



INVESTIGATION OF ENERGY EFFICIENCY IN USING FLAT-PLATE SOLAR COLLECTORS FOR HEATING SYSTEM LOAD COVERAGE

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Abstract: *This article analyzes the energy efficiency of flat-plate solar collectors (FPSC) in heat supply systems. The thermal performance characteristics of modern flat-plate solar collector designs, their heat losses, and the factors affecting the efficiency coefficient are examined. The article also analyzes technical solutions such as equipping flat-plate solar collectors with thermal storage units and optimal pipe placement. The use of flat-plate solar collectors to cover heating loads creates opportunities to reduce consumption of traditional fossil fuels and ensure environmental sustainability.*

Keywords: *flat-plate solar collector, energy saving, heat losses, selective coating, thermal storage unit, nanofluids.*

1. INTRODUCTION

The growing global energy consumption and the limited reserves of fossil fuels are increasing the demand for alternative energy sources. The use of solar energy in the field of heat supply is considered a particularly promising direction. Flat-plate solar collectors are widely used in hot water supply and heating systems due to their structural simplicity, reliability, and relatively low cost.

The main advantages of flat-plate solar collectors are their durability (service life exceeding 20 years), pressure resistance (above 1.0 MPa), and adaptability to building architecture. However, the reduction in their efficiency under cold climatic conditions and increased heat losses remain one of the main challenges [4].

The objective of this study is to assess the energy-saving potential of flat-plate solar collectors in covering heating system loads, to analyze the factors affecting their efficiency, and to identify directions for improving energy performance.

2. RESEARCH METHODOLOGY

A flat-plate solar collector consists of four main components: a tempered glass cover with high transmittance, a selective absorber coating, a pipe network through which the heat-transfer fluid flows, and thermal insulation. Modern flat-plate solar collectors use low-iron glass that can transmit up to 94% of solar radiation [5]. This figure is significantly higher than that of conventional glass and has a positive effect on the overall efficiency of the collector.

Selective absorber coatings are applied by magnetron sputtering in a vacuum chamber. These coatings have the following characteristics:

- High absorptance ($\alpha > 0.95$) — absorbs more than 95% of incident solar radiation;
- Low emissivity ($\varepsilon < 0.10$) — minimizes heat re-emission from the collected thermal energy to the surroundings.

Table 1. Main Technical Parameters of the Flat-Plate Solar Collector

Parameter	Value
Dimensions	2000 × 1000 × 80 mm
Working pressure	0.6 MPa
Maximum temperature	100 °C
Peak efficiency	0.78
Thermal capacity	400–997 W/m ²
Fluid volume	1.6 L

The thermal efficiency of a flat-plate solar collector depends on a number of factors: solar radiation intensity, ambient temperature, wind speed, inlet temperature of the heat-transfer fluid, and flow rate. The following results were obtained from an experimental study conducted in Bucharest (Romania) during the winter–spring period of 2024–2025:

- Average monthly solar radiation: 420–620 W/m²;
- Wind speed: 1.5–3.5 m/s;
- Instantaneous efficiency: 30% to 75% (average 55–60%);
- Capacity utilization factor (CUF): 7%–11%.

Heat loss analysis showed that total heat losses range from 4.0 to 7.0 kW, with the largest share attributed to top-surface losses (3.0–5.2 kW). These results highlight the importance of improving insulation in the collector design [3].

Recent studies indicate that the use of Si₃N₄ water-based nanofluids can significantly improve the thermal efficiency of flat-plate solar collectors. Application of Si₃N₄ nanoparticles at a volumetric concentration of 0.09% yields the following results:

- Increases thermal conductivity by 33%;
- Improves thermal efficiency by 8%;
- Reduces the required collector area by 6.1%.

Equipping flat-plate solar collectors with thermal storage units is an effective method of increasing energy efficiency:

- Placing pipes inside a thermal storage material (bottom configuration) increases the average system efficiency by 8% compared to a conventional collector;
- Cumulative energy storage increases by approximately 12%;

- Pipe placement is the primary factor affecting efficiency — correct positioning is more important than increasing thermal capacity.

In modern flat-plate solar collectors, heat losses have been reduced to below 5%. This is achieved through the use of seamless insulation technology and high-quality thermal insulation materials (mineral wool, polyurethane foam) [6, 7].

The efficiency of flat-plate solar collectors varies depending on climatic conditions. Studies conducted in the Siberian region showed that the main challenge is the decrease in FPSC efficiency in cold weather and the high cost of evacuated tube collectors. At the same time, solar activity in these regions remains at a high level, which creates opportunities to improve efficiency through refinement of the collector design [12].

The effectiveness of the heat transfer process is assessed through the heat removal factor and the collector efficiency factor. These parameters depend on the geometric dimensions of the collector, the thermal conductivity of the materials, and the parameters of the heat-transfer fluid.

3. RESULTS AND DISCUSSION

3.1. Economic Efficiency Analysis

The economic efficiency of flat-plate solar collectors depends on a number of factors: initial capital investment, operating costs, conventional energy prices, and climatic conditions. The payback period when using nanofluids is 5.5 years, which is 15% shorter than for conventional systems. The use of FPSCs in large-scale projects (residential complexes, schools, hospitals, industrial enterprises) is considered most economically efficient [11].

Table 2. Energy-Saving Potential by Application Sector

Application Sector	Potential Energy Savings	Key Features
Residential complexes	High (40–60%)	Centralized hot water supply
Schools and hospitals	Moderate (30–50%)	Hot water supply during off-peak hours
Industrial facilities	High (50–70%)	Process water heating

3.2. Summary of Key Findings

Flat-plate solar collectors have significant energy-saving potential in covering heating system loads [10]. Modern FPSCs produced on the basis of advanced technologies offer the following advantages:

- High efficiency: up to 78% efficiency can be achieved through selective coatings ($\alpha > 0.95$) and low-emissivity coatings ($\varepsilon < 0.10$);
- Low heat losses: heat losses below 5% due to improved insulation;
- Innovative solutions: the use of nanofluids increases efficiency by 8%, and integration with PCM materials increases energy storage by 12%;
- Economic viability: payback period of 5–7 years, service life exceeding 20 years.

Analysis shows that copper-absorber collectors achieve the highest efficiency, but their cost is significantly higher than aluminum or steel alternatives. Also noteworthy is the fact that a smaller-area absorber (0.74 m²) outperforms in terms of exergy efficiency (13.21% vs. 10.85%). This implies that when analyzing energy quality, reducing collector size may improve the quality of energy conversion [9].

Evacuated flat-plate collectors (EFPC) allow a dramatic reduction in heat losses compared to conventional flat-plate collectors. According to the research results:

- Maximum thermal efficiency: 78% (in June);
- Maximum outlet temperature: 98 °C (summer), 69 °C (January);
- Peak useful power output: 1,300 W (January).

These results demonstrate the ability of the evacuated design to maintain high thermal output even during winter months.

3.3. Research Gaps Identified

Analysis of the Scopus database identified a shortage of research in the following areas:

- Geometric optimization — optimizing collector shape and dimensions;
- Phase change materials (PCM) — for thermal energy storage;
- Computational simulation — automated design and control;
- Exergy analysis — accounting for energy quality.

4. CONCLUSION

The energy efficiency of flat-plate solar collectors depends on their design, ambient conditions, and quality of system integration. The best results (up to 78% efficiency) were recorded with evacuated flat-plate collectors, although their payback period (7.4 years) is longer than that of standard variants. Most importantly, there is no single optimal collector — the choice must be determined by local solar radiation, required temperature, budget, and operating conditions [8].

The most significant finding of the research is that conventional flat-plate collectors have been proven capable of saving up to 53–57% of electrical energy under certain conditions. At the same time, innovative solutions such as geometric

optimization and PCM have yet to be thoroughly studied, and these areas have the potential to significantly improve system efficiency in the future.

From a practical standpoint, FPSC-based systems are economically justified particularly in remote rural areas where centralized gas supply is unavailable. Furthermore, the use of FPSCs in a hybrid scheme with other renewable energy sources (e.g., heat pumps) can further increase energy efficiency.

Future research on improving the energy efficiency of flat-plate solar collectors may continue in the following directions:

1. Development of next-generation selective coatings;
2. Creation of hybrid systems combining solar collectors with heat pumps;
3. Introduction of effective thermal accumulation methods using PCM;
4. Development of designs adapted to cold climatic conditions.

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