Comparative analysis of various heating sources for individual dwellings

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Abstract. In the modern world there is a huge variety of different options for heating systems that we can use in the design and construction of residential buildings. The choice of the most economically and technically advantageous heating system plays a big role for the further comfortable living of people. The article discusses the performance and cost effectiveness of various heating systems using modern materials and technologies in the conditions of the city of Irkutsk. Based on the calculations made, we performed an analysis of heating systems with various heat sources using the example of both classic water heating systems and various sources of electric heating from the already widespread underfloor heating to the less common infrared heating systems. We also considered the possibility of using alternative energy sources to cover the consumption of electricity when using electric heating.

1. Introduction

Heating systems used in individual dwellings have a number of features different from similar systems used in multi-apartment residential buildings, administrative and industrial buildings. It plays a major role whether a house is used all year round or seasonally. If we are talking about seasonal use or use on weekends, it makes sense to consider autonomous heating electrical appliances. However, more and more often, city dwellers choose life out of town, and in Russia there are a large number of small settlements mainly with individual dwellings, and to live a comfortable life one needs high-quality and, if possible, cost-effective life support systems.

The question of choosing the most optimal heating system in this situation becomes relevant and is considered by scientists [1].

Heating systems used in individual dwellings can be of various types, for example:
1) Water system
2) Air system
3) Electric system
4) Combined system

To choose the optimal system, it is necessary to focus on external factors:
1) Proximity of central heat supply systems
2) Uninterrupted power supply
3) Climatic features of the region of construction
4) Architectural features of the building
5) Financial capacity of residents

The combination of these factors usually dictates the choice of a heating system. The most popular is an autonomous heating system with a boiler and a water heater. The type of boiler is also selected...
depending on a number of factors. If the region is gasified, it makes sense to consider natural gas as fuel, as well as electric boilers or solid fuel boilers. Most often, the cost of electricity and power outages, especially in remote or new settlements, are a big problem, since the high rate of the construction of cottage villages is not always a guarantee of the timely construction of life support systems in them. This factor generally determines the choice of a combined boiler type that will operate using several heat sources.

However, currently on the market one can find is a wide selection of heating equipment suitable for individual dwellings. Water and electric underfloor heating is now being widely used. Recently, the use of panel radiant heating systems has gained popularity. The technology consists in heating objects and floors in a heated room with a stream of radiant energy carried by electromagnetic waves in the infrared range, due to this, the reflected heat is distributed from the bottom up to warm the air in the room [2]. Relatively recently, plinth heating systems have appeared that work similarly to the underfloor heating system, but nevertheless have their own features [3].

2. Methods
For the study, we used data on the thermotechnical characteristics of the equipment in question, which are publicly available on the official websites of manufacturers. Calculation of the required heat capacity was performed in accordance with [4,7]. The cost of equipment was taken at the prices indicated on the websites of manufacturers or dealers for the city of Irkutsk.

3. Experimental Part
To choose a system, we performed a thermotechnical calculation in accordance with [4].

The object of the study is a one-story individual dwelling located in the town of Slyudyanka, Irkutsk Region. Unlike the rest of the region, the climate in Slyudyanka is moderately continental, which is a consequence of its location on the shores of Lake Baikal.

Outside air parameters are determined for 3 seasons of the year: cold, transition and warm (Table 1). Data are taken according to [5].

| Season of the year | Air temperature, °C | Enthalpy, kJ/kg | Wind speed, m/s |
|-------------------|---------------------|-----------------|----------------|
| Cold (parameters B) | -28 | -37.1 | 2.8 |
| Transition | 8 | 26.5 | - |
| Warm (parameters A) | 21.8 | 50.2 | 2.2 |

Data for determining the internal air parameters are taken according to [6] for residential dwellings and structures, taking into account the category of a room (Table 2).

| No. | Name of a room       | Category of a room | tᵢ, °C | φ, %     |
|-----|----------------------|--------------------|--------|---------|
| 101 | Kitchen              | 1                  | 19     | No more than 60 |
| 102 | Guest room           | 1                  | 20     | No more than 60 |
| 103 | WC                   | 6                  | 18     | Not standardized |
| 104 | Bathroom             | –                  | 21     | Not standardized |
| 105 | Living (dining) room | 1                  | 21     | No more than 60 |
| 106 | Bedroom              | 1                  | 22     | No more than 60 |
| 107 | Nursery              | 1                  | 22     | No more than 60 |
| 108 | Hall                 | 1                  | 18     | No more than 60 |
Information about the object:
Region of construction – Slyudyanka.
Object - an individual dwelling.
Orientation of the building - the main facade to the southeast.
Number of floors - 1 floor with a height of 3.2 m
Building envelope - brick with external plaster.

When calculating heating systems, we considered the cold season. The selection of the calculated parameters of the outside air was made depending on the geographical location of the object, taking into account the requirements for the room.
Design outside air parameters, Slyudyanka
Average temperature of the heating season with an average daily outside temperature of less than 8 degrees - (-6.4)
Duration of the heating season – 254 days.
Wind speed – 1.5 m/s

Thermotechnical calculation of building envelope

\[ HSDD = (t_u - t_{h,s}) \cdot z_{h,s} = 253 \cdot (20 + 6.4) = 6705.6 \, ^\circ C \cdot \text{day} \]  \hspace{1cm} (1)

The calculation of the reduced heat transfer resistance is shown in Table 3.

| Envelope | Formula                        | Reduced heat transfer resistance, (m² ∙ °C)/W | Heat transfer coefficient, W/(m² ∙ °C) |
|----------|--------------------------------|---------------------------------------------|---------------------------------------|
| Wall     | 1.2+0.0003∙HSDD                | 3.21                                        | 0.31                                  |
| Door     | 0.6∙ (1.2+0.0003∙HSDD)         | 1.92                                        | 0.52                                  |
| Window   | 0.2+0.00005∙HSDD               | 0.53                                        | 1.88                                  |
| Ceiling  | 1.6+0.0004∙HSDD                | 4.28                                        | 0.23                                  |

The calculation of the reduced heat transfer resistance through the floor is based on the breakdown of the floor into zones. The entire floor area is divided into 4 zones, each of which is assigned a specific value of heat transfer resistance in accordance with [4]:

1 zone:
\[ R = 2.1 \, (m^2 \cdot ^\circ C)/W, \quad k = 0.476 \, W/(m^2 \cdot ^\circ C). \]

2 zone:
\[ R = 4.3 \, (m^2 \cdot ^\circ C)/W, \quad k = 0.232 \, W/(m^2 \cdot ^\circ C). \]

3 zone:
\[ R = 8.6 \, (m^2 \cdot ^\circ C)/W, \quad k = 0.116 \, W/(m^2 \cdot ^\circ C). \]

4 zone:
\[ R = 14.3 \, (m^2 \cdot ^\circ C)/W, \quad k = 0.07 \, W/(m^2 \cdot ^\circ C). \]

Heat loss through the underground part of the outer walls of the basements is determined by considering the underground part of the outer walls as an extension of the floors on the ground.

To determine the required amount of heat, we performed a thermotechnical calculation according to the methodology given in [7] based on the above characteristics in accordance with the plan of the residential dwelling (Figure 1).

As a result of the calculation, the total heat loss of the building amounted to 8347.3 watts.

To compensate for the calculated heat loss, it is necessary to provide a heating system equivalent in power.
First of all, we considered a traditional heating system with radiators. As radiators, we chose Rifar aluminum radiators made in Russia. Aluminum radiators are the most optimal solution for individual dwellings because of their relatively low cost in comparison with cast iron and bimetal radiators. Characteristics of the chosen radiators:

- Height 415 mm
- Width 324 mm
- Depth 90 mm
- Power 548 W
- Working pressure 20 Atmospheres
- Burst pressure 100 Atmospheres
- Center distance 350 mm

The number of sections of radiators chosen for various rooms is shown in Table 4.

| Room No. | Q, W  | t_i | t_s | Q_{app} | Number of sections |
|----------|-------|-----|-----|---------|-------------------|
| 101      | 891.3 | 19  | 95  | 1197    | 5                 |
| 102      | 947.8 | 20  | 95  | 1313    | 5                 |
| 104      | 429.5 | 21  | 95  | 602     | 2                 |
| 105      | 3305  | 21  | 95  | 4559    | 18                |
| 106      | 1168  | 22  | 95  | 1681    | 6                 |
| 107      | 1300  | 22  | 95  | 1859    | 7                 |
| 108      | 250.3 | 18  | 95  | 329     | 1                 |
| Total number of radiator sections | 44 |

The cost of such a heating system will consist of the cost of heating appliances, a boiler and pipelines, it will also include the cost of design and installation work as well as the cost of fuel used in
operation. In this work, we consider only the cost of the main equipment and the cost of fuel, without taking into account the cost of the system design and installation work.

The cost of one section of Rifar radiators in Irkutsk amounts to 650 rubles, hence the total cost of the required number of sections is 28,600 rubles.

Thermostatic equipment is installed on each radiator; its cost depends on the manufacturer. Let us accept the estimated cost of each set of equipment equal to 1,500 rubles. The total cost will amount to 12,000 rubles.

In the work, we used a combined solid fuel boiler “KVO 10 kW”, the cost of which in the city of Irkutsk amounts to 27,530 rubles.

Since the design of the water heating system was not carried out as part of the work, the cost of the pipes is assumed to be conventionally equal to 10,000 rubles. The cost of shut-off and control valves is not taken into account.

Thus, the total cost of the main equipment of such a system only will be about 80,000 rubles.

In the Slyudyanka Municipality, for the Administrative Forestry Enterprise of the Irkutsk Region, the limit prices for firewood - 1491 rubles for 1 m\(^3\) were set by the order of the Tariff Service dated August 2, 2018.

The cost of electricity for the rural population amounts to 0.777 rubles/kW.

From January 1, 2017, according to the methodology for calculating the annual consumption rates of solid fuel in the presence of furnace heating, the consumption rate of solid fuel for the Irkutsk Region amounts to 0.486 cubic meters per square meter per year (dense firewood). Thus, for our residential dwelling we get a rate of 53 m\(^3\). At the existing tariff, the cost will be 79,419.01 rubles.

When using a block of heating elements to maintain the temperature of the heat transfer medium, it is additionally necessary to take into account the cost of heating elements that are not included in the standard package of a boiler. For this boiler, it is possible to install a block of heating elements with a power of 6 kW. Considering the cost of electricity, the cost for the heating season, taking into account the operation of the heating elements at full capacity 10 hours a day, will amount to 11,934.72 rubles.

The low cost of electricity in the Irkutsk Region provides ample opportunities for the use of electrical systems. One of the possible options is a film heating system based on ceiling heaters (Figure 2). The basis of this system is infrared radiation, which is emitted by the elements of the film system when an electric current is applied to them. Infrared rays reach solid surfaces (walls, floors, furniture, etc.) and heat them, and they, in turn, give off heat to the surrounding space.

Advantages of a film heating system
1) Cost efficiency
2) Durability
3) Short payback period
4) Safety
5) High comfort
6) Versatility
7) High design potential
8) Quick installation

Disadvantages of a film heating system
1) Good thermal insulation of rooms (according to the requirements of the Construction Rules), otherwise the effectiveness of film heating drops sharply;
2) Power supply sufficient to operate the system;
3) Operating costs of film heating: the heating ceiling is 1.5 times greater than that of water heaters.
A film heating system is installed over the entire ceiling area of the room. Accordingly, for this object, the film consumption will amount to 56.68 m$^2$, if the system is installed in all rooms except bathrooms, subject to the recommended installation - 65% of the ceiling area.

The cost of 1 m$^2$ of ZEBRA EVO-300 film in the city of Irkutsk amounts to 1,349 rubles. Thus, the cost of the main equipment will be 76,461.32 rubles.

The energy consumption by this film heating system is 10-20 W∙h/m$^2$, based on the film consumption, the total electricity consumption at the maximum consumption will be 1.14 kW∙h, i.e. 6,949.44 kW for the heating season. Given the cost of electricity in the region, the cost of electricity for heating during the heating season will amount to 5,399.715 rubles.

The second non-standard heating system is a plinth type system (Figure 3). This system operates based on the Coanda effect, due to the low pressure generated at the surface, the flow of hot air transfers thermal energy to the wall. The subsequent uniform distribution of thermal energy over the room proceeds from the wall surface, creating a comfortable microclimate in the room [3].

This system is installed on the wall instead of the plinth, on the outer walls of the heated room. It is a series of heating elements consisting of copper pipes with brass fins interconnected and covered by an external aluminum profile. In the external duct formed by the slats, there are 2 horizontal slots. One of them is in the upper part near the wall itself, and the second is near the floor (Figure 3). The cold air penetrating into the duct is heated and, obeying the Coanda principle, is distributed along the wall surface, heating the wall material. And then the wall evenly radiates the accumulated heat. There is a liquid, electric and combined version of the system. In the liquid version, water or antifreeze act as the heat transfer medium; in the electric version, a tubular electric heater is inserted into the lower tube; the combined version can be used in the transition season of the year and allows for combining the the heat transfer liquid and electricity. The system is compatible with any type of boiler equipment, including alternative energy sources.
Advantages of plinth type heating:
1) Optimum heat flow
2) Exclusion of excessive humidity of the external walls
3) Thermally safe and injury free
4) Suitable for any floor covering
5) Compactness
6) Cost efficiency

Disadvantages of plinth heating
1) Sufficiently high initial cost, which also includes an expensive installation. You can install a plinth heating system by yourself, but the price of the heating system elements is due to the high cost of the materials they are made of;
2) You can not install decorative pads on the radiator, as they can significantly reduce heat transfer;
3) Radiators should be very tight against the wall, which often leads to warping of the film finish of the walls in the room;
4) The room with the installed plinth heating system must be kept more free, the plinths and walls should not be blocked with cabinet furniture. This may affect heating effectiveness.

The appliances are installed around the perimeter of the outer walls. For this residential dwelling, the number of heating appliances is 43 (in meters).

The cost of the main equipment in this system, as mentioned above, is quite high and varies depending on the size, characteristics, color of the case, and manufacturer. For example, combined systems are produced in Italy and the price of a running meter can reach 30,000 rubles. We do not consider this option since it is not suitable for heating in the winter season in our climatic conditions according to the characteristics of the manufacturer. For comparison, we take an electric plinth heating system of the Russian manufacturer mr. Tektum. The cost of one running meter in the assembly will be 5,900 rubles. Thus, the cost of the equipment for the entire object will be 253,700 rubles.

One running meter of the plinth consumes 1.92 kW per day, respectively, this will amount to 82.56 kW∙day for the entire system. Given the cost of electricity in the region, the cost for the heating season will be 16,293.88 rubles.

The next option is an autonomous heating system with an underfloor heating feature (Figure 4). This system consists of parallelly connected stainless rods powered by electricity. These rods are laid in the screed, and the finishing floors are laid on top of them. Let us consider EcoOndol, a variant of this system manufactured by Sammyung Tech (South Korea).
The rod is made of stainless steel, with a nichrome heating element installed inside. All the free space inside the rod is filled with magnesium oxide (MgO), a material accumulating heat.

**Figure 4. Structure of underfloor heating with EcoOndol.**

Characteristics of the heating rod:
- Working temperature: heating to 130° in ~10 minutes
- Rod length: 1 to 3.5 m (increment: 0.5 m)
- Number of rods in one section: 12 pieces
- Distance between the rods: 25 cm
- Rod diameter: 11 mm

Advantages of the system
1) Cost efficiency
2) Durability
3) Aesthetics
4) Autonomy
5) Versatility
6) Green operation
7) Safety

Disadvantages of the system
1) Dependency on uninterrupted power supply
2) Effectiveness of the system decreases with poor-quality insulation of building envelopes
3) Inability to dismantle this structure

A preliminary calculation of the cost of the heating system, taking into account the cost of thermostats in each heated room, showed that the cost of the equipment will be 355,720 rubles.

The average energy consumption per 1 m² of this system is 21 watts, so the energy consumption for the heating season will be 14,030.55 kW. The cost of electricity will amount to 10,901.74 rubles.

The graphs (Figure 5, 6) show a comparison of the calculated options.
In the Irkutsk Region, due to the sufficient amount of solar radiation, it is possible to use solar panels as a source of electricity, and a solar collector as a heat source, which may be relevant for remote areas, and also to reduce the cost of using the system in the future. Global trends and the effectiveness of using solar energy are shown in [8, 9, 10, 11]. Although in this case, the initial cost of the system will increase.

Based on the length of daylight hours in Slyudyanka [12] and the required amount of electricity, taking into account the consumption of electricity for household needs, we calculated the necessary number of solar collectors and solar panels. The Sokol-Effect solar collector, with an efficiency of 82%, was taken as a solar collector (SC) for the water heating system. The calculated amount of energy received from one solar collector ranged from 3.2 to 6.3 kW·h/m²·day for the heating season. The number of solar collectors is taken equal to 6, this number of collectors covers the need for heat for the most part of the year. According to preliminary estimates, the cost of such number of SC will be 327,060 rubles. Approximately 40% of the SC cost will be the cost of the tank, i.e. 130,824 rubles. It is also necessary to take into account the cost of pipes, connectors, etc. So, we add 20% of the collector cost. Thus, the cost of the system with SC will amount to about 523,296 rubles.

If we use heating systems that use electric energy, the installation of solar panels (SP) can reduce the cost of electricity in the future. A preliminary calculation of the number of SP was carried out taking into account the minimum cost of electricity for household needs and the cost of each system separately. The calculation result is shown in Table 5. The cost of SP was taken as 15,000 rubles for SP with a capacity of 300 W. It may vary slightly depending on the manufacturer.
Table 5. Number and cost of solar panels.

| System                  | cost of household needs, kW∙h/day | cost of heating, kW∙h/day | average load, kW∙h/day | number of SP | Cost of SP, rubles |
|-------------------------|-----------------------------------|---------------------------|------------------------|--------------|-------------------|
| Electric boiler         | 10                                | 48                        | 58                     | 63           | 945000            |
| Film heating system     | 10                                | 27.36                     | 37.36                  | 41           | 615000            |
| Plinth heating          | 10                                | 82.56                     | 92.56                  | 100          | 1500000           |
| Underfloor heating      | 10                                | 55.24                     | 65.24                  | 70           | 1050000           |

When using SP, there will also be costs for batteries to accumulate electricity for night time, and network inverters to convert the electricity received from SP and transfer it to the network. Additional equipment is also quite expensive, for example, one network inverter with a capacity of 15 kW costs about 150,000 rubles, while it is used for a maximum of 19 SP. Also, when using SP, an electric power generator is needed as a backup power source in case of prolonged cloudy weather and a possible shortage of electricity generated by SP to fully cover the demand.

The values given are preliminary. For a more detailed calculation, it is necessary to calculate each individual project in more detail, taking into account the characteristics of the location, type of SC or SP, and the installation method.

4. Summary and Conclusion

At the moment, there are many options for designing a heating system. Each of them has a number of advantages and disadvantages. Electric heating systems are efficient and quite cost-effective, however, it is worth considering the necessity of uninterrupted power supply. To ensure this condition, it is necessary to provide an individual dwelling with a backup diesel generator in case of an unexpected power outage. The results of preliminary calculations have shown the feasibility of using electric heating systems in relation to fuel costs. Currently, it is also quite advantageous to use solar collectors for heating. Due to the high consumption of electricity and its low cost in the region, the use of solar panels in terms of initial investments will be a very expensive solution, but perhaps newer developments and cheaper equipment will allow them to be used in the future.

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