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Prospects of Using Air Heat Pumps for Supplying Heat to Residential Buildings under Different Climatic Conditions

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Abstract—Specific features connected with using air heat pumps under the conditions of cold climate are considered. Ways for achieving more efficient operation of these pumps are shown. Results from technical–economic studies on analyzing the prospects of using air heat pumps for supplying heat to low-rise buildings in different regions of Russia in comparison with alternative solutions are presented.

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High capital intensity of soil geothermal heat pumps is one of the main factors hindering their use in Russia [1]. In constructing heat supply systems for low-rise buildings on the basis of geothermal heat pump units (HPUs) with vertical probes, the costs for drilling boreholes and fitting them with surface facilities reach 20% of the total investments.

Air HPUs, in which atmospheric air is used as a source of low-potential heat, due to which there is no need to carry out expensive drilling work, are an alternative solution with respect to geothermal HPUs. Water or air can be used in air HPUs as a heated heat carrier.

SPECIFIC FEATURES RELATING TO THE USE OF AIR HEAT PUMP UNITS

In "air–water" HPUs, the heat of working medium (refrigerant) is transferred to water, which is forwarded to the building's heat supply system for the purposes of heating (a radiator system) and hot-water supply (HWS). In "air–air" HPUs, the heat of working medium is transferred to air, which is supplied directly to the heated premises via air ducts (air heating). In this case, the heat carrier can be heated to a lower temperature, due to which it becomes possible to operate the heat pump condenser at lower pressure and temperature. As a result, smaller work is required for compressing the refrigerant, and better heat transformation ratio in the HPU is achieved. However, a low temperature of the heated heat carrier is a factor that limits the possibilities of using "air–air" HPUs for supplying hot water to consumers. In addition, when water is replaced by air, the condenser operates with a poorer coefficient of heat transfer, which leads to a growth of its metal intensity and overall dimensions.

Operation of air HPUs in regions with cold climate, which are usually characterized by significant daily and seasonal variations of temperature and very low values of outdoor temperature in winter, involves a number of serious problems.

First of all, it should be pointed out that the main characteristics of an HPU depend essentially on the temperature of surrounding medium ($t_{s.m}$). As $t_{s.m}$ decreases, the HPU output and the heat transformation ratio show quite a rapid drop (Fig. 1). The dependences shown in Fig. 1 were constructed as applied to the Vitocal 350-A heat pump with a heat capacity of 18.5 kW produced by Viessmann for two levels of water heating temperature equal to 50 and 65°C.

The above-mentioned regularities are explained as follows. When $t_{s.m}$ decreases, so does the temperature difference in the evaporator, i.e., the difference of temperatures between atmospheric air and boiling refrigerant (t_{ev}). As a result, with constant values of the heat transfer surface area in the evaporator (F_{ev}) and heat transfer coefficient (k_{ev}), a smaller amount of heat is supplied from the surrounding medium to the HPU working medium ($Q_{s.m}$). This entails a drop in vaporization intensity, compressor output, and HPU heat output (Q_{HPU}). When $t_{s.m}$ decreases, the value of $Q_{s.m}$ drops much more rapidly than the power consumed by the compressor for maintaining the required pressure of refrigerant in the condenser. As a result, the heat transformation ratio (φ) decreases, which can be seen from the following elementary relations:

$$Q_{HPU} = Q_{s.m} + L;$$

$$Q_{s.m} = k_{ev}F_{ev}(t_{s.m} - t_{ev});$$

$$\varphi = (L + Q_{s.m})/L = 1 + Q_{s.m}/L.$$

In the limiting case in which $t_{s.m} = t_{ev}$, we have $Q_{s.m} = 0$, $Q_{HPU} = L$, and $\varphi = 1$, and the HPU becomes in fact an electric heater.

When $t_{s.m}$ drops below a certain level, the HPU is no longer able to keep the required temperature of heated heat carrier. The lower this temperature, the wider the HPU working range and the higher the value of φ at the same $t_{s.m}$ (see Fig. 1).

Air HPUs can be made more efficient by using a more complex thermodynamic cycle and, accordingly, a more complex thermal circuit of the installation. If the heated heat carrier at the HPU inlet has a rather low temperature, it is possible to implement a cycle with additional cooling of working medium downstream of the condenser by installing a suitable heat exchanger. The use of this measure makes it possible to achieve a higher heat output and heat transformation ratio in the HPU. An HPU cycle with regeneration of heat can also be implemented. To do so, the refrigerant vapor arriving from the evaporator is heated in the additional heat exchanger installed downstream of the condenser, and this vapor is then supplied to the compressor inlet.

One way in which a wider working range of $t_{s.m}$ in air HPUs is obtained consists in implementing a cycle with intermediate cooling of working medium (Fig. 2). Part of liquid refrigerant (α) obtained at the condenser outlet (C) is throttled through the throttle Thr_1 (process *3–6*) to the pressure p_6, after which it is supplied to the intermediate heat exchanger (IHE), where it cools the main flow (process *3–4*) and evaporates (process *6–7*). Having passed the intermediate heat exchanger, the main flow $(1 - \alpha)$ is throttled in the throttle Thr_2 (process *4–5*) and is fed to the evaporator, where it takes heat from the surrounding air (process *5–1*). After that, the main flow of refrigerant is forwarded to the compressor (Cmp), where it is compressed to the pressure p_6 (process *1–7'*). Cold vapor-like refrigerant is injected into the compressor at this pressure (the flow α), where it is mixed with the main flow of refrigerant, as a result of which an equilibrium temperature settles (point *7"*). After that, the resulting flow is compressed to the pressure p_1 and is forwarded to the condenser, in which its heat is transferred to the heated heat carrier. Thus, two-stage compression with intermediate cooling is organized in this circuit, due to which it becomes closer to isentropic compression conditions with the corresponding saving of the compressor work.

A considerably wider working range of outdoor air temperatures is obtained for air HPUs by implementing a more complex thermodynamic cycle and using various technical novelties and new working fluids. Thus, the "air–air" HPUs of the ZUBADAN Inverter series produced by Mitsubishi are able to operate at outdoor air temperatures down to –25°C. However, these measures turn to be insufficient for fully covering the heating loads by means of HPUs in regions with

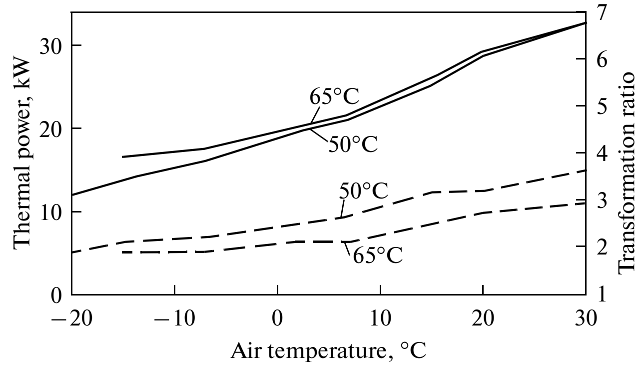

Fig. 1. Thermal power and heat transformation ratio of an "air–water" HPU vs. the outdoor air temperature. Solid curve is for thermal power, and dashed curve is for heat transformation ratio.

lower design temperatures, which comprise the larger part of the country's territory. In addition, the use of a more complex cycle inevitably entails a higher cost of the HPU.

Freezing of the evaporator's heat-transfer surfaces is one else problem encountered in operation of air HPUs under the conditions of cold climate. At low temperatures of atmospheric air, the moisture contained in the evaporator precipitates on its surface in the form of frost or ice, thus deteriorating heat transfer and increasing the pressure drop. For removing frost, the heat exchanger temperature has to be increased. This is achieved by switching over the HPU to operate in the inverted mode, in which warm gaseous refrigerant from the compressor is supplied to the evaporator and melts the frost accumulated on its external side. In regions with cold climate, up to 15–20% of the electric energy supplied to the HPU is spent for removing frost and ice.

SCHEMES OF HEAT SUPPLY SYSTEMS MADE ON THE BASIS OF AIR HEAT PUMP UNITS

Air HPUs, as geothermal ones, are universal climatic devices able to maintain comfortable parameters of indoor air in premises during the whole year and to supply hot water for consumers. Radiators, warm floors, and fan coil units can be used as heating devices in heating systems equipped with "air–water" HPUs. The use of "air–air HPUs makes it possible to do without heating devices at all. Apart from performing heating functions, air HPUs can be used for air conditioning, which is achieved by changing the thermal circuit. The functions of condenser and evaporator are mutually inverted by switching over the flows of working fluid. When the system is set to operate as an air

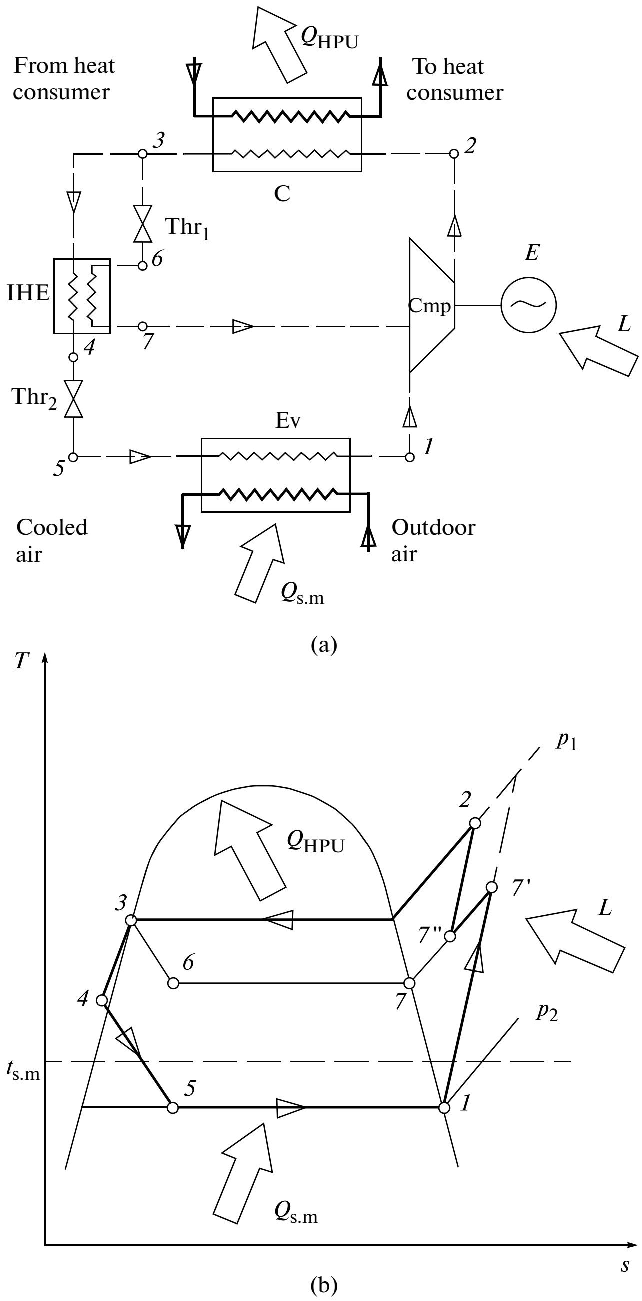

Fig. 2. Basic process circuit of a heat pump with steam injection into the compressor (a) and the *T, s* diagram of the cycle (b).

conditioner, liquid refrigerant passes through the inner heat-transfer unit, where it evaporates and takes heat from the cooled premise. When passing through the external heat-transfer unit, the cooling agent is condensed, and the heat contained in it is transferred to the outdoor air. This heat can also be used for preparing hot water for HWS purposes in the summer season.

As was shown earlier, air HPUs are frequently unable to fully cover the heating load at the design temperature of outdoor air. As a result, additional sources of heat have to be incorporated in the heat supply system. Electric boilers or convectors are commonly used as such devices. The specific capital investments in such sources are smaller than in air HPUs, whereas the consumption of electric energy for obtaining the same amount of heat is higher. This circumstance generates the need to find the optimal distribution between the installed capacity of the HPU and the additional heat source, and to determine their optimal loading.

The mode in which an HPU and additional heat source operate jointly on a heat load has been called a bivalent mode. Accordingly, the mode in which the heat load is covered by a single heat source is called a monovalent mode. The outdoor air temperature at which the additional heat source is switched into operation determines the bivalent point.

Figure 3 shows three most prospective schemes of systems for supplying heat to residential buildings on the basis of air HPUs:

—a series connection scheme of an “air–water” HPU and electric boiler with the heating system operating according to the 60/50°C temperature schedule;

—a parallel connection scheme of an “air–water” HPU and electric boiler, in which the heat pump operates for the “warm floor” heating system, and the electric boiler is connected to its own radiator heating system; and

—a parallel connection scheme of an “air–air” HPU and electric convector in a heating system, and with using a storage-type water heater for supplying hot water.

Figure 4 shows the graphs depicting the coverage of heat load by air HPUs for the above-mentioned schemes with a heat pump having a capacity optimized for the conditions of Moscow.

In the two first schemes (see Figs. 3a and 3b), the heat pump heats water, which is forwarded through a three-way valve to the heating system’s buffer reservoir or to the HWS storage water heater. The heat pump unit covers the entire heat load down to the temperature $t_{s.m}$ determining the bivalent point. At lower temperatures of atmospheric air, the electric boiler is switched into operation. When $t_{s.m}$ drops below certain level (–15°C in Fig. 4a and –20°C in Fig. 4b), the HPU is disconnected, and the electric boiler covers the entire heat load, including that for preparing hot water. For this reason, the boiler has to be designed for the maximal heat load.

In the last scheme (see Fig. 3c), a few “air–air” HPUs are usually installed for supplying sufficient amount of heat to all premises in a building. Electrical convectors are installed in parallel to them as addi-

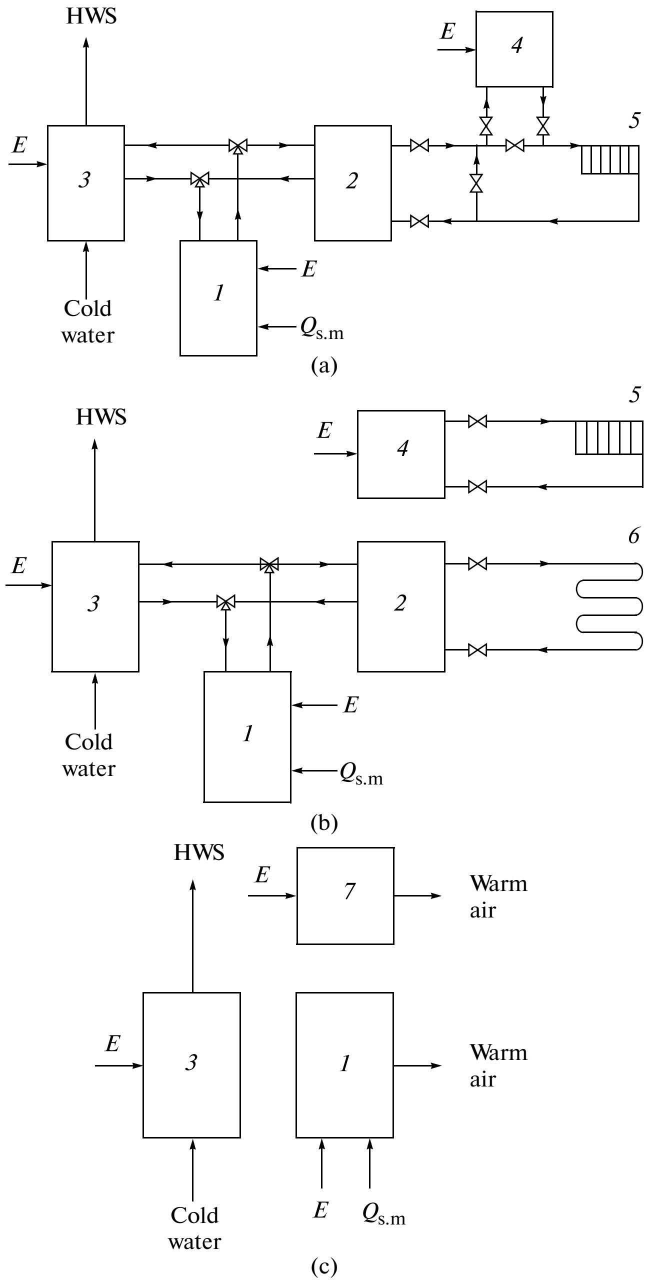

Fig. 3. Schemes of heat supply for an individual house with the use of an HPU. (a) Series-connected scheme with an electric boiler, (b) parallel-connected scheme comprising the "warm floor" system and an electric boiler, and (c) parallel-connected scheme with a convector. (*1*) Heat pump, (*2*) buffer reservoir, (*3*) storage HWS water heater, (*4*) electric boiler, (*5*) radiator heating system, (*6*) "warm floor" heating system, and (*7*) electrical convector. *E* is electric energy, and $Q_{s.m}$ is the heat from surrounding medium.

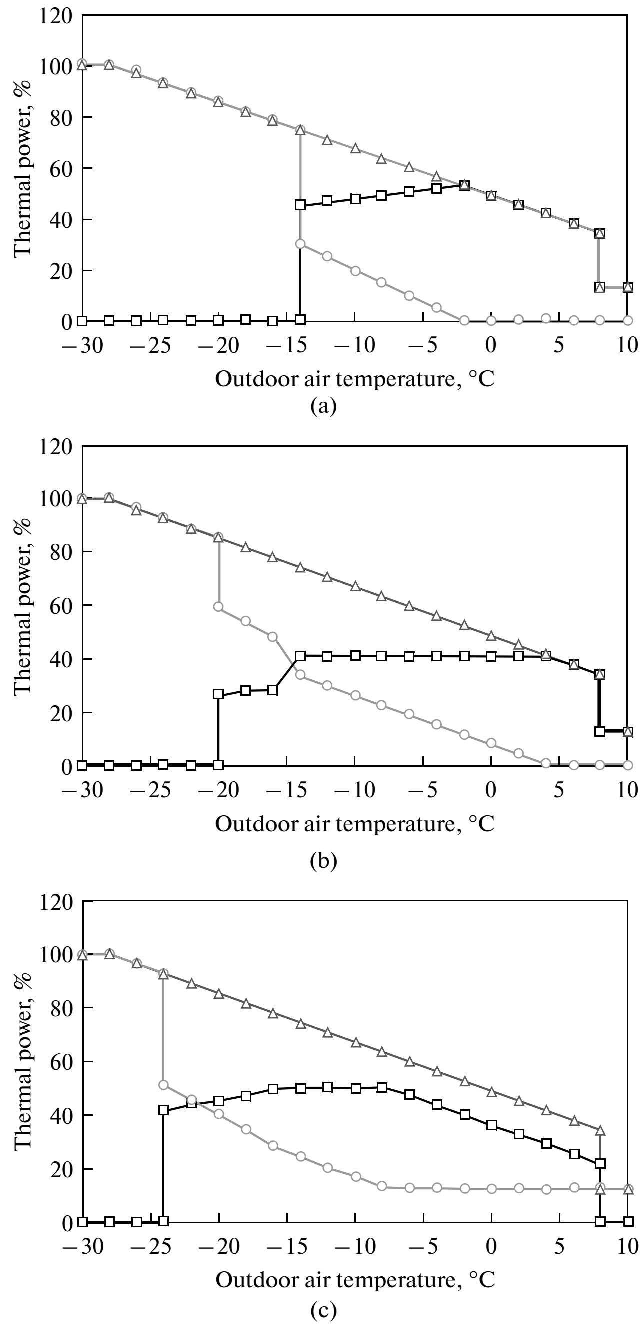

Fig. 4. Optimal schedules of covering heat load by air HPUs for different HPU connection schemes for the conditions of Moscow. (a) Series connection scheme with an electric boiler (□ "air–water" HPU, ○ electric boiler, and △ total power); (b) parallel-connection scheme with the "warm floor" system and electric boiler (□ "air–water" HPU, ○ electric boiler, and △ total power); and (c) parallel-connection scheme with a convector (□"air–air" HPU, ○ electric boiler, and △ total power).

tional heat sources, the use of which makes it possible to do without a water heating system. Hot water is prepared by means of an independent storage electric water heater (see Fig. 4c). The advantage of this scheme is that in the summer season, "air–air" HPUs can provide air conditioning in the same premises without the need to make any changes in the thermal circuit.

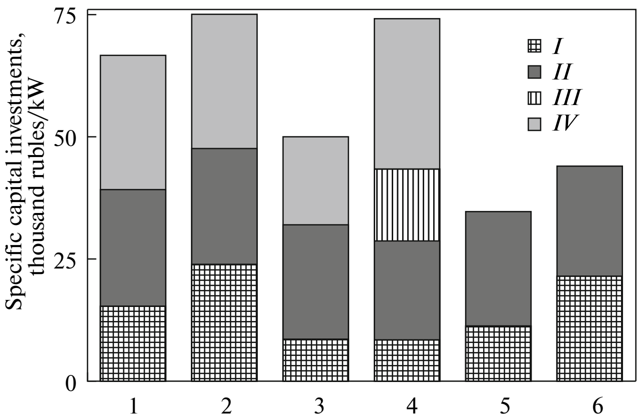

Fig. 5. Specific capital investments in the considered versions of heat supply systems (for the conditions of Moscow). (*1*) "Air–water" HPU with a backup electric boiler, (*2*) "air–water HPU with the "warm floor" system and peaking electric boiler, (*3*) "air–air" HPU with a peaking convector, (*4*) geothermal HPU with a peaking convector, (*5*) sole electric boiler, and (*6*) sole gas-fired boiler. (*I*) Electric boiler, gas-fired boiler, and radiators; (*II*) electric substation and gas distribution station; (*III*) drilling, and (*IV*) HPU.

TECHNICAL-ECONOMIC COMPARISON OF DIFFERENT VERSIONS

Six versions of a system for supplying heat to low-rise residential buildings were compared. In three of these versions, air HPUs are used, the connection schemes of which were considered above. A geothermal HPU with a convector that was determined earlier as the most efficient solution for this type of HPUs [1], a "purely" electric heat supply system constructed on the basis of an electric boiler, and a heat supply system on the basis of a gas-fired boiler were considered as alternatives to the first three versions.

We studied a heat supply system for a cottage settlement [1] consisting of 200 houses each having a heated area of 200 m^2 with constant population of 800 people. The settlement is situated at a distance of 10 km from the nearest electric substation (35 kV) and gas mains (1.2 MPa). The studies were carried out for three settlement location versions: in the northern, central, and southern regions of Russia. The climatic characteristics of these regions correspond to those in Arkhangelsk (North), Moscow (Center), and Pyatigorsk (South). The heat loads of buildings, which include heating and HWS, were determined according to [2] and are equal to the following values, respectively: 27.1, 22.9, and 19.2 kW. The levels of current prices (as of early 2012) were taken as follows. For electric energy: 3.32 in the North, 4.02 in the Center, and 2.99 rubles/kW in the South, and for natural gas: 3200 in the North, 3370 in the Center, and 4100 rubles/1000 m^3 in the South.

The estimated specific capital investments in the considered versions of heat supply system for the conditions of Moscow are shown in Fig. 5. The following components are separated in the structure of capital investments: outlays for the HPU; outlays for the electric boiler (convector), gas-fired boiler, radiator heat supply system, and other thermal engineering equipment; outlays for drilling and equipping the vertical probe for the geothermal HPU; and infrastructural outlays for constructing the electric substation and gas distribution station of the appropriate capacity. Among the considered versions of heat supply system equipped with heat pumps, "air–air" HPUs are characterized by the minimal capital investments because they do not involve costs for drilling and making a radiator heat supply system.

The considered versions were compared in terms of the total discounted outlays for implementing the settlement heat supply system for the period covered by calculations, which was taken equal to 30 years. The minimum of total discounted outlays was adopted as

Table 1. Annual average indices of macroeconomic indicators for the period, %

Indices	2012–2015	2016–2020	2021–2025	2026–2030	After 2030
Indices of the physical amount of gross domestic product	104.2	105.8	105.5	105.3	104.3
Price (tariff) for electricity	112.5	112.0	105.1	102.0	101.5
Price for natural gas	115.3	112.2	106.9	103.5	102.2
Indices of consumer prices	105.6	106.2	104.8	103.2	102.1
Indices of the prices of electric equipment producers	105.6	105.5	105.6	103.2	101.9
Deflator indices of industrial production	106.2	108.5	105.8	103.3	102.4
Deflator indices of capital investments	107.6	107.7	105.7	104.2	103.2
Real income of population	104.9	105.7	105.5	105.3	104.2

the optimality criterion. The calculations were carried out using the predicted tariffs for fuel and electric energy and price indices of producers corresponding to the innovation scenario of the long-term development of the country's economy that was worked out at the Ministry of the Russian Federation for Economic Development in 2011. The macroeconomic characteristics used in the calculations are given in Table 1.

In shaping different versions, we optimized their schematic solutions and parameters. The optimal fractions of HPU participation in covering the heat load of consumers and the bivalent points corresponding to them were determined as applied to the three considered regions. In so doing, we took into account the density of the curve characterizing the persistence of outdoor air temperatures in the regions, schemes of heat supply for houses, cost ratios of the heat pump and peak-duty heater, and cost of electric energy in regions. In varying the fraction of HPU in covering the heat load, we took into account different claimed levels of the electric power of settlement loads in the heat supply versions. For making the versions comparable, differences in the outlays for the electric networks and substation were taken into account. The minimum of total discounted costs for the settlement heating system was used as the optimization criterion in determining the optimal fraction of HPU load.

For the scheme containing an "air–water" HPU connected in series with an electric boiler, the optimal fraction of HPU in covering the heat load comprises 50–60% for different regions, and the corresponding values of atmospheric air temperature at the bivalent point vary from –6 to –2°C. For the scheme containing an "air–water" HPU connected in parallel with the "warm floor" system and an electric boiler, the optimal fraction of HPU in covering the heat load is at a level of 35–50%, and the values of $t_{s.m}$ at the bivalent point are in the range from –6 to –4°C. For the "air–air" HPU, the optimal fraction of the building's heat supply system load covered by the heat pump is around 50% for all regions, and $t_{s.m}$ at the bivalent point varies from –8°C in the north to –2°C in the south.

For a geothermal HPU with a peaking convector, the HPU fraction in covering the heat load under the considered conditions is 60–70%, and the value of $t_{s.m}$ at the bivalent point is in the range from –8 to –4°C.

The expenditures of electric energy in the versions with air HPUs were determined taking into account the additional expenditures of energy for removing frost and ice during cold spells, which were taken equal to 15% of the total electric energy consumed by the HPU during its operation in the period with $t_{s.m} < 0$°C.

According to the results obtained from the performed studies, the use of air HPUs instead of electric boilers in systems supplying heat to low-rise buildings reduces the consumption of electric energy by a factor of 1.7–2.0 (Table 2). In the northern and central regions of Russia, the scheme comprising an "air–air" HPU and a peaking converter was found to be the most energy-efficient one. In the southern regions, the scheme comprising an "air–water" HPU and the "warm floor" system becomes more advantageous. This is explained by a shorter duration of the heating season in the southern regions, due to which HWS accounts for a larger fraction in the total heat load. In contrast to the alternative versions comprising air HPUs, the heat pump used in the heat supply system based on an "air–air" HPU does not participate in covering the HWS load (hot water is obtained only by means of electric heater, see Fig. 3). Therefore, with a

Table 2. Consumption of electric energy for supplying heat to the settlement, million (kW h)/year

Version of heat supply system	North	Center	South
"Air–water" heat pump unit with a backup electric boiler	12.2	8.2	5.5
"Air–water" heat pump unit with the "warm floor" system and peaking electric boiler	12.6	7.6	5.1
"Air–air" heat pump unit with a peaking convector	10.6	7.2	5.5
Geothermal HPU with a peaking convector	7.4	4.7	3.3
Electric boiler	18.2	13.0	10.0

Table 3. Electric load of the settlement, MW

Version of heat supply system	North	Center	South
"Air–water" heat pump unit with a backup electric boiler	5.4	4.6	3.8
"Air–water" heat pump unit with the "warm floor" system and peaking electric boiler	5.4	4.6	3.1
"Air–air" heat pump unit with a peaking convector	5.4	4.6	3.0
Geothermal HPU with a peaking convector	3.3	2.6	2.2
Electric boiler	5.4	4.6	3.8

Table 4. Total annual expenditures of fuel for supplying heat to the settlement, tce/year

Version of heat supply system	North	Center	South
"Air–water" heat pump unit with a backup electric boiler	3849	2569	1747
"Air–water" heat pump unit with the "warm floor" system and peaking electric boiler	3961	2403	1606
"Air–air" heat pump unit with a peaking convector	3350	2272	1743
Geothermal HPU with a peaking convector	2340	1481	1042
Electric boiler	5748	4104	3157
Gas-fired boiler	2339	1670	1285

Table 5. Total discounted outlays for supplying heat to the settlement for the period covered by calculations, million rubles

Version of heat supply system	North	Center	South
"Air–water" heat pump unit with a backup electric boiler	755	640	470
"Air–water" heat pump unit with the "warm floor" system and peaking electric boiler	774	654	482
"Air–air" heat pump unit with a peaking convector	624	535	374
Geothermal HPU with a peaking convector	622	530	429
Electric boiler	767	672	452
Gas-fired boiler	329	291	269

shorter heating season, the energy saving effect from using a heat pump is less pronounced than in the regions with a longer heating season. As a result, for the southern regions the expenditure of electric energy in the scheme comprising an "air–air" HPU is larger than in the scheme comprising an "air–water" HPU with the "warm floor" system. In all considered climatic zones, air HPUs are less energy efficient than the heat supply system on the basis of geothermal HPUs.

Many regions of the country experience a shortage of electric power, due to which certain difficulties arise in connecting new consumers to public electric networks. Minimizing the electric load is a topical issue for consumers in such regions. Studies have shown that the use of air HPUs instead of electric boilers yields energy saving only in the southern regions of the country. It is important to note that this statement is valid only for schemes comprising an "air–water" HPU with the "warm floor" system and for "air–air" HPUs (Table 3). Attempts to reduce the electric load in the central and northern regions by installing air HPUs will not be met with success due to limitations imposed on their operation in connection with low temperatures of outdoor air. Since air HPUs have to be disconnected at low values of $t_{s.m}$, a backup heat source in the form of electric boiler must be incorporated in the system (see Fig. 4). Air HPUs are essentially inferior to geothermal HPUs in saving of electric power.

In view of fuel consumption at power stations for producing electric energy, the use of air HPUs instead of electric boilers allows essentially smaller expenditures of fuel to be achieved for supplying heat to the settlement (Table 4). In our calculations, the average specific consumption of fuel at power stations was taken equal to 315 gce/(kW h). However, the use of gas-fired boilers and geothermal HPUs with a convector is more efficient in terms of this indicator.

By the economic criterion, the heat supply scheme comprising an "air–air" HPU with a peaking convector was found to be the best one among the air-type HPUs. In its economic efficiency, this system outperforms electric boilers in all of the considered regions of the country (Table 5). In the north and center of Russia, this system is equivalent in economic efficiency to geothermal HPUs, and in the south it is noticeably outperforms them. At the same time, none of the considered heat supply systems with HPUs can compete with gas-fired boilers up to 2030.

Assessments of the potential capacity of the market for HPUs in the considered regions have been obtained. The calculations were carried out proceeding from the following conditions. Heat pump units are used for supplying heat to newly constructed low-rise residential buildings in rural areas in which it is not easy to connect the consumers to gas mains. The amounts in which low-rise residential buildings will be commissioned in the Northwest, Central, and Southern federal districts (including the North Caucasian one) will grow by the year 2020 to 1.7, 7.5, and 9.3 million m^2 a year, respectively, after which they will stabilize at the achieved level. The fraction of the commissioned low-rise residential buildings without guaranteed connection to the gas network and which can be equipped with HPUs comprises in the above-mentioned districts 44, 21, and 15%, respectively. Calculations show that by 2020, up to 250 MW of air and geothermal HPUs can be needed annually in the considered districts (Fig. 6). By 2030, the total installed capacity of HPUs in these regions could be around 4 GW, which would make it possible to save around 220000 tce per annum.

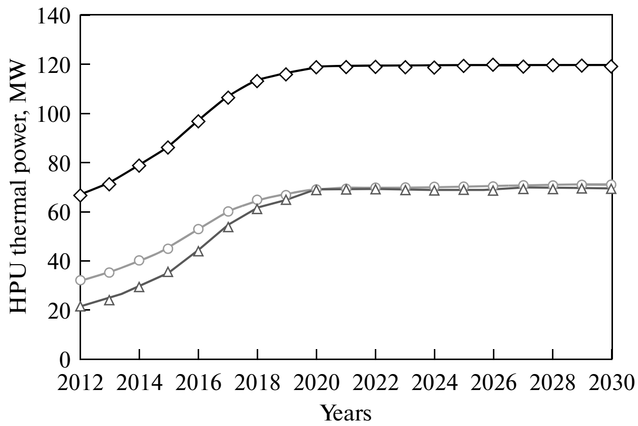

Fig. 6. Assessments of the potential capacity of market for HPUs for the future period up to 2030. ○ North, ◇ Center, and △ South.

CONCLUSIONS

(1) Applications of air heat pumps have limitations resulting from a drop of their thermal power output and heat transformation ratio at low temperatures of atmospheric air, which is an essential drawback under the conditions of cold climate. Additional heat sources designed for 100% of heating load must be installed in the northern and central regions of Russia for overcoming these limitations, which unavoidably entails a higher cost of the heat supply system.

(2) Additional consumption of electric energy for removing frost in the evaporator of an air HPU and the corresponding drop of its efficiency must be taken into account for HPUs operating under the conditions of cold climate.

(3) More efficient operation of air heat pumps is achieved through the use of new working fluids and a more complex thermodynamic cycle of the HPU, which entails a growth of its cost.

(4) The scheme comprising an "air–air" HPU with a peaking convector is the most efficient one of the considered systems constructed on the basis of air heat pumps.

(5) None of the considered schemes with the use of air HPUs can compete with gas-fired boilers. Use of air HPUs like that of geothermal HPUs can be economically justified in regions not covered by gas supply networks, and electric boilers may become a competing technology.

(6) The potential capacity of market for HPUs for the period up to 2020 in the considered regions of Russia can make up to 250 MW per annum.

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