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Renewable Energy Sources in Heating Systems: Practical Applications and Analysis of Scientific Research

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Abstract. This study analyses the use of solar energy in the heating systems of residential buildings and various sectors of the economy, based on scientific research conducted both in foreign countries and in Uzbekistan. The data show that there is significant potential for efficient utilization of solar energy in the southern regions of the country, considering the available solar resources and climatic conditions. However, there are challenges related to the integration of solar-based heating systems into combined configurations. Studies have focused on the effectiveness of using solar energy through the integration of solar collectors, photovoltaic panels, and heat pumps as well as on reducing energy consumption and optimizing production processes. Special attention is given to methods and directions for the efficient use of solar energy that are suitable for Uzbekistan's specific climatic conditions.

1 Introduction

Currently, fossil fuel-based energy resources are the primary sources of thermal and electrical energy consumed in the Republic of Uzbekistan. This situation, on the one hand, indicates the country's reliance on existing natural reserves, and on the other hand, highlights the need for diversification within the energy sector. At the same time, the energy consumption volume across economic sectors is significantly higher than that in developed countries. This underscores the importance of increasing energy efficiency, rationally using resources, and implementing modern technologies [1].

In Uzbekistan, comprehensive and long-term strategies are being developed and consistently implemented to ensure a stable and continuous supply of fuel and energy resources, support economic growth, and improve living standards. These strategies encompass modernization and innovative development of the oil and gas, electric power, coal, chemical, and construction materials manufacturing sectors [2].

Moreover, in the context of changes in the global energy market, requirements for environmental sustainability, and risks associated with climate change, the transition to renewable energy sources, the widespread adoption of energy-efficient technologies, and the implementation of "green economy" principles have become strategically important. Currently, modernization of the energy sector places a strong emphasis on the integration of innovative technologies and the adoption of international best practices. Digital management systems, smart energy infrastructures (smart grids), and automated monitoring and control technologies play a crucial role in improving the efficiency of energy resource use.

2 Materials and methods

Advanced technologies for harnessing solar energy have been widely used in developed countries. Buildings constructed under the concept of "solar homes" play a vital role in ensuring environmental sustainability and energy efficiency. The significant investment directed toward such projects reflects the growing global interest in renewable energy sources. Experience shows that by utilizing solar energy for thermal and electrical power, households' dependence on conventional energy sources can be reduced by 50% to 90%. This not only increases economic efficiency but also significantly decreases anthropogenic impacts on the environment. Uzbekistan is also keeping pace with these global trends, prioritizing the widespread integration of renewable sources in the modernization of its energy sector. Considering best international practices, the country is implementing comprehensive measures aimed at improving energy efficiency by effectively utilizing existing natural and economic resources as well as untapped potential. In the foreseeable future, priority will be given to reducing the energy and resource intensity of the economy, introducing energy-saving technologies for industrial production, and gradually increasing the share of renewable energy sources. These efforts aim not only to ensure a stable energy supply, but also to reduce production costs, lower product prices, and enhance overall competitiveness. Moreover, improving energy efficiency has a positive impact on

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labor productivity. Achieving a higher output with lower energy consumption is one of the key indicators of a modern economic model [3].

Table 1. Energy Saving Indicators through 'Solar Homes' in Developed Countries. [4-5]

Country	Average Energy Saving (%)	Average Annual Energy Saved (kWh)	Energy Source Covering the Demand (%)
Germany	60–80%	5 500	Solar power station (SPS), water heating systems
USA (United States of America)	50–70%	4 800	Solar panels, heat-insulated houses
Japan	65–85%	6 000	Photovoltaic panels, energy storage systems
Sweden	70–90%	5 900	Heat pumps, solar collectors
South Korea	55–75%	4 500	Solar panels, energy-efficient materials

Table 2. Use of Renewable Energy in Uzbekistan and Central Asian Countries (as of 2024) [4-5]

Country	Average Energy Saving (%)	Average Annual Energy Saved (kWh)	Energy Source Covered (%)
Uzbekistan	10–12%	1200	Solar panels (photovoltaic), wind turbines
Kazakhstan	15–18%	1800	Wind power stations, solar panels
Kyrgyzstan	8–10%	9 00	Hydroelectric power stations (HPP), solar collectors
Turkmenistan	5–7%	750	Solar water heaters, small wind generators
Tajikistan	12–15%	1300	Hydroelectric power stations, small solar and bioenergy systems

Innovative Technologies and Efficient Use of Solar Energy in Modern Energy Systems

Currently, the development of energy systems is primarily characterized by the rapid advancement of technology and engineering solutions. The growing demand for the development and implementation of energy- and resource-efficient technologies further emphasizes the strategic importance of the energy sector. Along with many developed and developing countries, Uzbekistan is actively pursuing measures to enhance energy efficiency and widely implementing energy-saving technologies across all sectors of the economy.

In this context, the creation of a new generation of energy-efficient technologies based on the use of renewable energy, particularly solar energy, is considered one of the most important priorities. Solar energy— a clean, sustainable, and environmentally safe source— is at the center of strategic energy policies in many countries. Currently, significant scientific research and practical projects conducted in India, Japan, Korea, China, Sweden, Germany, Greece, as well as in the Middle East and Asian countries have yielded substantial results in unlocking the full potential of solar energy.

The current state, development strategies, and prospects of solar energy use in these countries have been extensively studied. Advanced technologies such as flat-plate collectors (FPCs), photovoltaic-thermal (PVT) systems, and solar-powered heat pumps have been developed and successfully implemented. These technologies serve as key tools for significantly reducing dependence on fossil fuels, lowering production costs, and ensuring environmental safety.

Developing national policies on the use of solar energy, supporting them through legislative frameworks, and strengthening the integration between research institutions, the private sector, and government bodies in the implementation of advanced technologies are among the crucial mechanisms for achieving energy independence and sustainable economic growth. [3].

Table 3. Comparison of Solar Energy Utilization and the Introduction of Advanced Technologies in Developed Countries [4-5]

India:	The share of solar energy utilization is around 8–10%. Photovoltaic collectors (FPC) and photovoltaic thermal (PVT) systems are widely used. Expanding solar energy and developing green policies are key components of India's development strategy.
Japan:	The share of solar energy utilization is 15–20%. In Japan, photovoltaic panels, heat pumps, and other advanced technologies have been implemented. The country has set a strategy for developing innovative technologies and transitioning to clean energy systems.
South Korea:	The solar energy utilization level is 12–15%. South Korea uses PVT, solar collectors, and smart grid technologies. Development strategies focus on digital energy systems and highly efficient energy solutions.
China:	Solar energy accounts for 25–30%. China widely uses photovoltaic panels, batteries, and PVT technologies. The country is implementing strategies to expand renewable energy production on a global scale.
Germany:	The share of solar energy utilization is 35–40%. In Germany, photovoltaic collectors, wind, and solar hybrid systems have been introduced. The country's development strategy prioritizes the integration of solar and wind energy and the liberalization of the energy market.
Sweden:	Solar energy accounts for 30–35%. Solar collectors and heat pumps are widely used in Sweden. The country focuses on supporting renewable energy sources as part of its sustainable development strategies.
Greece:	The share of solar energy utilization is 15–18%. In Greece, photovoltaic collectors and heat pumps are common. The implementation of solar energy in large-scale infrastructure projects is a key priority.
United States:	The share of solar energy utilization is 20–25%. Photovoltaic panels, PVT, and energy storage systems are utilized in the U.S. The

	development of renewable energy continues under green energy policies, supported by taxes and subsidies.

Studies on the selection of optimal energy supply systems for heating individual residential homes using solar energy systems have scientifically substantiated the efficiency, affordability, and environmentally positive impact of solar thermal heating systems. Among the analyzed energy systems, the main differences in terms of energy consumption, emissions, and costs were found to depend more on the type of system selected rather than the type of fuel used. This is because, unlike conventional energy systems, the primary energy source in these studies was solar radiation.

Research conducted by Sharma, Tiwari, and Sud has examined the potential of renewable energy and technologies to address long-term energy challenges in developing countries [6]. Solar energy contributes not only to the addition of new power capacity, but also enhances energy security, addresses environmental issues, and supports leadership in the renewable energy market. Solar thermal energy (STE) and concentrated solar power (CSP) are emerging technologies in the renewable energy sector and are considered key options for future electricity generation.

3 Results and discussions

The use of solar energy to heat buildings and structures is considered an alternative method that leads to a reduction in grid electricity and fossil fuel consumption. In a study conducted by Christos et al.. Moschos and Antonopoulos developed and modeled four types of solar thermal heat pump heating systems as energy- and cost-effective solutions. Systems using photovoltaic collectors, flat-plate collectors (FPC), photovoltaic-thermal (PVT) systems, and FPC-based heat pumps for air heating were compared. The impact of electricity prices was analyzed based on data from recent years. Experts have noted that when the electricity price reaches 0.23 €/kWh, air-based PV heat pumps provide a stable economic solution. Moreover, if the electricity prices are higher, the ability of PVT heat pumps to connect to water sources is considered an additional advantage. At a rate of 0.2 €/kWh, a 20 m² PV system can offset up to 67% of the annual energy cost required to run an air-source heat pump using solar energy [7].

The main objective of the study conducted by M. Nájera-Trejo, I.R. Martín Domínguez, and J.A. Escobedo-Bretado was to analyze the economic efficiency of solar thermal systems, particularly for domestic hot water and underfloor heating [8]. Subsequently, the thermal load of the two-story house model was calculated. TRNSYS software was used for the system design and thermal analysis, while Microsoft Excel was employed for economic evaluation. Economic indicators were used to determine the optimal type and number of solar thermal collectors and the volume of thermal storage tanks. The optimal configuration for the vacuum tube collector system consists of eight collectors with a capacity of 40 L/m² each. In comparison, the flat-plate system required 12 collectors with capacities of 50 L/m². The payback period for the flat-plate system was found to be 9 years, whereas that for the vacuum tube system was approximately 11 years.

Owing to environmental problems and other negative impacts associated with fossil fuels, as well as the growing demand for energy, many countries are focusing on researching and utilizing renewable and environmentally friendly energy sources. Solar energy is one of the most environmentally benign renewable energy sources. To reduce the dependence on fossil fuels and ensure the efficient use of solar energy, various nations have developed solar energy policies. In a study by Solangi et al., global approaches to solar energy utilization were analyzed [9]. Based on a literature review, Feed-in Tariffs (FIT), Renewable Portfolio Standards (RPS), and subsidies have been identified as the most effective energy policies in many countries. These policies serve as key motivations and incentives for the development and deployment of renewable energy technologies. Furthermore, the current state of solar energy policy in Asian countries and its comparison with that of developed nations are discussed.

In many European countries, solar thermal systems (heliosystems) are widely used to heat residential buildings. An analysis of the climatic conditions of Europe shows that the average levels of direct and diffuse solar radiation on horizontal surfaces confirm the effectiveness of using solar energy for heating purposes. In studies conducted by Rutkovsky, a researcher at the Belarusian National Technical University, climate-related factors were analyzed to assess the efficiency of heliosystems, and design calculations for solar energy use systems were provided based on experimental results [10].

Several researchers have proposed methods for utilizing solar energy in residential homes with low energy consumption. For example, Kungs et al. proposed a system designed to supply heat and electricity using solar radiation as well as to heat homes using geothermal energy. This system is considered to be effective for households and has low capital and operational costs. However, it requires significant initial capital investment, which may prolong the payback period and increase the cost of the produced energy [11].

Starovoitov examined the prospects of using solar energy in Russia's Rostov region. In the heating system, solar energy is accumulated using tank accumulators, and the ability of the system to cover energy consumption was assessed. The seasonal and annual potential for using solar energy and the effectiveness of applying flat-plate collectors tailored to regional conditions were substantiated. However, a major drawback of the proposed system is the lack of comprehensive justification and conclusions regarding the effectiveness of solar energy utilization on flat collector surfaces [12].

Shishkin and Ilyin evaluated the efficiency of the integrated use of solar collectors and solar water-heating systems [13]. High-efficiency solar collectors have been shown to experience significant thermal losses, with optical efficiency dropping from 0.93 0.63. However, these collectors still achieve high energy efficiency. Experiments demonstrated that the energy efficiency coefficient of solar collectors ranged between 0.54–0.57, which is not lower than that of mass-produced collectors. The use of combined collector-accumulator systems in solar energy applications can increase the efficiency of multi-stage solar water heating systems by 5%. The main limitation of this study is its reliance solely on experimental results without the development of mathematical models or industrial prototypes.

Scientists from France, Indonesia, and Bali have developed systems based on solar energy as sustainable energy sources suitable for tropical climates. This study primarily addresses the reduction of energy consumption in air conditioning systems by using photovoltaic elements and incorporating solar batteries into vapor-compression heating and cooling systems (Fig. 1).

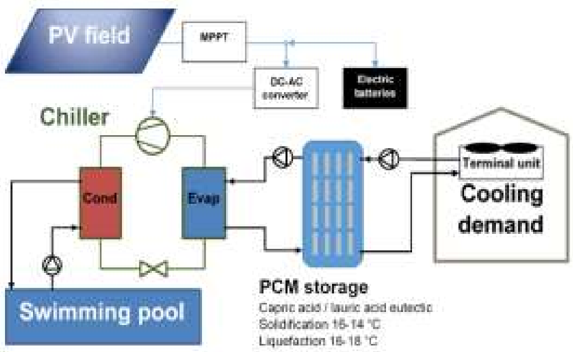

Fig. 1. Technological process diagram of a steam-compression heat pump system using solar photovoltaic panels.

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The main disadvantage of the proposed system is that the efficiency indicator of the vapor-compression device is not sufficiently substantiated. This is because the volume of the building using the cooling system was not considered during the process of transferring heat from the cooling system to the evaporator part of the heat pump. Second, there is no technically or economically substantiated conclusion regarding whether the amount of heat accumulated in the condenser is sufficient for heating the swimming pool. Third, the use of 25 m² photovoltaic panels to power the heat pump compressor requires a high capital investment.

Researchers at the University of California, USA, have studied the efficiency of aluminum-based mini-channel solar water heaters under various weather conditions throughout the year. This study identified the advantages of using solar energy in water heating systems to reduce operating costs and decrease reliance on natural gas and electricity. Typically, in solar water heaters, construction in which heat pipes are connected to absorbers is considered efficient. Copper pipes with high thermal conductivity are used in these devices. However, alternative materials with high thermal performance can also be applied to other heat-transfer constructions. For this purpose, researchers proposed a dimensioned construction of an aluminum-based mini-channel solar water heater, as shown in Fig. 2.

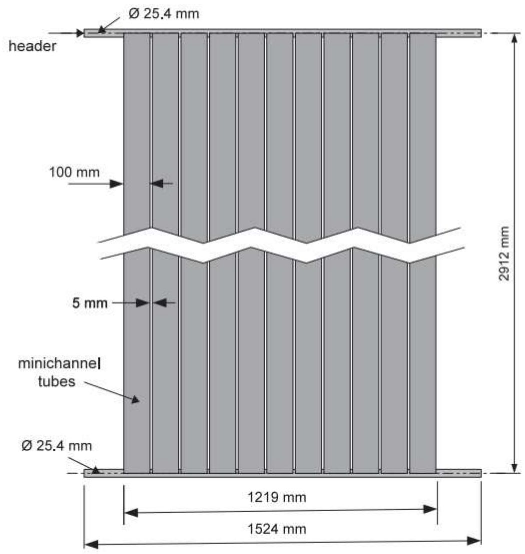

Fig. 2. Dimensions of the mini-channel water heater.

Based on this research, a schematic diagram of the experimental strip-type solar water heater shown in Fig. 3 was developed.

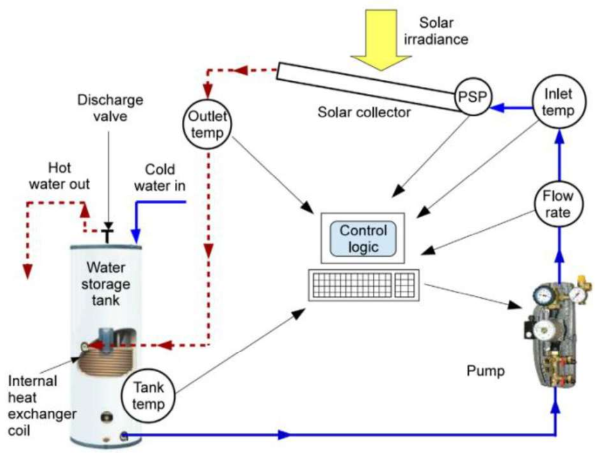

Fig. 3. Experimental schematic of the device.

Based on the proposed schematic, the potential of obtaining thermal energy in the form of hot water using solar radiation during different seasons and weather conditions throughout the year was evaluated.

In a study conducted by Indian researchers R. L. Shrevasteva et al., modeling and simulation of solar water heaters using the Transient System Simulation Tool (TRNSYS) program was considered a promising research direction. Using this software, the water-heater system was interpolated using an iterative method. The evaluation was performed by adapting it to standard test conditions. A schematic representation of the device obtained through modeling is presented in Fig. 4.

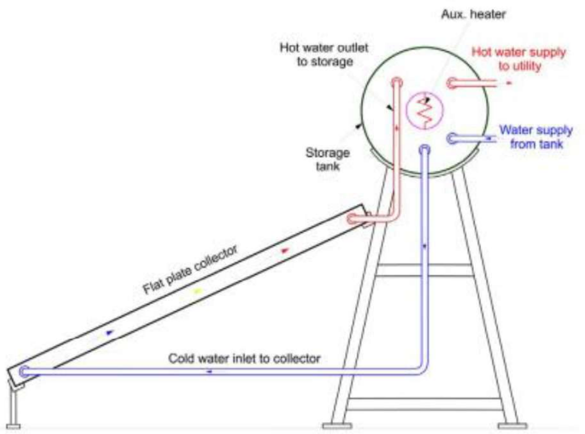

Fig. 4. Schematic layout of the flat plate solar water heater (SWH).

Based on the TRNSYS simulation, the modeled system had an error margin of 5–10%. However, the study did not consider extreme (random) conditions, such as wind, cloudy weather, or fog, indicating the need for further improvement in this field of research.

An experimental analysis was conducted by Kanimoji and other researchers on the use of porous materials in solar water-heating systems. The main objective of this study is to enhance the thermal efficiency of the system during the process of transferring energy from the solar collector to the working fluid. The experiment was conducted using a solar collector filled with crushed stone, as illustrated in Fig. 5.

Fig. 5. Appearance of the experimental device.

The heat absorption and storage characteristics of the crushed stone layer were studied to determine its capability to transfer heat to the pipe through which the working fluid flowed. Experiments were also conducted without a porous medium, and based on the measured temperature and thermal indicators, an increase in the thermal efficiency of the system was observed.

According to studies conducted by the Institute of Physics and Technology of the Academy of Sciences of the Republic of Uzbekistan, during the cold season, tests of a double-circuit solar water-heating device showed that systems equipped with an intermediate accumulator tank had improved thermal efficiency. These studies were conducted using flat-plate solar water-heating collectors in a solar heating system, as shown in Fig. 6.

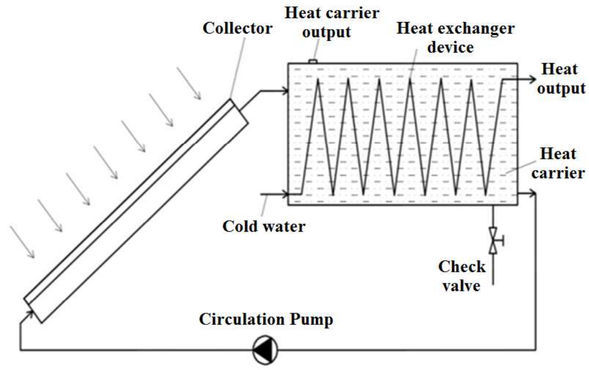

Fig. 6. Principal scheme of a double-circuit solar water heating system.

The principal scheme of the double-circuit solar water heating system, which includes a flat solar collector and intermediate tank, is presented in Figure 6. The research was conducted in Tashkent, and the experimental analysis was based on data obtained in December 2016 and January–February 2017. According to researchers, under the climatic conditions of Tashkent, when the ambient temperature ranged between 5 and 9°C, hot water with a temperature of 40–52°C could be obtained.

Solar heating and cooling systems combined with heat pumps were developed by Zakhidov and A.I. Anarbayev [14]. The technical and socioeconomic aspects of using such combined systems, which utilize solar energy to provide heating and cooling for residential buildings, were investigated. The principal scheme of the proposed system is shown in Fig. 7.

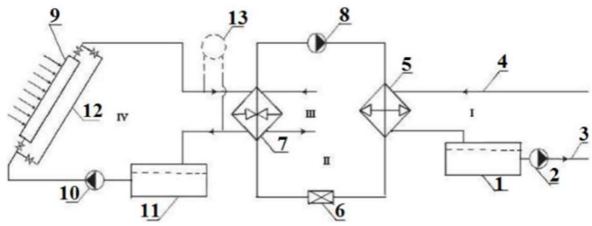

Fig. 7. Principal scheme of a low-temperature solar heat supply system combined with heat pumps:

1. Accumulator tank 2. Circulation pump 3, 4. Heat transfer and return pipes 3. Inq (inverter condensing) condenser and 4. Throttle 5. Evaporator 6. Compressor 7. Low-temperature solar collector 8. Pump 9. Ground heat exchanger for low-temperature heat accumulation 10. Cooling supply circuit 11. Circulation bypass pipe. Heat-carrier circulation circuit. II. Refrigerant circulation circuit. III. Water transfer circuit from the ground accumulator to the evaporator. IV. Solar energy utilization system using a solar collector.

4 Conclusions

Based on these studies, the efficiency of solar energy utilization and its technical-economic aspects under various climatic conditions were analyzed. Through the examined systems and methodologies, new technologies and systems adapted for efficient solar-energy use have been developed. In particular, it was shown that integrating solar heat supply systems, their combined variants, solar collectors, heat pumps, and photovoltaic panels can optimize energy consumption.

However, more information and clarity are required regarding the efficiency of certain systems, such as steam compression machines and heat exchangers. Additionally, the lack of consideration of specific climatic and extreme weather conditions (such as cloudy or foggy weather) indicates the need to improve the practical efficiency of existing systems.

Furthermore, the broader application of solar energy as a primary energy source, especially in the southern regions of our country, requires effective utilization of its high solar energy potential. In the future, a more in-depth analysis of the technical and economic aspects of solar energy use, along with the development of new approaches and technologies, will be of significant importance.

The results of this research and experiments also show promising prospects for future scientific work to enhance the efficiency of solar energy systems and adapt them to the climatic conditions of different regions. In turn, this can contribute to solving global issues related to environmental protection and energy resource conservation.

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