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Efficiency of Using Heat Pumps for Heat Supply of Low-Storied Housing Areas

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Abstract—Results of technical and economical comparison of competing schemes of heat supply to low-storied housing areas for different regions of Russia are presented. Limitations on using heat pumps for these purposes are analyzed.

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Housing systems are one of the largest consumers of fuel and energy resources (FER) in the country [1]. In 2009, about 2116 million GJ of heat was spent for centralized heat supply of housing systems and more than 70 million t.c.e. of fuel of different kinds, mainly natural gas (52 million t.c.e.), was used for heating and hot water supply (HWS) of low-storied housing areas.

It is forecasted that construction of residential buildings will be intensified in the future. In this connection we can anticipate that the needs of the population in fuel and energy will increase. At the same time, we must pay attention to two important trends: a rise in the volume of low-storied housing constructions and an increase in the population's requirements for the quality of living conditions. In 1995–2009, the annual commissioning of low-storied residential houses increased from 9 to 28 million m^2. In recent years, the share of low-storied houses in the total volume of the houses commissioned was within 40–47% and the trend for the growth of this figure was clearly seen. The Government of the Russian Federation actively supports the course on further increase in the volume of low-storied house construction. If the program of residential-housing construction is fulfilled, the annual increase in the low-storied housing fund in the country can reach 50–60 million m^2 per year until 2020.

The level of accomplishment of residential housing in the country is constantly being increased. For example, from 1990 to 2009, the provision of the residential-housing fund for hot water increased from 51.2 to 64.6%, including that of cities from 67 to 79.9% and of rural areas, from 8.9 to 24.7%. During the same period of time, the level of provision of residential-housing fund for centralized heating increased from 64.9 to 82.6%, including that of cities, from 83.9 to 91.7% and that of rural areas, from 18.5 to 58.9% [2].

It is anticipated that in the near future tariffs for natural gas and electricity in the country will considerably increase. This fact can sharply aggravate the problem of the high cost of the provision with heat of low-storied residential buildings having independent heat supply systems, which already exists. At the same time, in this sector, there exist rather many competing technologies, which are based on using different kinds of FER. Therefore, the objective of the choice of the most economically promising technologies in this field becomes more and more acute.

Among the technologies of provision with heat of low-storied building areas heat pumps seem to be very attractive. This makes it possible to usefully utilize natural sources of low-potential heat (ground itself, underground waters, surface water basins, atmospheric air) and thus to save fossil fuel and electricity, the costs of which permanently grow. With the use of a heat pump unit (HPU) heat is extracted from a low-potential heat source and transferred (using working fluid) to a consumer. In so doing, a temperature of the working fluid is increased. Spending 1 kW of electric (or mechanical) power for driving heat pumps we can obtain 3–4, and up to 5–6 kW under certain conditions, of thermal power at a consumer's side. It is necessary to note that in HPU electricity is spent not for generating heat, as in an electric heater, but for the working-fluid compression and circulation. Naturally, in a real compression process, part of electricity consumed is spent for heating the working fluid. Nevertheless, the main part of heat supplied to a consumer (65–80%) is transferred ("pumped") from a low-potential source.

In addition to saving of the purchased energy, HPUs have certain other attractive consumption properties. These installations are environmentally friendly, explosion and fire safe. They can be serviced in a completely automated mode, and their servicing comprises only seasonal technical inspection and periodic control. The HPU's lifetime until it needs an overhaul reaches 20–25 years [3]. The main shortcoming of GTU is, apparently, its high cost.

Abroad, heat-pump technology has been widely used for heating residential and office buildings for more than 30 years. The start was in the 1970s during the world energy crisis that gave a pulse for heat-pump technology development. By 2003, the amount of heat pumps using ground heat reached 1.1 million units. Their total installed capacity was 12 GW and annual production of heat was 72 GJ (20 000 thousand GWh) [4]. Annual increments in HPU commissioning reached 10%. The world leaders in introducing of such type HPUs are USA (600 000 units, 6.3 GW) and Sweden (230 000 units, 2.3 GW). A great amount of HPUs is in operation in Japan, Germany, and Switzerland. Recently, ground HPUs intensively began to be used in China. An increase in prices for energy continues to encourage introducing of HPUs in the world market. At the present time, in the USA, about 50 000 HPUs of different types are annually commissioned, and the payback time for these installations is 5–10 years [3].

In many countries, wide application of HPUs was promoted by relatively soft climate, which allows use of low-temperature heating systems, environmental legislation, and the requirements of energy policy of certain countries regarding reducing green-house gas emissions and increasing the efficiency of energy production and usage. However, the most important factor is direct support of the State's institutions of HPUs market development. The companies, which propose environmentally clean installations have certain tax privileges while house owners that buy such equipment obtain grants, subsidies, and privileges for credits.

Abroad, to supply heat to low-storied buildings HPUs which extract ground heat are more and more widely used. An external circuit of these HPUs is formed by a set of loops, usually made of polymeric tubes with nonfreezing heat-transfer agent circulating through them. These loops constitute a horizontal collector or vertical borehole. The advantage of the horizontal collector is its relatively low cost, however, free land space of significant area is needed to arrange such a collector. In the future, this space will almost be completely lost for house holding. In particular, constructions should not be erected and trees and bushes should not be planted on this space. A vertical borehole is located in a specially drilled well, the depth of which is determined by thermophysical properties of the ground and usually is equal to 50–100 m and more. With the same heat output, a vertical borehole costs many times greater than a horizontal collector. However, if there are limitations in space to arrange the collector, one has no alternatives than to choose the vertical borehole. Presently, in systems of individual heat supply, HPUs with vertical boreholes become increasingly widespread. The lifetime of modern systems of ground-heat extraction is 50 years and more, for both collectors and boreholes [3].

In Russia, the experience from using HPUs for heat supply is small so far. This is caused by objective reasons, both economical and technological ones. We have studied the influence of the most important factors on the effectiveness of using HPUs for heat supply to low-storied building areas under Russian climatic conditions. Three regions were considered, the climatic conditions of which correspond to Arkhangel'sk (the North), Moscow (the Central region), and Pyatigorsk (the South).

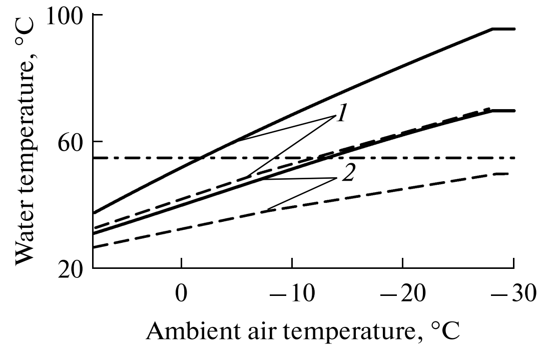

Fig. 1. Dependence of direct and return water temperatures in the heat supply systems on the ambient air temperature (the conditions of Moscow). (*1*) High-temperature system (95/70°C); (*2*) low-temperature system (70/50°C); — direct water; --- return water; -·-·- maximum water temperature at the outlet from HPU.

Conditions of Using HPUs for Heat Supply of Low-Storied Building Areas

We can separate five conditions which have the most significant effect on the efficiency of using HPUs for heat supply of low-storied residential building areas.

Limitations on the temperature of the heat-transfer agent at the outlet from a heat pump. The maximal temperature of the heated coolant, which can be provided by a heat pump, is determined, first of all, by thermophysical properties of the HPU's working fluid. Usually, it is 55°C; in some HPU models, it is 60–65°C. At the same time, in Russia, heat supply systems that operate according to the water temperature schedule of 95/70°C are most widely used for heating residential buildings. These systems are based on a single heat source that provides meeting the maximal heat load. In these systems qualitative method of heat load control is applied (as the simplest one) and high parameters of the heat-supply agent are used (to provide saving with heat release devices). In such systems water temperatures in direct and return mains depend on the temperature of the ambient air (t_{air}) and at maximal load they are equal to 95 and 70°C, respectively (Fig. 1).

For the conditions of Moscow [5, 6], while maintaining an air temperature in the heated apartments at the standard level (20–22°C), at $t_{air} \leq -12$°C, the water temperature in the return mains will be higher than that heat pump can provide (see Fig. 1). This means that the HPU will be practically switched-off from the heat-supply system and the entire heat load

Table 1. Limits of using HPU for covering heat-supply load at different regions of Russia

Indicator	North	Center	South
Rated temperature of the ambient air for designing heat-supply systems, °C	–31	–28	–20
Mean temperature of the heating period, °C	–4.4	–3.1	0.9
Duration of the heating period, h/year	6072	5136	4200
Limiting temperature of the ambient air for using HPU (with respect to return-water temperature), °C	$\frac{-14}{<-31}$	$\frac{-12}{<-28}$	$\frac{-7}{<-20}$
Limiting duration of using HPU (with respect to return-water temperature), h/year	$\frac{4900}{6072}$	$\frac{4365}{5136}$	$\frac{3595}{4200}$
The same, % of duration of the heating season	$\frac{81}{100}$	$\frac{85}{100}$	$\frac{86}{100}$
Minimal temperature of the ambient air for independent operation of HPU, °C	$\frac{-3}{-15}$	$\frac{-2}{-13}$	$\frac{1}{-9}$
Duration of using HPU in independent operation mode, h/year	$\frac{2785}{5010}$	$\frac{2570}{4480}$	$\frac{1928}{3805}$
The same, % of duration of the heating season	$\frac{46}{83}$	$\frac{50}{87}$	$\frac{46}{91}$

Note: Numerator gives the values for 95/70°C temperature schedule, denominator, the values for 70/50°C temperature schedule.

must be covered from an additional heat source. Thus, the limitations with respect to return-water temperature determine the conditions, at which the HPU is switched-off.

The range of independent (without connection to the peak heat source) operation of HPU in heat supply systems is determined by the limitations with respect to direct-water temperature. For the conditions of Moscow, the minimal temperature of the ambient air (t_{air}^{min}), at which direct-water temperature is equal to the maximal water temperature provided by the HPU is –2°C, for the heat-supply system with a temperature schedule of 95/70°C (see Fig. 1). When this happens, the heat capacity of the HPU reaches its maximum. For the regions under consideration, the value of t_{air}^{min} when the heat load can be covered only by HPU, varies from +1 at the South to –3°C, at the North. These figures are considerably higher than the rated temperature for designing heat-supply systems (Table 1). Therefore, HPUs can completely cover the heat load required by a consumer only during 46–50% of the heating period. In the rest of the time, at lower temperatures of the ambient air, a peak or redundant heat source (gas-fired boiler or electric heater) must be switched-on into operation. The HPU can provide hot-water load during the entire year since it ensures the rated hot-water temperature (55°C).

To increase the effectiveness of using available HPU capacity and expand the range of its independent operation (as to t_{air} range), it is necessary to change over to low-temperature heating systems. With the 70/50°C temperature schedule it is possible to completely cover the required heating load during 83–91% of the heating season, depending on the region under consideration (see Table 1). However, when so doing, the heat-transfer area of the heating devices in the buildings should be increased (because of a decrease in the available temperature difference in them), which will lead to additional expenses. In the system with the 70/50°C temperature schedule minimal t_{air} for covering the heat load only with the use of HPU decreases and constitutes from –9, at the South, to –15°C, at the North.

Arrangement decisions on HPU application. As to the sequence of switching-on the HPU and a peak source of heat, all possible heat-supply schemes for low-storied building areas with the use of HPUs can be subdivided on series and parallel.

In a series scheme of connecting the sources of heat to a traditional heat-supply system of a building with radiators (Fig. 2a), the heat pump is in independent operation up to the appearance of limitation with respect to direct-water temperature. At this moment the HPU operates with maximum heat output. At colder weather, the peak source of heat is switched-on in operation; the heat supply from HPU becomes to decrease (because of an increase in the return-water temperature). When the limit with respect to return-water temperature is reached, the HPU forcedly switches-off from the heating system and only a peak (redundant, in principle) source of heat remains to be in operation. Therefore, the peak heat source is forcedly designed on the maximal consumer's heat load. The advantage of this scheme is the possibility to connect a HPU to the existing system of heating the building, while the main shortage is a decrease in the effectiveness of HPU use. Hot-water load can be covered by the HPU during the entire year. This is the case for the parallel scheme of connecting heat sources, as well.

In the parallel scheme of heat source connection (Figs. 2b, 2c), the heat pump is in operation in the heating system during the entire heating season. When this happens, up to the ambient-air temperature corresponding to the limit with respect to direct-water temperature (–2°C in Moscow with 95/70°C temperature schedule) the heat pump operates in the independent mode and reaches its maximal output at this temperature (Fig. 3). At lower temperatures of the ambient air, the heat pump continues to operate with maximum output, while the heat lacking to support standardized air temperature in the heated apartments is generated with the peak heat source. Boilers burning

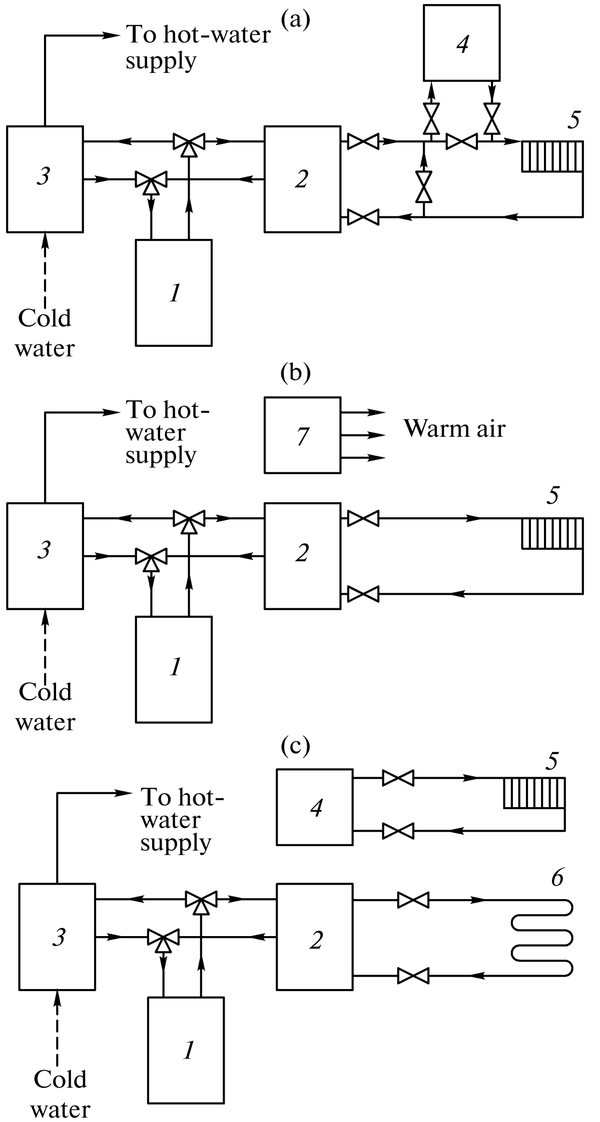

Fig. 2. Heat-supply schemes for individual house with HPU. (a) Series scheme with electric boiler; (b) parallel scheme with radiators and convector; and (c) parallel scheme with "warm floor" and electric boiler. (*1*) heat pump; (*2*) intermediate tank; (*3*) accumulating water heater for hot-water supply; (*4*) electric boiler; (*5*) heating system with radiators; (*6*) "warm floor" heating system; (*7*) electric convectors.

gaseous, liquid, or solid fuel, electric boiler (EB), and convective and infrared electric heaters can be used as such peak heaters.

The following two schemes of HPU parallel connection were considered:

(i) with a water heating system for 55/40°C parameters with radiators having an extended heat-transfer area and peak electric convector (see Fig. 2b) and

(ii) with a "warm floor" system and peak electric boiler with its own water circuit (95/70°C temperature schedule) and usual radiators (see Fig. 2c).

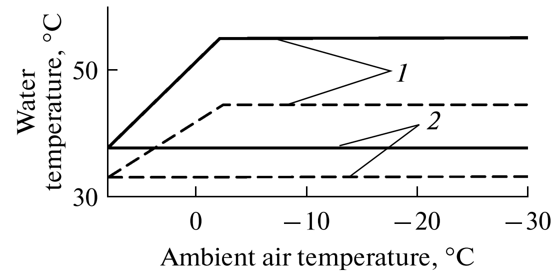

Fig. 3. Temperatures of direct and return water in parallel schemes of heating with HPU (for the conditions of Moscow). (*1*) system with radiators; (*2*) "warm floor" system; — direct water; --- return water.

We should note that, under the conditions of cold climate, the second scheme has additional limitation, i.e., the value of useful heat power that can be obtained from the system "warm floor."

The low-temperature heating system "warm floor" generates a heat flowrate of 50–150 W/m^2 at a temperature of the heating agent of 35–55°C. This heat flowrate depends on the construction arrangement of the system: the diameter and pitch of the tube stacking and thickness and heat conductivity of concretion and floor coating. When so doing, additional limitations appear, which are put on the interior elements: it is not recommended to use carpet coatings and it is desirable to not change the original plan of furniture arrangement. According to SNiP (Construction Norms and Rules) [7], the mean temperature of the floors in apartments with permanent attendance of people should not be greater than 26°C. Therefore, the HPU with the "warm floor" system will operate under the conditions of practically constant temperature of direct and return water during the entire heating period (Fig. 3). The total capacity of the underfloor heating system is determined by the heat flowrate released and the area of the tube stacking. When a "warm floor" is constructed it is necessary to provide proper distance between walls and a boundary of the tube-stacking area. Therefore, in the general case, the maximum "warm floor" area constitutes 60–70% of the heated one. We should also note that, under the conditions of the cold climate of Russia, high inertia of the underfloor heating system does not allow promptly controlling heat release at a sharp decrease in the ambient air temperature by 10–15°C. Therefore, while applying the "warm floor" heating system it is thought to be advisable to have additional thermal blanketing enclosing elements of the building, which, naturally, will require additional expenses.

A principal distinction in the effectiveness of using HPUs with different schemes of their arrangement is shown in Fig. 4. With series arrangement a HPU operates for heating only in zone *2.* In zones *3* and *4* heating loads are covered by a redundant source. With parallel arrangement the region of HPU operation prop-

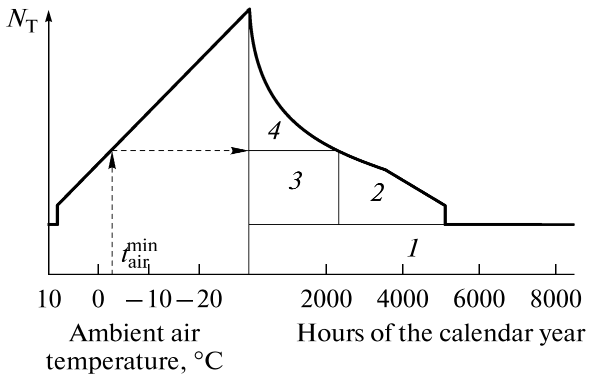

Fig. 4. Zones of HPU operation at the diagram of heat loads duration.

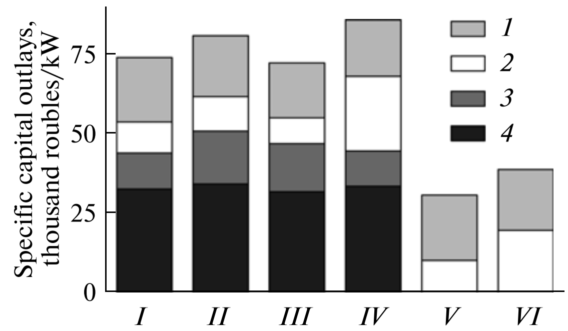

Fig. 5. Specific outlays in alternative versions of heat-supply (for the conditions of Moscow). (*I*) HPU with redundant electric boiler (EB) (90/70°C temperature schedule); (*II*) HPU with redundant EB (70/50°C schedule); (*III*) HPU with peak convector; (*IV*) HPU with "warm floor" system and peak EB; (*V*) one EB; (*VI*) one gas boiler; (*1*) substation, gas-distribution station; (*2*) electric or gas boiler and radiators; (*3*) drilling; (*4*) HPU with assembling works.

agates to zones *2* and *3*. The peak heat source operates only in zone *4*. Zone *1* is the area of the year-round covering of hot-water loads with the use of the HPU.

Thus, under the conditions of Russia, with any arrangement of the HPU for heating a low-storied building area, it is necessary to install a peak source of heat and additional heat transfer surfaces, the type and heating capacity of which are determined by optimization calculations with an account for climatic and cost factors in each particular case.

High specific capital investments in a HPU. Presently, the HPU market is only under development. It includes mainly heat pumps manufactured abroad (in Germany, Austria, and the USA) and they are rather expensive. In addition to the high cost of the main equipment, its assembling and adjustment, HPUs with a vertical borehole require very expensive drilling works. For the conditions of the central regions of the country the cost of this work is assessed as 1800–3000 rubles per running meter of the well and it depends on geological characteristics of the site and drilling depth.

We have made assessments of specific outlays into competing heat-supply systems of low-storied building areas ("turnkey" construction) (Fig. 5). Calculation studies were conducted regarding a settlement comprising 200 houses of 200 m^2 living area each, which are equipped with individual heat supply systems that provide heating and hot-water delivery. The amount of population permanently living in the settlement is 800 persons. The heat indicators of buildings meet the requirements of Standards [8]. Each house is located on the territory of 1000 m^2. The total area of the settlement is 0.2 km^2. The distance between the settlement and the nearest 35 kV sub-station of the electric grid is 10 km and that from the gas mains (1.2 MPa) is 10 km also.

Six alternatives of the building heat-supply systems are considered, namely: four alternatives with a HPU (with a vertical borehole) and two, with traditional individual heat-supply sources, i.e., gas and electric boilers. In the calculations, the outlays in the common for the settlement energy infrastructure (electric substation, gas-distribution station (GDS), overhead electric lines and a gas pipe) were accounted for. From Fig. 5 we see that all the alternatives with the use of a HPU are 2.4–2.8 times more expensive as compared to the traditional system with a gas boiler. The alternative of a HPU with a "warm floor" heating system appeared to be the most expensive.

Due to high specific outlays it is expedient to use the HPU for covering the base part of the rated heat load and to cover the rest of the load using a cheaper peak heater. Determination of the share of the HPU in the total heat load of consumers is an optimization problem. The result depends on several factors: heat-load structure (heating and hot-water supply), a "density" of the diagram of the ambient-air temperature distribution in time in the region, a chosen arrangement of the heat-supply system for the given building, a correlation between the costs of HPU and peak heater, and costs for electricity, gas, and others fuels in the region.

Effect of climatic factors on the ground temperature. A very important factor that determines the effectiveness of HPU operation is the ground temperature. For the near surface layers of the ground it is formed by climatic parameters (a density of incident solar irradiation and a temperature of the atmospheric air) and a flowrate of the radiogenic heat from the earth depths. Characteristics of the underlining surface, first of all, a thickness of the snow bed and duration of its existence, as well as thermophysical properties of the ground stratified over its depth are also very important. The influence of seasonal variations in climatic conditions [5, 6] is perceptible only in the upper layer of the ground, down to 5–10 m (Fig. 6). Below this level, the ground temperature is formed practically due to the effect of the depth heat and experiences no seasonal fluctuations. Ground temperature at the lower boundary of the zone of its fluctuations approximately corresponds to the annually averaged temperature of the ground surface; it is only by 1–3°C higher due to heat insulating properties of the underlining surface.

Seasonal fluctuations of the ground temperature considerably limit the effectiveness of using HPUs with horizontal collectors under Russian climatic conditions, especially in northern regions. This factor should be accounted for while designing HPUs for supplying heat to low-storied building areas.

With other conditions (heat conductivity, density, specific heat, and humidity of the ground, as well as the flowrate of the depth heat) being equal, annually averaged climatic indicators determine the differences in the ground temperature at the working depth of the HPU's vertical borehole in different regions. In south regions the ground temperature will be greater than that in the north regions (see Fig. 6). It is known that the higher the ground temperature, the greater the HPU's transformation coefficient, which is calculated by the following formula

$$\varphi = Q/N_{HPU} = (h_2 - h_3)/(h_2 - h_1),$$

where Q is the HPU's heat power; N_{HPU} is the electric power consumed by the HPU's compressor; h_1, h_2, and h_3 are the enthalpies of the working medium at the beginning and the end of the compression process, and at the end of heat transferring to the heated agent.

Table 2 presents the calculated data on the annually averaged ground temperature at a depth of 50 m and 100 m for different regions of the country, which have been obtained at comparable conditions. In this same table the data on annually averaged values of transformation coefficients of HPU with the borehole depth of 100 m, which correspond to the above ground temperatures, are also presented. This data were calculated on the basis of working performance of the Vitocal 300 heat pump (Germany). It is known that the higher the annually averaged transformation coefficient, the less electric energy is spent in HPU for producing one and the same amount of heat. Specific heat flowrate for the vertical borehole for all regions was taken equal to 50 W per 1 current meter.

Cooling of the ground in the course of HPU operation. The removal of thermal energy during a heating season from the ground body causes a decrease in temperature in it, especially near the tubes of the heat collection system [9, 10]. During summer the heat potential of the ground does not have sufficient time to recover. This is especially the case for Russia with its short summer almost in the entire territory of the country. Therefore, at the beginning of the next heating season the ground has reduced temperature. This factor is weaker at the South than that at the North. Removal of heat during the next heating season causes further cooling of the ground. The effect of many years

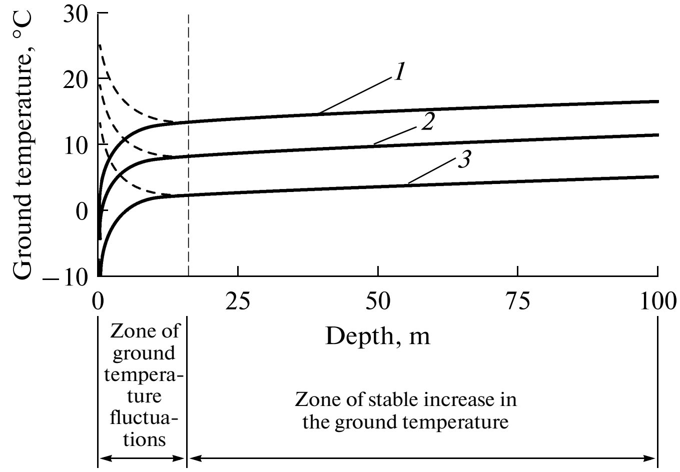

Fig. 6. Distribution of the ground temperature in depth (with an account for seasonal fluctuations). (*1*) South; (*2*) Center; (*3*) North; — winter; - - - summer.

of operation of a HPU on natural ground temperature is exponential in nature [9, 10]. Relative stabilization of the temperature value occurs approximately in 5–7 years of operation, with the ground temperature being reduced by approximately 1.5°C. When designing heat-supply systems on the HPU basis the above effect should be accounted for and the design ground temperature should be taken as that anticipated at the 6–8th year of operation [9–11]. The presence of the effect of reducing ground potential with respect to heat removal decreases the effectiveness of HPU application under the climatic conditions of Russia.

Economic Efficiency of HPU Application

A search for the most economically efficient scheme of individual heat-supply system for a low-storied building area was performed by sorting out alternatives

$$i_{opt} = i(\min C_i), \quad i = 1, \ldots, n,$$

where i_{opt} is the number of the most efficient alternative, C_i are the total discounted expenses in the i-th alternative, and n is the number of alternatives.

Minimum of total discounted expenses into a heat supply system of a cottage settlement during the design

Table 2. Ground temperature and transformation coefficient of HPU

Indicator	North	Center	South
Ground temperature at a depth of 50/100 m, °C	4/5	10/11	15/16
Annually averaged transformation coefficient of HPU with a borehole of 100 m in depth	2.9	3.2	3.5

Table 3. Consumption of electricity for heat supply of the settlement, million kWh/year (numerator) and electric power of the settlement's heat-supply system, MW (denominator)

Heat source	North	Center	South
Electric boiler	18.7/7.6	12.9/6.6	9.5/5.6
HPU with redundant EB (95/70°C temperature schedule)	11.5/7.6	7.4/6.6	5.7/5.6
HPU with redundant EB (70/50°C temperature schedule)	7.5/6.8	5.4/6.0	3.2/5.0
HPU with peak convector*	7.0/6.0	4.4/4.9	3.0/4.7
HPU with "warm floor" system and peak EB	8.2/6.1	4.7/5.1	2.9/4.2

* With the basic share of heating load obtained as a result of optimization calculations and constituting 50%, for the North, 60%, for the Center, and 40%, for the South.

Table 4. Total discounted expenses for heat supply to the settlement during the calculated period, million roubles

Heat source	North	Center	South
Gas-fired boiler	280	245	218
Electric boiler	475	364	329
HPU with redundant EB (95/70°C temperature schedule)	599	471	431
HPU with redundant EB (70/50°C temperature schedule)	529	473	385
HPU with peak convector	483	411	363
HPU with "warm floor" system and peak EB	554	472	423

period, which was taken to be 30 years, was assumed as the criterion of optimization. This same criterion was used in problems of determining the optimal basic share of HPU load and optimal temperature regime for each of the schemes considered. The alternatives compared differ only in the part of expenditures and incomes; therefore, a variable part of expenditures was taken into account while solving optimization problems. The total expenditures for each of the alternatives considered were determined by discounting all expenses and incomes by the years of the design period with constant discount rate

$$C_i = \sum_{t=1}^{T_c} (K_{it} + I_{it})(1 + E_d)^{-t}, \quad i = 1, \dots, n,$$

where K_{it} are the investments in the i-th alternative in the t-th year; I_{it} are operational expenses and (or) income in the i-th alternative in the t-th year; E_d is the discount rate; and T_c is the calculation period.

While varying basic (provided by the heat pump) and peak shares of the heating load, different heat-supply alternatives have different demand for the announced electric power of the settlement. In this respect, to ensure comparability of the alternatives, the differences in expenditures in electric grids and substation were accounted for. The calculation of investments into generating and electric grid elements was conducted using specific indexes that reflect the currently existing level of prices on the market of equipment (Fig. 5). The following tariffs for electricity were assumed: the North, 1.79; the Center, 1.69, and the South, 2.00 roubles/(kW h); and those for natural gas: the North, 2583; the Center, 2535; and the South, 2580 roubles/thousand m^3.

Table 3 presents the total consumption of electricity for supplying heat to the cottage settlement for the alternatives under comparison. We see from this table that the use of HPUs provides saving of electricity as compared with electric boilers in all alternatives. When this happens, in the north and central regions of the country, the scheme of a HPU with a peak convector appears to be the most energy efficient. It provides 2.7–2.9-fold decrease in electricity consumption as compared to the case of electric heating. In south regions, the schemes of HPUs with "warm floor" systems become more advantageous, they make it possible to reduce electricity consumption by 3.3 times.

In schemes using a HPU we also see a decrease in the announced electric power by approximately 21–26% (see Table 3), which reduces electric load in the electric system and provides saving expenses for connection to the grid. The series scheme of HPU arrangement with 95/70°C temperature schedule represents an exception because of the necessity to install an electric boiler for the full heat load.

With current tariffs for electricity and the levels of specific capital investments for heat sources, the use of HPUs for heat supply of low-storied building areas appears to be economically unjustified. In Table 4 we see the calculated values of the total discounted expenses for competitive alternatives of the settlement heat supply for the calculated period (30 years) with the discount rate being 10% ($E_d = 0.1$) for economic conditions of 2010. From the analysis of the results obtained it follows that in settlements covered by the natural-gas grid, HPUs cannot compete with gas-fired boilers in heat-supply systems; HPUs can be an alternative to electric boilers only. However, in this case also, even with the optimal choice of the scheme, temperature schedule, and heat-transfer surfaces, the total discounted expenses for a HPU-based heat-supply system appear to be greater than those for the heat-supply system based on electric boilers.

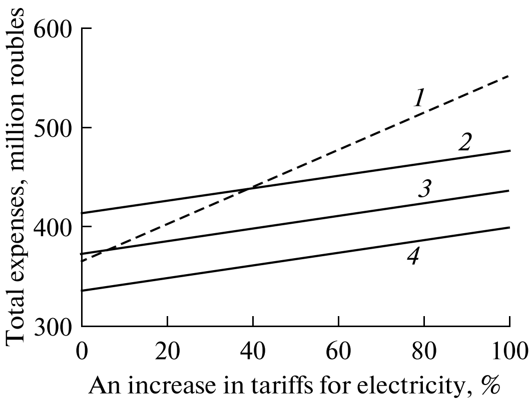

Fig. 7. Effect of an increase in tariffs for electricity and a decrease in specific capital investments for HPUs (ΔK) on competitiveness of HPU relative to electric boilers while supplying heat to cottage settlement (Central region). (*1*) electric boiler; (*2*)–(*4*) HPU; ΔK, %: (*2*) 0; (*3*) 20; (*4*) 40.

The studies showed (Fig. 7) that the use of HPUs instead of electric boilers becomes economically justified in the following cases:

(i) with an increase in tariffs for electricity by more than 10% at the North, by 40%, at the central regions, and by 50%, at the South (with current level of specific investments for HPUs);

(ii) with a decrease of specific investments for HPUs (including the system of low-potential heat extraction) by 40% and more (with current tariffs for electricity).

The total annual consumption of conditional fuel was determined for the considered alternatives of the settlement heat supply, i.e., with an account for fuel consumption at power plants for generating electricity, which is used for heat-supply needs (Table 5). In so doing, specific consumption of fuel at power plants was taken to be 340 g.c.e./ (kW h). The results of calculations show that in northern regions neither scheme of heat supply with HPU can be considered as an energy saving one. In the central and south regions of Russia, if choosing the optimal scheme and parameters of the heat-supply system with a HPU, it is possible to obtain fuel saving of 17 and 24%, respectively, as compared to using gas-fired boilers. The use of HPUs instead of electric boilers reduces fuel consumption by 2.4–3.2 times depending on the region of HPU location.

Table 5. Total annual consumption of fuel for heat supply of settlement, t c.e./year

Heat source	North	Center	South
Gas-fired boiler	2602	1804	1326
Electric boiler	6372	4417	3247
HPU with redundant EB (95/70°C temperature schedule)	4076	2509	2006
HPU with redundant EB (70/50°C temperature schedule)	2697	1853	1117
HPU with peak convector	2642	1496	1433
HPU with "warm floor" system and peak EB	2782	1604	1002
Maximal possible saving of fuel while using HPU	0	308	324

CONCLUSIONS

(1) The heat-supply system on a HPU basis for low-storied building areas requires considerably greater capital investments as compared to traditional schemes with individual heat sources, i.e., gas-fired and electric boilers.

(2) The use of heat pumps in the heat-supply systems has certain restrictions connected with a low potential of the utilized heat and a low temperature of the heated working fluid at the HPU outlet. To overcome these limitations, it is necessary to develop special technical and schematic decisions, which require considerable capital investments in additional heating surfaces and a peak heat source.

(3) The effectiveness of the application of HPUs for heat-supply needs considerably depends on climatic and other regional conditions, which gave to a certain extent opposite effects. The ground heat potential and correspondingly the HPU transformation coefficient increase from the North to the South. The duration of the heating season and the coefficient of using a HPU installed capacity and, thus, a degree of realization of the energy saving capability of heat pumps decreases from the North to the South.

(4) At the present time, HPUs can not compete with gas-fired boilers in the heat-supply systems for low-storied building areas. An economical niche for HPUs is the no gasified regions of the country, while the competitive technology is the electric boiler.

(5) Heat-pump units will become more efficient than electric boilers in economic sense if tariffs for electricity become higher by more than 10% in the northern, 40%, in the central, and 50%, in the southern regions of the country (relative to 2010 level) or if specific capital investments in HPUs decrease by 40% and more (with current tariffs for electricity being retained).

(6) Using HPUs instead of electric boilers in the heat-supply systems makes it possible to reduce the demand for electric power by 21–26%.

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