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IMPROVING THE EFFICIENCY OF AUTONOMOUS HEATING SYSTEMS IN RESIDENTIAL BUILDINGS THROUGH RENEWABLE ENERGY INTEGRATION

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Abstract: The building sector is one of the largest energy consumers worldwide, accounting for about 30% of global final energy use and 26% of energy-related carbon emissions. In Uzbekistan, residential buildings consume approximately 40–50% of total final energy, with heating representing the dominant share of demand. This paper analyzes modern approaches to improving the energy efficiency of residential heating systems through the integration of renewable energy technologies, including solar collectors, photovoltaic systems, heat pumps, and hybrid energy systems. Based on international and regional studies, it is shown that hybrid heating solutions can cover up to 50–70% of heating demand, reduce conventional fuel consumption by 3–12 tons per year, and significantly lower CO_2 emissions. The study highlights the importance of climate-specific optimization and demonstrates the technical and economic feasibility of autonomous renewable-based heating systems for residential buildings.

Introduction

At present, the building sector is one of the largest consumers of energy in the global energy system, accounting for approximately 30% of total final energy consumption worldwide. According to the 2025 report of the International Energy Agency (IEA), buildings account for about 30% of global final energy consumption and approximately 26% of energy-related emissions worldwide [1]. In particular, energy consumption in the residential sector represents the largest share of total building energy demand – around 70%, while the remaining 30% is attributed to commercial and public buildings [2]. The residential sector also occupies a significant share in the energy consumption structure of Uzbekistan. According to IEA data, the residential sector accounts for approximately 40% of the total final energy consumption in Uzbekistan [3]. This figure is closely linked to global trends and necessitates the modernization of heating technologies for buildings. According to local statistics, the building sector in Uzbekistan exceeds industry and transport in terms of final energy consumption and accounts for approximately 50% of total final energy use [4; pp. 87–92]. Along with global energy and environmental processes, local climate, infrastructure, and economic factors play a decisive role in shaping the energy demand of heating systems. For example, IEA data indicate that worldwide energy demand for heating buildings remains high, and natural gas continues to be the primary energy source for heating, accounting for approximately 42%, while the remaining share is covered by electricity and other resources [5]. This situation demonstrates the global need for new solutions aimed at improving the efficiency of heating systems and reducing carbon emissions.

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The introduction of renewable energy sources and improvement of energy efficiency are among the priority directions of Uzbekistan's climate and energy policy. As noted in the analyses of the United Nations Development Programme (UNDP), to achieve Uzbekistan's climate-related goals, it is necessary to expand the use of renewable energy sources and accelerate energy efficiency measures [6]. This further strengthens the practical relevance of research on autonomous heating systems under regional conditions. In addition, Uzbekistan's Energy Strategy until 2030 sets strict objectives for expanding the use of renewable energy sources and implementing energy efficiency measures. At the same time, the number of studies aimed at reducing energy intensity in residential buildings, modernizing heating systems, and implementing autonomous PV and other alternative systems in local scientific and practical fields is increasing. This indicates that the topic is oriented not only toward theoretical issues but also toward solving real practical problems in Uzbekistan.

Therefore, the development of energy-efficient, environmentally friendly, and economically viable autonomous heating systems is one of the important scientific and practical tasks of today. The factors mentioned above necessitate a systematic analysis of existing scientific research in this area.

Uzakov et al. [7; pp. 9–15] analyze hybrid heating systems as highly efficient solutions combining several energy sources. According to the results, the use of solar energy in a 180 m² rural house in the conditions of Karshi allowed saving 2440–2449 kg of conventional fuel annually for hot water supply and reducing energy consumption by 65–70%. The combination of a water heated floor and a solar collector can cover 50–55% of the heating load on sunny days and save 3230–3236 kg of conventional fuel per heating season. Choriev [8; pp. 129–131] substantiates that in the conditions of Southern Uzbekistan, it is possible to reduce energy consumption for heating and hot water supply through the use of geothermal energy. In the Surkhandarya region, groundwater temperature remains almost constant at around 19–20℃ throughout the year. Measurements taken in an 8-meter-deep well in the Angor district showed that water temperature remains at 20°C year-round. Under these conditions, a heat pump extracts 10–12℃ of heat from well water and transfers it to the building heating system. According to the author, one low-capacity heat pump can heat an area of 200–250 m², and the optimal distance between wells should be 30–40 m.Safarov et al. [9] substantiated that trigeneration systems in Bukhara and Kashkadarya regions increase the continuity and reliability of energy supply (Fig. 1).

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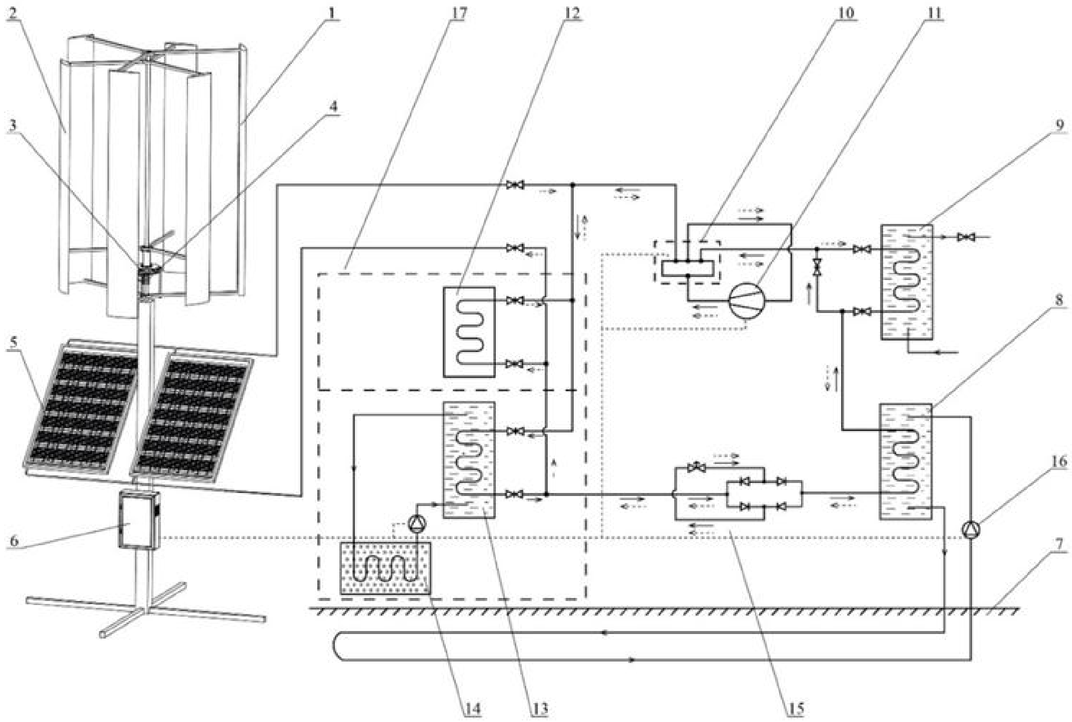

1, 2 – outer and inner blades of the wind turbine; 3 – electric drive; 4 – brush collector; 5 – solar photovoltaic module; 6 – control system; 7 – geothermal energy source; 8 – condenser/evaporator; 9 – hot water tank; 10 – check valve; 11 – compressor; 12 – cooler; 13 – condenser; 14 – heated floor; 15 – throttle valve; 16 – circulation pump; 17 – autonomous consumer

Figure 1. Autonomous trigeneration scheme

In these regions, average daily solar energy is about 4.5 kWh/m², wind speed ranges from 5.5 to 8.5 m/s, and the specific power of wind flow reaches 300–580 W/m², which makes small wind installations effective. Ground temperature at depths of 3–5 m is +10…+12℃, which is considered a stable low-potential source for heat pumps. It is stated that a heat pump can produce 2.5–5 kWh of heat per 1 kWh of electricity consumed, resulting in energy savings of up to 70%. In a subsequent study by Uzakov et al. [10; pp. 107–114], it is noted that the use of a hybrid heat and power supply system in a typical rural house significantly increases energy efficiency. Calculations show that the household electric load is 2.5–2.74 kW, and a 5.0 kW solar photovoltaic station can fully meet this demand. Experimental results indicated an average generation of 2.76 kW with an average efficiency of 15.8%. The solar collector provides 300 liters of hot water at 50–60℃ per day, which allows saving 5000–5400 kWh of electricity annually. It is also established that during the heating season, the system can cover 50–55% of the load using solar energy and save 11,500–12,000 kg of conventional fuel. Kamolov et al. [11; pp. 115–122] proposed a hybrid system based on a vacuum solar collector and a heat pump for energy-efficient heating and hot water supply in rural model houses (Fig. 2).

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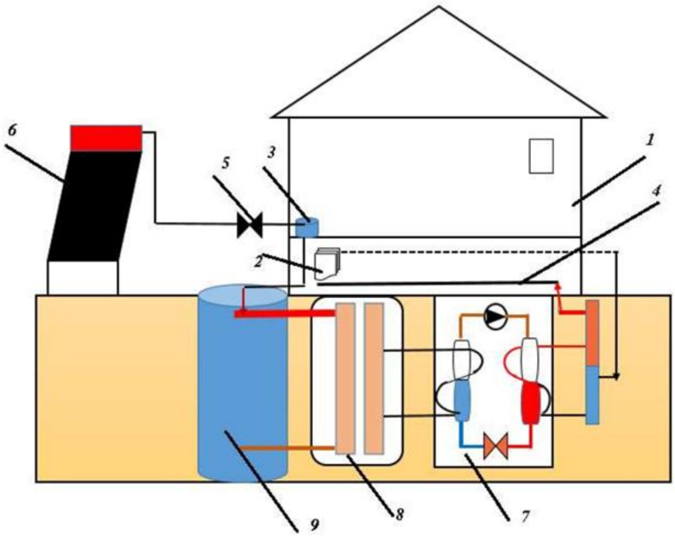

1 – house; 2 – heating system; 3 – hot water supply; 4 – heated floor; 5 – valve; 6 – vacuum tube solar collector; 7 – heat pump; 8 – recuperator; 9 – sewage tank

Figure 2. Hybrid heat and hot water supply system of residential buildings

The study demonstrated that a 2.5 kW heat pump can generate 12.5–17.5 kW of heat energy, which is 5–7 times more efficient compared to traditional boilers and electric heaters. Considering the meteorological conditions of Kashkadarya region, the system can save 39,600 kWh of electricity or 12–14 tons of conventional fuel annually. The average efficiency of the vacuum solar collector was 68.5%, sufficient to fully meet hot water demand. However, system efficiency is significantly dependent on seasonal fluctuations in solar radiation and outdoor temperature, and therefore adaptive control and backup energy sources are required to ensure the stable operation of this hybrid system. Toropov [12] substantiates the necessity of a comprehensive assessment of energy efficiency, economic costs, environmental impact, and operational safety when selecting heating systems for multi-storey residential buildings. According to the research results, the efficiency of electric water heat generators ranges from 0.94 to 0.99, whereas under real operating conditions gas boilers demonstrate efficiencies of only 0.5–0.7. It is shown that due to the sharp differences in electricity tariffs between countries, the economic efficiency of electric heating strongly depends on regional conditions. It is emphasized that the special low electricity tariffs introduced in Belarus have made electric heating competitive with centralized heating systems. On this basis, the author proposes a gradual transition to electric heating for newly constructed urban residential buildings as the most optimal long-term strategy. Mohammadi and Bahman [13] prove through scientific modeling that it is possible to achieve full energy autonomy for residential buildings in hot and arid climate conditions. The study revealed that when energy demand is reduced from 49,661 kWh to 24,831 kWh, the number of required photovoltaic modules decreases from 362 to 181 units, and battery storage capacity decreases from 3,415 kWh to 1,710 kWh. The “5Z” concept developed by the authors (zero carbon, zero energy, zero grid, zero bills, zero-emission transport) enables the integration of buildings and electric vehicles into a unified energy system. As disadvantages of the system, the authors note the high initial investment costs and the limited roof area available for installations. Zaafouri et al. [14] substantiate that the integration of solar water heating (SWH) systems into buildings is one of the most effective ways to reduce energy consumption and carbon emissions. The authors demonstrate that the use of SWH systems can reduce the energy consumption for domestic hot water in a typical household by approximately 20%. It is shown through experimental and modeling results that roof- and façade-integrated systems can cover up to 85% of a building's hot water demand, while thermal efficiency varies between 32% and 85% depending on material properties, geometry, and operating conditions.

Canale et al. [15] point out that buildings account for more than 30% of global final energy consumption and nearly 40% of CO_2 emissions, and emphasize the need for accelerated implementation of renewable energy technologies in this sector. The authors state that through the concept of hybrid renewable energy systems and multi-energy buildings, it is possible to manage electrical, heating, and cooling loads within a single optimized system. The study demonstrates that combinations such as wind-solar, solar-geothermal, and solar-biomass increase the stability of energy supply due to the complementary nature of different energy sources. It is also noted that the introduction of energy storage systems and demand response mechanisms is necessary to reduce temporal mismatches between energy production and consumption. As a result, the authors conclude that functional integration not only enhances building energy independence but also improves the stability of the entire energy system. Akram et al. [16] indicate that buildings account for approximately 40% of global final energy consumption and 33% of greenhouse gas emissions, emphasizing that the implementation of energy-saving technologies in this sector is a strategic necessity. The authors note that in the United Kingdom, the use of double-glazed windows in commercial buildings enables energy savings of 39–53%, and that maintenance of central heating systems can reduce energy consumption by 11%. It is confirmed through experimental studies and literature analysis that automated control systems can reduce heating loads by an average of 20%. At the same time, the article critically emphasizes that technological solutions will not deliver the expected results unless they are aligned with government policies, construction standards, and economic incentive mechanisms.

Musiał et al. [17] systematically analyze modern thermal energy storage systems intended for autonomous buildings and substantiate that significant energy savings are achievable only through short- and medium-term thermal storage. The study shows that although water-based thermal storage systems require relatively low investment, they have limited efficiency due to large volume requirements and high heat losses. Phase change materials (PCM) provide high energy density; however, their thermal conductivity is limited to 0.2–0.7 W/(m·°C), which reduces heat transfer rates. Therefore, the authors recommend integrated solutions combining high-conductivity composite materials with active/passive hybrid storage systems as the most promising direction. Toropov [18; pp. 1779–1788] demonstrates that carbon emissions from heat generators in autonomous water-based heating systems of residential buildings are strongly dependent on the national energy balance, climatic conditions, and the type of heating equipment used. In the climatic conditions of Russia, emissions from convection gas boilers operating with radiators range from 240 to 300 g CO_2/kWh, while for condensing gas boilers they range from 220 to 280 g CO_2/kWh. For electric boilers, taking into account electricity generation and transmission losses, emissions can reach up to 410 g CO_2/kWh. Although air-to-water heat pumps show low emissions in mild climates, their efficiency decreases significantly at temperatures below –5°C, and their environmental advantages disappear. Therefore, the author concludes that hybrid systems combining heat pumps and condensing gas boilers provide the lowest carbon emissions (on average 160–180 g CO_2/kWh) for houses larger than 100 m^2.

Ayodeji et al. [19; pp. 31–59] establish that in Nigeria, buildings account for 42% of total energy consumption, and domestic hot water preparation is one of the most energy-intensive processes in households. It is shown that 87.5% of electricity generation in the country relies on natural gas and that more than 70% of the population uses electric water heaters, which creates unsustainable pressure on the energy system. The authors compare flat-plate and vacuum-tube solar collectors, which operate effectively in temperature ranges of 30–70°C and 60–120°C respectively, and analyze their technical and economic advantages. It is found that heat pumps have a coefficient of performance ranging from 2 to 4.5 and consume several times less energy compared to electric heaters. Based on this, the article concludes that hybrid systems combining solar energy and heat pumps represent the most promising and sustainable solution for Nigeria. Stenin et al. [20; pp. 78–87] substantiate through mathematical modeling and experiments that it is possible to optimize the use of energy resources in autonomous heating systems based on multi-circuit spiral heat exchangers. The authors demonstrate that there is a strict functional relationship between the flow rate of heat carriers and the amount of heat transferred, and that this relationship can be used to select optimal design parameters. Experimental tests conducted on a test stand confirmed the validity of the theoretical model and showed the possibility of its application in industrial projects. Thygesen [21] evaluates the impact of various solar heating systems on the energy performance of multi-apartment buildings using TRNSYS simulations and proves that the choice of the main heating system has a decisive influence on energy results. According to the study, a building equipped with a heat pump and heat recovery ventilation reduces specific energy demand to 36 kWh/m²·year, which is significantly lower than that of a centrally heated building (57 kWh/m²·year). Photovoltaic panels reduce energy demand by only 1.3 kWh/m²·year in centrally heated buildings, while in combination with heat pumps the reduction reaches 12.5 kWh/m²·year. It is shown that the impact of solar thermal collectors almost ceases after 30 m² of collector area and reduces energy demand by approximately 5 kWh/m²·year. Based on these results, the author emphasizes that the heat pump + PV combination is the most energy-efficient option.

Stritih et al. [22] prove through modeling that a complex system combining a solar-assisted heat pump and phase change material (PCM) thermal storage can significantly reduce building energy consumption and carbon emissions. The study shows that under the climatic conditions of Adana, Rome, and Ljubljana, up to 80% of heating energy during the heating season can be provided by solar energy, and the coefficient of performance (COP) of the heat pump can reach 5.7. In Stockholm, due to limited solar resources, the maximum COP was 5.12, and up to 85% of heating demand had to be covered by biomass. The potential for CO_2 emission reduction ranges from 53–77% in Adana and Rome and 66–81% in Ljubljana, while in Stockholm it reaches 98–99%. At the same time, the article notes that system efficiency is strongly climate-dependent and that stable operation in cold regions is not possible without backup energy sources. Khamrayev and Ibragimov [23; pp. 28–32] substantiate through technical and economic calculations that combined solar-based heating systems in residential buildings significantly reduce dependence on traditional fuels. Under the conditions of Karshi city, the use of such a system allows saving 6,263 kg of conventional fuel or 50,923 kWh of electricity annually during the heating season. It was also determined that the use of solar energy for hot water supply reduces annual energy consumption by 2,449 kg of conventional fuel or 19,909 kWh. The above analyses show that the high share of energy consumption in residential buildings and climate-related constraints are making the transition to autonomous, energy-efficient, and renewable energy-based heating systems an inevitable process. International and local studies confirm that hybrid systems based on solar, geothermal, and heat pump technologies have high potential for energy efficiency and carbon emission reduction. At the same time, the economic efficiency of these systems, their dependence on climate, and the need for initial investment indicate the necessity of optimizing them according to regional conditions. From this point of view, the organization of the electrical and thermal components of energy supply and the in-depth study of their autonomous operating characteristics acquire special scientific importance.

Conclusion

The analysis shows that residential buildings consume a significant share of energy, accounting for about 30% of global final energy use and up to 40–50% in Uzbekistan. Heating

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systems represent the largest portion of this demand. Studies confirm that hybrid renewable-based heating systems can cover 50–70% of heating needs, reduce conventional fuel consumption by 3–12 tons annually, and decrease electricity use by up to 39,000–50,000 kWh per year. Heat pumps demonstrate high efficiency, producing 2.5–5 kWh of heat per 1 kWh of electricity, which enables energy savings of up to 70% and substantial CO_2 emission reduction. The effectiveness of these systems depends on climatic conditions and proper system design. Therefore, the implementation of autonomous solar and heat pump-based heating solutions is a practical and effective approach for improving energy efficiency and reducing environmental impact in residential buildings.

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