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Calculation of Energy Efficiency Indicators of the Combined Heat Supply System of Standard Houses Using Solar Energy

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ABSTRACT: Currently, the utilization of renewable solar energy in residential heating systems is one of the most pressing issues. This article examines the application of solar energy in the heat supply of model houses, specifically the use of solar-powered battery and water-based radiant floor heating systems in residential heating. It also presents the energy efficiency indicators of solar energy utilization in domestic hot water supply systems. Additionally, the study provides an assessment of the amount of energy saved and the reduction in heat energy consumption for conventional heating systems when solar energy is integrated into the heat supply system.

I. INTRODUCTION

Scientific research is being conducted worldwide to improve the heat supply systems of residential buildings by enhancing their energy efficiency through the optimization of thermal-technical parameters and the use of renewable energy sources. In this direction, priority is given to the development of energy-efficient heating systems for rural houses, reducing energy consumption in combined heat supply systems by effectively utilizing solar energy, and increasing energy efficiency. Consequently, special attention is paid to designing energy-saving combined heat supply systems with solar collectors for rural residential buildings and substantiating their key thermal-technical parameters [1-5].

Despite the positive scientific results achieved, there is still insufficient research on developing energy-efficient combined heat supply systems for rural houses located far from centralized heat supply networks, improving the energy efficiency of solar-based underfloor heating systems, and effectively utilizing low-potential solar heat in heat supply systems. Additionally, the issues of providing continuous heating energy during the heating season and year-round hot water supply for autonomous and local consumers have not been sufficiently addressed. Therefore, the development and optimization of an energy-efficient combined heat supply system with solar thermal equipment for rural houses remain an urgent scientific and technical issue [6-8].

To reduce the consumption of conventional fuel and energy resources (such as natural gas and coal) in rural prototype houses while ensuring uninterrupted heating energy supply, a combined heat supply system based on solar energy and conventional fuels has been developed. The proposed system ensures a continuous heat energy supply for residential buildings, enabling space heating through battery and underfloor heating systems, as well as year-round hot water provision.

II. MATERIALS AND METHODS

The energy efficiency indicators of implementing a combined heat supply system for rural houses based on renewable energy sources are evaluated based on the amount of saved equivalent fuel. The annual amount of saved equivalent fuel when utilizing a solar thermal supply system is determined using the following formula [9,15]:

$$B = \frac{3{,}6Q_y}{Q_q^i \eta_{q.q}} \qquad (1)$$

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where: Q_y – annual solar radiation amount, $MJ/year$; Q_q^i – lower heating value of equivalent fuel (assumed to be 29.31 MJ/kg); $\eta_{q.q}$ – efficiency of the boiler unit (typically assumed to be 0.55).
Table 1 presents the monthly and annual solar radiation values for the conditions of Qarshi city.

III. SYSTEM ANALYSIS

Table 1 presents the monthly and annual solar radiation values for the conditions of Qarshi city.

Table 1
Monthly and Annual Solar Radiation Intensity in Qarshi City, $J/month$ [10]

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Total
Solar radiation $MJ/month$	337	356	424	519	753	899	897	884	741	622	386	304	**7120**

Monthly Thermal Efficiency of the Solar Collector [11]:
The monthly thermal performance of a solar collector is determined using the following equation:

$$Q_f = Q_{oy} K_{q.h} F_k \eta_k \quad (2)$$

where: Q_{oy} – monthly solar radiation, MJ/year; $K_{q.h} = 1{,}23$ – average monthly conversion coefficient; F_k – surface area of the solar collector, m^2; η_k – efficiency of the solar collector.
The coefficient of heat load coverage by solar energy is given by the formula [11]:

$$f = \frac{Q_f}{Q_{i.yu}} \quad (3)$$

In Uzbekistan, one-story three-room houses based on the 184-46s-16 standard project, two-story four-room houses based on the 144-41s-16 standard project, and one-story four-room houses based on the 184-33s-10/13I standard project have been constructed. Ensuring a stable heat supply, especially for newly built rural houses located far from centralized energy networks, remains one of the pressing issues today.
A typical one-story, three-room house constructed according to the 184-46s-16 standard project has dimensions of 8.62 × 9.0 m with a 2.7 m ceiling height, including living rooms, a bathroom, a kitchen, and a hallway. The walls are made of solid bricks, and the floors are covered with laminate and ceramic tiles. The general view of the house, its front facade, and sectional diagrams are provided in Figure 1 and Section I.1.

Figure 1. General view of a one-story three-room house (based on the 184-46s-16 standard project)

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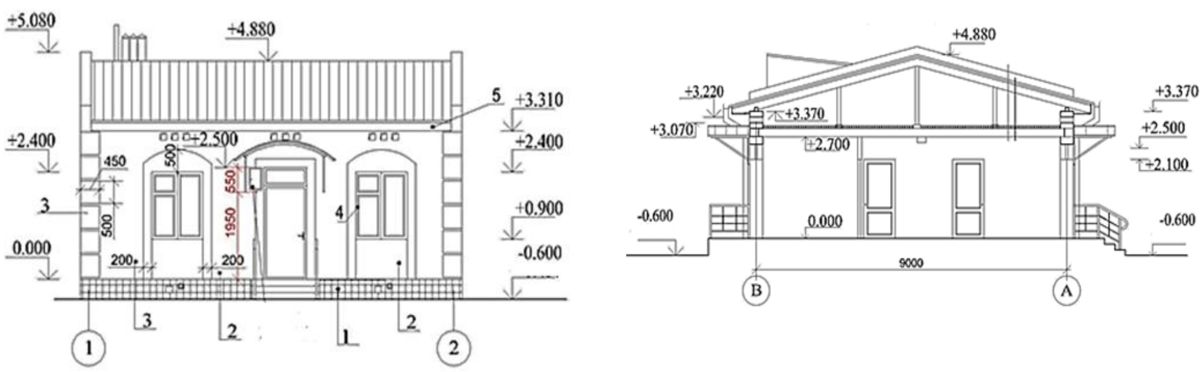

Front facade and sectional diagrams of a one-story three-room house built according to the 184-46s-16 standard project

Calculation of Energy Efficiency Indicators: A Case Study of a Three-Room Sample House

In this section, we will analyze the energy efficiency indicators of a three-room sample house. The dimensions of the house are as follows: length = 15 m, width = 11.5 m, and height = 2.7 m. The total window area is considered to be 10% of the total external wall area, represented as φ = 0.1. The heat transfer coefficients for various structural elements are as follows: for the walls, $k_{wall} = 1{,}2\frac{\mathrm{W}}{\mathrm{m}^2\cdot{}^\circ\mathrm{C}}$ for the windows, $k_{window} = 3.23\frac{\mathrm{W}}{\mathrm{m}^2\cdot{}^\circ\mathrm{C}}$ for the ceiling, $k_{ceiling} = 0{,}9\frac{\mathrm{W}}{\mathrm{m}^2\cdot{}^\circ\mathrm{C}}$, and for the floor, $k_{floor} = 0{,}77\ Vt/(m^2\cdot{}^\circ\mathrm{C})$ [12]. The temperature difference coefficients are as follows: $\psi_{wall} = \psi_{win} = 1$, $\psi_{sceiling} = 0{,}8$, and $\psi_{floor} = 0{,}6$. The internal air temperature is set at $t_{in} = 18℃$, while the external air temperature during the heating period is $t_{out} = -15℃$ [13,16].

1.External Wall Surface Area: The total external surface area of the house is calculated as:

$$F_{wall} = (15 + 11{,}5) \times 2 \times 2{,}7 \times 0{,}9 = 128{,}8\ m^2$$

2. Total Window Area: The total window area is calculated as:

$$F_{window} = (15 + 11{,}5) \times 2 \times 2{,}7 \times 0{,}1 = 14{,}3\ m^2$$

3. Total Ceiling and Floor Area: The areas of the ceiling and floor are given by::

$$F_{ceiling} = F_{floor} = 15 \times 11{,}5 = 172{,}5\ m^2$$

4. External Volume of the Building: The external volume of the building is:

$$V = 15 \times 11{,}5 \times 2{,}7 = 465{,}75\ m^3$$

5. Relative Heat Loss Through the External Wall: The relative heat loss through the external wall is defined as:

$$q_0 = \frac{\sum kF\psi}{V} = 0{,}9\frac{Vt}{(m^3\cdot{}^\circ\mathrm{C})}$$

6. Calculated Heat Loss Through the External Wall: The calculated heat loss through the external wall is:

$$Q'_y = q_0V(t_i - t_t) = 0{,}9\cdot 465{,}75(18 + 15) = 13{,}8\ kW$$

7. Living Area of the Building: The living area of the building is calculated as:

$$F_j = \frac{V}{K_h} = 72{,}8\ m^2$$

8. Internal Heat Dissipation: The internal heat dissipation is given by:

$$Q_{i.a} = q_{i.a}F_j = 20\cdot 72{,}8 = 1{,}456\ kW\ ;$$

9. Heat Loss Due to Infiltration: For an external temperature of $t_t = -15\hat{a}ll$, the heat loss due to infiltration is calculated as:

$$Q'_i = \mu Q'_y = b\sqrt{2gL\left(1 - \frac{T_t}{T_i}\right) + K_{aer}(w\beta)^2}Q'_y = 1{,}269\ kW;$$

Here, the constants are as follows.

- $b = 0{,}035\ s/m$; (a constant),
- $g = 9{,}81\ m/s^2 -$ (acceleration due to gravity);
- $L = 0{,}25\cdot 2{,}7 = 0{,}675\ m -$ (calculated height of the house),
- T_t, T_i – are the temperatures of the external and internal air, respectively, K;
- $K_{aer} = 0{,}6$;

- $w = 5\ m/s$ – (average wind speed),
- $\beta = 0{,}6$ – (a correction factor to account for wind speed and external air temperature mismatch).

10. Heating Load for the House: The total heating load for the house is the sum of the heat loss through the external wall, infiltration, and internal heat dissipation:

$$Q_i = Q_y' + Q_i' - Q_{i.a} = 49{,}68 + 4{,}57 - 5{,}24 = 49\,\frac{MJ}{hour}$$

11. Average Heating Load During the Heating Season: The average heating load during the heating season is expressed as::

$$Q_i^{avarage} = Q_i\,\frac{t_i - t_t^{avarage}}{t_i - t_t} = 49\,\frac{18 - t_t^{avarage}}{18+15} = 1{,}48\left(18 - t_t^{avarage}\right), \frac{MJ}{hour}$$

Table 2: Technical and Economic Indicators of the Heating System

Month	I	II	III	XI	XII	Total
Average external air temperature, °C	3,3	4,7	7,2	8,2	5,7	-
Number of days	31	28	10	30	31	130
Heat load, $Q_h, 10^3\ MJ/month$	16,19	13,23	3,84	10,44	13,54	57,24
Useful heat, $Q_{us}, 10^3\ MJ/month$	6,22	6,57	2,49	7,12	5,61	28,01
Compensation coefficient	0,38	0,51	0,64	0,84	0,39	0,55
Equivalent fuel consumption, kg of oil equivalent per year	1390	1469	557	1593	1254	6263
Electric energy equivalent of fuel, kWh	11305	11942	4529	12949	10198	50923

When an underfloor heating system is added to the heating system of a building, the heat load supplied through the underfloor heating system is calculated as follows:

$$Q_{i.p} = q_0 V(t_i - t_t) = 0{,}455 \cdot 465{,}75(18 + 13) = 6{,}56\ kW;$$

or 23.6 MJ per hour.

Here, $q_0 = 0{,}455\ kW/(m^3 \cdot °C)$ is the normative comparative characteristic of the heat consumption for heating systems in residential buildings with underfloor heating [14].

During the heating season of the year, the heat load on the underfloor heating system in the desired months is given in Table 3.

In the winter season, the heat load for the hot water supply is:

$$Q_{i.s.q}^{avarage.h} = \frac{GMc\rho(t_{i.s} - t_{s.s})}{n} = \frac{60 \times 5 \cdot 4190 \times 1(60-5)}{24} = 2{,}88\,\frac{MJ}{hour}$$

In the summer season, the heat load for the hot water supply is:

$$Q_{i.s.yo}^{avarage.h} = \frac{a\varphi_{yo}Mc(t_{i.s} - t_{s.s})}{n} = \frac{60 \times 0{,}8 \times 5 \cdot 4190(60-15)}{24} = 1{,}88\,\frac{MJ}{hour}$$

- $a = 60$ – is the average daily hot water consumption per person.
- c- is the specific heat capacity of water $J/(kg\hat{A} \cdot °C)$;
- $t_{i.s}$ – is the temperature of the hot water, 60°C.
- $t_{s.s}$ – is the temperature of the cold water: 5°C in winter and 15°C in summer.
- n – is the number of hours in a day.
- $\varphi_{yo} = 0{,}8$ – is the coefficient taking into account the reduction in hot water consumption for hot water supply in the summer season.

The heat load for the hot water supply system in any selected month of the year is presented in Table 4.

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Table 3
Energy Performance Indicators of the Underfloor Heating System

Month	I	II	III	XI	XII	Total
Average Outdoor Temperature, °C	3,3	4,7	7,2	8,2	5,7	
Number of Days	31	28	10	30	31	130
Heat Load, $MJ/month$	8,34	6,82	1,98	5,38	6,98	29,50
Useful Heat, $MJ/month$	3,21	3,39	1,29	3,68	2,9	14,47
Coverage Coefficient	0,38	0,51	0,64	0,84	0,39	0,55
Saved Equivalent Fuel, $kg.e.f./year$	718	759	288	823	648	3236
Equivalent Electrical Energy of Fuel, kWh	5841	6170	2340	6690	5269	26310

Table 4
Technical and Economic Indicators of the Hot Water Supply System

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Total
Average Outdoor Temperature, °C	3,3	4,7	7,2	18,1	22,3	27,7	30,4	27,5	21,9	15,7	8,2	5,7	
Number of Days	31	28	31	30	31	30	31	31	30	31	30	31	
Heat Load, MJ/month	2,14	1,94	1,64	1,35	1,40	1,35	1,40	1,40	1,35	1,40	2,07	2,14	18,63
Useful Heat, MJ/month	0,52	0,55	0,65	0,80	1,16	1,38	1,38	1,36	1,14	0,96	0,59	0,47	10,95
Coverage Coefficient	0,24	0,28	0,40	0,59	0,83	1,02	0,99	0,97	0,84	0,68	0,29	0,22	0,66
Saved Equivalent Fuel, kg.e.f./year	116	122	146	178	259	309	308	304	255	214	133	105	2449
Equivalent Electrical Energy of Fuel, kWh	942	995	1185	1451	2105	2513	2508	2471	2071	1739	1079	850	19909

IV. CONCLUSION

Conclusions Based on the Analysis of Technical and Economic Indicators
Utilizing solar energy for the heating system allows for an annual saving of 6,263 kg of equivalent fuel or 50,922 kWh of electrical energy, reducing the heat energy consumption of the traditional heating system by 55-60%.
The use of a hydronic underfloor heating system covers 51.55% of the total heat load of the building. If the underfloor heating system operates on solar energy, it enables an annual saving of 3,236 kg of equivalent fuel or 26,310 kWh of electrical energy, reducing the heat energy consumption of the conventional heating system by 55-60%.

Integrating solar energy into the hot water supply system results in an annual saving of 2,449 kg of equivalent fuel or 19,909 kWh of electrical energy, leading to a 65-70% reduction in heat energy consumption for hot water supply.

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