can be an effective solution for buildings with moderate winter temperatures. Air source heat pumps can also be used to cool rooms in summer, making them versatile options for year-round comfort. These results confirm the above study, as both types of heat pumps demonstrate high energy efficiency and reliability in different climatic conditions. Geothermal pumps operate efficiently even at low temperatures, reducing energy costs, while air-source heat pumps are ideal for temperate zones, providing consistent comfort in all weather.

The use of advanced insulation materials significantly reduces heat loss through the walls, windows and roof of the building. Aerogels and vacuum insulation panels show the best results in this area. They provide a high level of thermal insulation at a relatively low thickness, which is important for preserving usable space in buildings. Kan et al. (2022) analysed this phenomenon and noted that advanced insulation materials, such as aerogels and vacuum panels, have a high thermal conductivity coefficient with a relatively small material thickness, which allows for significant usable space in the building. For instance, aerogels have a low density and low thermal conductivity, which makes them ideal for use in thermal insulation systems, reducing energy costs and increasing indoor comfort. Moreover, Elshazli et al. (2022) determined that there are certain challenges associated with the use of advanced insulation materials. For instance, the high cost of aerogels and vacuum panels can make it difficult to use them widely in construction. Their resistance to moisture and mechanical damage is also crucial in ensuring a long service life and effective insulation properties. These data confirm the importance of advanced insulation materials in reducing heat loss through walls, windows and roofs. Aerogels and vacuum panels demonstrate the highest thermal insulation efficiency with minimal thickness, which is critical for preserving interior space.

Low-temperature heating systems, such as underfloor heating and radiator systems with low-temperature coolants, also contribute to energy efficiency. Underfloor heating ensures an even distribution of heat, which reduces the temperature of the coolant and, consequently, energy costs. Low-temperature radiators operate efficiently at lower temperatures, which also reduces energy consumption. Reguis et al. (2021) determined that low-temperature heating systems, such as underfloor heating and radiator systems with low-temperature coolants, are particularly relevant in the context of current requirements for energy efficiency in buildings and reduction of CO_2 emissions. They improve the quality of the indoor climate, providing optimal conditions for users and reducing heating costs. It is worth noting the study of Kalmár et al. (2023), which also demonstrated that the use of such systems is a promising area in construction, as they not only increase indoor comfort but also contribute to the sustainable use of energy resources, which is an important aspect. Comparing the data obtained during the research, low-temperature heating systems, such as underfloor heating and radiators with low-temperature coolants, demonstrate higher energy efficiency than traditional systems. They reduce energy consumption and increase comfort, making them attractive for modern construction projects.

Renewable energy sources, such as solar collectors and wind generators, are environmentally friendly and provide renewable energy for heating systems. Solar collectors efficiently use solar energy to heat water, which can be used in heating systems. Wind generators, in turn, provide electricity that can be used to power heating systems, reducing dependence on fossil fuels. Wang et al. (2023), concluded that the use of solar collectors provides efficient use of solar energy to generate heat, which can be used for water heating or direct space heating. This reduces dependence on traditional energy sources and promotes environmentally friendly living. In addition to this, the study by Nasser et al. (2022) determined that wind generators convert the kinetic energy of the wind into electricity, which can power heating systems. This technology is particularly beneficial in regions with windy conditions, where it can provide a stable power supply for heating systems. Study results analysis determined that both technologies contribute to reducing greenhouse gas emissions and reducing environmental impact, making them beneficial for modern construction projects aimed at reducing the carbon footprint and increasing the sustainability of energy supply.

All these advanced technologies and materials contribute to a significant increase in the energy efficiency of buildings, reducing energy consumption and heating costs, and increasing thermal comfort for occupants. Integrating these solutions into modern buildings is an important step towards sustainable development and reducing the negative impact on the environment.

5. Conclusions

Research into improving thermal comfort and energy savings in buildings through advanced approaches to optimal settings of heating structures and panels has shown significant potential for improving energy efficiency and enhancing occupancy comfort. The technologies and materials analysed, such as intelligent control systems, heat pumps, advanced insulation materials, low-temperature heating systems and renewable energy sources, have demonstrated high efficiency and the ability to be integrated into modern buildings.

The study confirmed the importance of using advanced technologies and materials to achieve efficiency in building heating. The recommendations for using triple-glazed windows with high thermal insulation properties, condensing gas boilers or heat pumps prove their effectiveness in reducing energy consumption. The use of mineral wool and extruded polystyrene foam for wall and roof insulation considers not only economic but also environmental aspects of construction, which contributes to sustainable development and improved living conditions in modern buildings.

Intelligent control systems, including smart thermostats and sensors, automatically adjust the temperature in rooms based on the presence of people and other factors, which significantly reduces energy consumption and ensures maximum comfort. Heat pumps, both geothermal and air-source, have proven to be extremely efficient in harnessing ambient heat to heat buildings. They can significantly reduce heating costs compared to traditional systems. Advanced insulation materials, such as aerogels and vacuum insulation panels, significantly reduce heat loss through walls, windows and roofs. This leads to a reduction in energy consumption and improves the overall energy efficiency of buildings. Low-temperature heating systems, such as underfloor heating and low-temperature radiator systems, ensure even heat distribution throughout the room and reduce heating costs. Renewable energy sources, such as solar collectors and wind generators, provide clean and renewable energy for heating systems, reducing dependence on fossil fuels. The introduction of advanced technologies and materials in building heating systems can significantly improve energy efficiency, reduce energy costs and ensure a high level of thermal comfort. This is a significant step towards sustainable development and reducing the negative impact on the environment.

One of the main limitations of the study is that the analysis of the efficiency of different heating systems was carried out under the conditions of theoretical modelling and may differ from the results in real operating conditions. For further research, it is necessary to study the impact of the combined use of various advanced heating technologies on energy efficiency and comfort in real operating conditions.

References

Bae, Y., Bhattacharya, S., Cui, B., Lee, S., Li, Y., Zhang, L., Im, P., Adetola, V., Vrabie, D., Leach, M., Kuruganti, T., 2021. Sensor impacts on building and HVAC controls: A critical review for building energy performance, Advances in Applied Energy, 4, 100068. https://doi.

org/10.1016/j.adapen.2021.100068

Cho, H.M., Yun, B.Y., Kim, Y.U., Yuk, H., Kim, S., 2022. Integrated retrofit solutions for improving the energy performance of historic buildings through energy technology suitability analyses: Retrofit plan of wooden truss and masonry composite structure in Korea in the 1920s, Renewable and Sustainable Energy Reviews, 168, 112800. https://doi.org/10.1016/j.rser.2022.112800

Cholewa, T., Dell'Isola, M., Canale, L., Ficco, G., Michnikowski, P., Siuta-Olcha, A., Olszewska, A., Sadowska, G., Dudzińska, M.R., 2022. On the influence of heat cost allocation on operation of heating system in buildings and possible, additional decrease of supply temperature, Energy and Buildings, 254, 111599. https://doi.org/10.1016/j.enbuild.2021.111599

Elshazli, M.T., Mudaqiq, M., Xing, T., Ibrahim, A., Johnson, B., Yuan, J., 2022. Experimental study of using Aerogel insulation for residential buildings, Advances in Building Energy Research, 16(5), 569-588. https://doi.org/10.1080/17512549.2021.2001369

Erdiwansyah, Mahidin, Husin, H., Nasaruddin, Zaki, M., Muhibbuddin, 2021. A critical review of the integration of renewable energy sources with various technologies, Protection and Control of Modern Power Systems, 6(1), 1-18. https://doi.org/10.1186/s41601-021-00181-3

Farzaneh, H., Malehmirchegini, L., Bejan, A., Afolabi, T., Mulumba, A., Daka, P.P., 2021. Artificial intelligence evolution in smart buildings for energy efficiency, Applied Sciences, 11(2), 763. https://doi.org/10.3390/app11020763

Güler, Ö., Başgöz, Ö., Yavuz, Ç., 2021. Production of new type insulation material: Expanded Perlite-Silica aerogel composite, Turkish Journal of Engineering, 5(3), 95-99. https://doi.org/10.31127/tuje.674035

Hałaj, E., Kotyza, J., Hajto, M., Pełka, G., Luboń, W., Jastrzębski, P., 2021. Upgrading a district heating system by means of the integration of modular heat pumps, geothermal waters, and PVs for resilient and sustainable urban energy, Energies, 14(9), 2347. https://doi.org/10.3390/en14092347

Heydari, A., Sadati, S.E., Gharib, M.R., 2021. Effects of different window configurations on energy consumption in building: Optimization and economic analysis, Journal of Building Engineering, 35, 102099. https://doi.org/10.1016/j.jobe.2020.102099

Himeur, Y., Alsalemi, A., Al-Kababji, A., Bensaali, F., Amira, A., Sardianos, C., Dimitrakopoulos, G., Varlamis, I., 2021. A survey of recommender systems for energy efficiency in buildings: Principles, challenges and prospects, Information Fusion, 72, 1-21. https://doi.org/10.1016/j.inffus.2021.02.002

Jasim, M.A., Ahmed, O.K., Alaiwi, Y., 2023. Performance of solar stills integrated with PV/Thermal solar collectors: A review, NTU Journal of Renewable Energy, 4(1), 97-111. https://doi.org/10.56286/ntujre.v4i1.456

Kalair, A., Abas, N., Saleem, M.S., Kalair, A.R., Khan, N., 2021. Role of energy storage systems in energy transition from fossil fuels to renewables, Energy Storage, 3(1), e135. https://doi.org/10.1002/est2.135

Kalmár, T., Bodó, B., Kalmár, F., 2023. Heat losses of low-temperature radiant heating systems, Energy Reports, 10, 1982-1995. https://doi.org/10.1016/j.egyr.2023.08.090

Kan, A., Zheng, N., Zhu, W., Cao, D., Wang, W., 2022. Innovation and development of vacuum insulation panels in China: A state-of-the-art review, Journal of Building Engineering, 48, 103937. https://doi.org/10.1016/j.jobe.2021.103937

Lamy-Mendes, A., Pontinha, A.D.R., Alves, P., Santos, P., Durães, L., 2021. Progress in silica aerogel-containing materials for buildings' thermal insulation, Construction and Building Materials, 286, 122815. https://doi.org/10.1016/j.conbuildmat.2021.122815

Lund, H., Østergaard, P.A., Nielsen, T.B., Werner, S., Thorsen, J.E., Gudmundsson, O., Arabkoohsar, A., Mathiesen, B.V., 2021. Perspectives on fourth and fifth generation district heating, Energy, 227, 120520. https://doi.org/10.1016/j.energy.2021.120520

Malewska, E., Prociak, A., Vevere, L., Vanags, E., Zemła, M., Uram, K., Kirpluks, M., Cabulis, U., Bryk, M., 2022. New thermo-reflective coatings for applications as a layer of heat insulating materials, Materials, 15(16), 5642. https://doi.org/10.3390/ma15165642

Merabet, G.H., Essaaidi, M., Haddou, M.B., Qolomany, B., Qadir, J., Anan, M., Al-Fuqaha, A., Abid, M.R., Benhaddou, D., 2021. Intelligent building control systems for thermal comfort and energy-efficiency: A systematic review of artificial intelligence-assisted techniques, Renewable and Sustainable Energy Reviews, 144, 110969. https://doi.org/10.1016/j.rser.2021.110969

Nasser, M., Megahed, T.F., Ookawara, S., Hassan, H., 2022. Performance evaluation of PV panels/wind turbines hybrid system for green hydrogen generation and storage: Energy, exergy, economic, and enviroeconomic, Energy Conversion and Management, 267, 115870. https://doi.org/10.1016/j.enconman.2022.115870

OPEN TECK profile systems., 2024. https://okna.ua/profiles/p-openteck

Osterman, E., Stritih, U., 2021. Review on compression heat pump systems with thermal energy storage for heating and cooling of buildings, Journal of Energy Storage, 39, 102569. https://doi.org/10.1016/j.est.2021.102569

Reguis, A., Vand, B., Currie, J., 2021. Challenges for the transition to low-temperature heat in the UK: A review, Energies, 14(21), 7181. https://doi.org/10.3390/en14217181

Saeidi, R., Karimi, A., Noorollahi, Y., 2024. The novel designs for increasing heat transfer in ground heat exchangers to improve geothermal heat pump efficiency, Geothermics, 116, 102844. https://doi.org/10.1016/j.geothermics.2023.102844

Stopps, H., Touchie, M.F., 2021. Residential smart thermostat use: An exploration of thermostat programming, environmental attitudes, and the influence of smart controls on energy savings, Energy and Buildings, 238, 110834. https://doi.org/10.1016/j.enbuild.2021.110834

Violante, A.C., Donato, F., Guidi, G., Proposito, M., 2022. Comparative life cycle assessment of the ground source heat pump vs air source heat pump, Renewable Energy, 188, 1029-1037. https://doi.org/10.1016/j.renene.2022.02.075

Wang, H., Zhou, Y., Li, X., Wu, X., Wang, H., Elnaz, A., Granlund, K., Lahdelma, R., Teppo, E., 2023. Study on the performance of a forced convection low temperature radiator for district heating, Energy, 283, 129036. https://doi.org/10.1016/j.energy.2023.129036

Wang, Z., Luther, M.B., Amirkhani, M., Liu, C., Horan, P., 2021. State of the art on heat pumps for residential buildings, Buildings, 11(8), 350. https://doi.org/10.3390/buildings11080350

Yang, X., Pan, L., Guan, W., Tian, Z., Wang, J., Zhang, C., 2022. Optimization of the configuration and flexible operation of the pipe-embedded floor heating with low-temperature district heating, Energy and Buildings, 269, 112245. https://doi.org/10.1016/j.enbuild.2022.112245

Zhang, G., Wu, H., Liu, J., Yang, J., Huang, H., Ding, Y., Xie, L., 2023. Dynamic performance and energy efficiency of reflective and insulative composite coating on building exterior wall, Building Simulation, 16(12), 2245-2259. https://doi.org/10.1007/s12273-022-0932-x

Zhang, S., Ocłoń, P., Klemeš, J.J., Michorczyk, P., Pielichowska, K., Pielichowski, K., 2022. Renewable energy systems for building heating, cooling and electricity production with thermal energy storage, Renewable and Sustainable Energy Reviews, 165, 112560. https://doi.org/10.1016/j.rser.2022.112560

Zhao, J., Dong, K., Dong, X., Shahbaz, M., 2022. How renewable energy alleviate energy poverty? A global analysis, Renewable Energy, 186, 299-311. https://doi.org/10.1016/j.renene.2022.01.005