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Creation of an energy-efficient and comfortable country house using "passive" energy sources

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Abstract. In the article the author considers one of the most important factors of life support – the creation of an energy-efficient and healthy microclimate country house through the use of complex engineering systems including the use of "passive" energy sources. Based on the results of the foreign and Russian market analysis of energy-efficient houses, the reasons for the low construction pace of such houses in Russia are estimated. A constructive engineering solution is proposed that can increase the efficiency using the modern heating, conditioning and humidification systems, thereby making them economically feasible and affordable for mass use.

1 Introduction

Studies of the suburban housing market in the Moscow region have shown that over the past decade, demand for these real estate properties continues to decline. These days the number of proposals on the market exceeds the demand by an order. This is primarily due to the glut of the market with obsolete houses, which were mainly built 20-30 years ago in the absence of modern materials and technologies. Also, during design and construction, the attention was not paid to energy efficiency, which subsequently led to the high cost of ownership of these houses. In addition, despite the external attractiveness, living in them became uncomfortable and sometimes unhealthy due to lack of ventilation. So today many owners of such houses are trying to sell them.

The author sees the main problem of low liquidity of many suburban real estate objects in the absence of complex equipment in the design solutions with additional engineering systems that provide a comfortable and healthy living environment. As a rule, sections of project documentation in the part of engineering systems consist only basic systems of power supply, heating, water supply and sewerage.

The purpose of this study is to form an integrated approach to the creation of a new suburban real estate object with an emphasis on its energy efficiency and the presence of the comfortable and healthy living environment in it. In the article it is analyzed the best practices in the construction of country houses in Finland as the most similar in climate to the central part of Russia. The author proposes a constructive solution for creation an energy-efficient and green home, taking into account the features of the Moscow region climate and the usage a "passive" energy source.

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2 Materials and Methods

In Russia the volume of suburban housing under construction continues to be high, despite the general stagnation of the real estate market (Fig.1). Therefore, the issue of energy efficiency is also one of the priorities of the state.

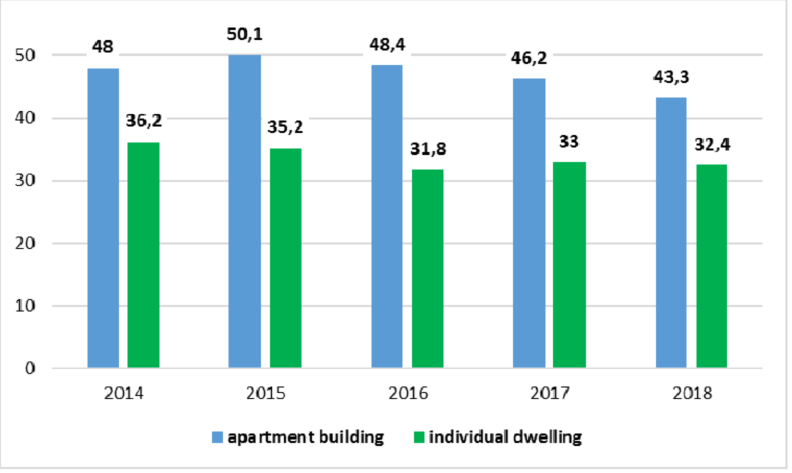

Fig. 1. The volume of commissioned housing in Russia in 2014-2018, mln sq m.

Also, various non-profit organizations support this direction, for example, the Non-Profit Partnership “Green Building Council”. But all these innovations have not yet brought noticeable results. The reasons for this is that energy-efficient houses seem for most of people something exotic and strange. Low demand for such facilities is caused by insufficient public awareness and the high cost of equipment and installation of systems. In addition, there are practically no specialists in this field in Russia, and insurance companies rarely understand the need to insure such a house. Despite this, today many owners and potential purchasers of suburban housing are beginning to understand the importance of energy conservation and interest in energy-efficient projects is growing steadily from year to year.

This section provides an overview of the main criteria for energy efficiency in the construction of country houses. An analysis of foreign experience in the use of “passive” energy sources was also carried out taking into account the similarity of climatic conditions with Central Russia. Suggestions are made for the use of these systems in combination with other engineering systems in order to increase energy efficiency.

According to the International Independent Energy Non-Governmental Organization (MIRES), about a third of the energy produced is spent on heating. For several decades, the key priorities of developed countries include research and development aimed at improving the energy efficiency of residential buildings under construction [1]. In a number of European countries, the economy on heat carriers makes from 50-70% thanks to an application of modern technologies in building construction. Also, according to the EU Directive, from 2020 in Europe it will be allowed to build houses with only zero energy consumption [2]. These will be fully autonomous buildings that provide themselves with all the necessary energy. The final stage in the development of energy efficiency is planned the mass construction of houses with excess energy associated with the production of energy by residential buildings and the transfer of surplus to the central network.

On the example of the development of suburban housing construction in Finland, where the government pays special attention to environmental issues and energy efficiency, the author analyzes the most successful engineering solutions for using a “passive” energy source.

Currently in Finland, approximately 40% of the population lives in their own homes. Located both within the city and beyond, in most cases, these houses do not externally differ in design refinement. Ergonomics, orientation of the glazed part of the house on the sunny side for natural light, the ability to maximize the existing area and the surrounding area are the basis of their design solutions. For this reason, modern Finnish houses, as a rule, are single-story with an area of 100 sq.m, two-story buildings and attic houses are rarely found. It is also the type of house, designed for several families, with a common wall isolated from each other, sometimes having separate entrances and courtyards. Energy saving is one of the important life principles for a resident of Finland.

On the example of the description of a typical Finnish frame house, it is possible to identify the main criteria for energy-efficient houses. According to Finnish laws, enclosing structures requires a thermal conductivity of not more than $0.17 W/m^2K$, so the building must be "massively" insulated. To withstand such high rates of energy saving in Finland for a frame house there are standards – the thickness of the walls should be at least 250 mm, and the thickness of the insulation of the ceiling is not less than 500 mm. The foundations are also insulated, mainly an insulated plate is used. It is rarely used screw piles, strip and other foundations where there is an underground. Their use is advisable only in homes for seasonal residence and in those places where water can rise high.

In energy-efficient houses, the most advanced and warmest window and door structures should be used. Professionally executed design solutions for eliminating cold bridges also play an important role. These are patented technologies for connecting nodes, the use of thermal breaks in various elements, cross-insulation, ways of laying cables and utilities without breaking the sealing of the house.

The air permeability of energy-efficient house structures should not exceed 0.6 h-1 (tested under technical supervision). It is important to note that the build quality of the house is checked at each stage, because according to Finnish laws, it is the responsibility of the customer to attract and pay for the services of specialized companies for conducting technical supervision.

A mandatory element of an energy-efficient home is also forced ventilation with heat recovery (heat transfer) with a minimum efficiency of 75%. At the same time, the air entering the building should not be colder than 17ºC. Ventilation with heat recovery is gradually becoming a standard not only for frame buildings, but also for other types of energy-efficient houses. In the absence of such ventilation it is impossible to solve the problem of energy saving in buildings in the climate with low winter temperatures.

Another key element of energy efficiency is the availability of engineering systems that allow the use of “passive” energy sources, such as geothermal, light and wind sources. In conditions of a “moderately cold climate”, with a small number of light days per year, as well as features of the relief and vegetation, the use of “passive” sources is limited only by geothermal sources [3]. In Finland, one of the most common heating methods is the use of heat pumps with a geothermal circuit using the "ground-to-water" or "ground-to-air" technology.

Given the scarcity and high cost of energy resources, this type of heating has proved to be such a breakthrough solution in the use of "passive" energy that the Finnish government has introduced a program to stimulate the installation of heat pumps. A potential buyer had to submit an application, obtain permission, purchase and install a heat pump, and then within 3-4 months receive compensation from the state for their costs. For example, in 2011, compensation amounted to 20% of the heat pump cost. As the popularity of using the heat pump grew every year and the government no longer needed to stimulate the purchase of this equipment, the volume of compensation has been reduced to 5-10%. Also, the owner of the heat pump can regain up to 40% of the cost of its installation through the return of part of the income tax.

The key indicator of the heat pump is a coefficient of performance (COP). This value shows how many times the heat pump produces more energy through the use of a geothermal heat exchanger than it consumes itself, that is, it determines the difference between the energy produced and consumed by the heat pump [5]. For example, the heat pump with the coefficient of performance of 5 produces an additional 4 kW of heat energy for each kW consumed by it [6]. Thus, out of every 5 kW of energy spent on heating, you have to pay only for 1 kW. The coefficient of performance is calculated using the following formula:

$$COP = T2/(T2-T1) \tag{1}$$

where $T1$ – the temperature at the outlet of the geothermal circuit, $T2$ – the temperature of the heat carrier in the heating circuit (temperature of the water circulating in the radiators of the heating system, underfloor heating pipes, warm plinth, etc.).

Thus, the COP value depends on the temperature of the heat source and the temperature in the heating system of the house (at the input and output of the heat pump).

When calculating the COP, the temperature is calculated in Kelvin. For example, a geothermal heat pump collects ground energy at +5ºC, or 278K, and releases this energy to the water in the heating circuit at +30ºC, or 303K. The following value is obtained:

$$COP1 = 303K/(303K – 278K) = 12 \tag{2}$$

Let's make one more calculation according to the most typical input conditions. The geothermal circuit outlet temperature is 0ºC or 273K, the heating circuit temperature is +70ºC or 343K. The COP will be:

$$COP2 = 343K/(343K – 273K) = 4,9 \tag{3}$$

It should be noted that this calculation gives an overestimated value, because it is calculated based on the efficiency of the heat pump equal to 100%. In practice, the efficiency is much lower due to the operation of the compressor, circulation pumps, fans, sensors, etc. Having analyzed the model lines of various manufacturers of heat pumps, the author introduced a correction factor, which is 0.5. The final coefficients of performance are obtained respectively: COP1 = 6; COP2 = 2.45.

On the basis of these calculations it is possible to draw a conclusion about creation of the most effective conditions of application of the heat pump. Since it is almost impossible to influence the temperature of the geothermal circuit, except for the additional connection of the geoconture to various heat exchangers [7], therefore it is necessary to strive to maintain the temperature at the outlet of the heat pump at the lowest possible level.

The possibility of using heat pump systems in the Moscow region, taking into account climatic conditions and the soil mass.

In addition to the above reasons for the low demand for these systems in Russia, there are generally accepted opinions that heat pump systems have a high cost of acquisition and installation, at a low cost in Russia for 1 kW of traditional energy carriers (gas, electricity) [8]. Under such conditions, the payback is more than twenty years, which makes such projects economically inexpedient. The author makes an attempt to destroy the opinion about inefficiency and inexpediency of introduction of such systems. Further, the author formulated three key conditions, the simultaneous implementation of which will make these systems recoupable for 6 years:

1. The design of the house and the build quality should ensure the thermal conductivity not higher than $0.17 W/m^2K$. Only in such a "massively" insulated house it is possible to

maintain optimal heating and ventilation using only the operation of the heat pump at the heat carrier temperature of +30ºC and the coefficient of performance of COP≥5.

2. The presence on the land of the soil massif with high thermal conductivity and heat capacity, or special soil preparation is possible. The higher the thermal conductivity and heat capacity, the higher the intensity of specific heat removal per unit length of the soil heat exchanger. This significantly affects the heat supply in general. Also, to improve the efficiency of heat removal will help such measures as the replacement of soil at the site of the heat exchanger, soil moisture through the creation of drainage, retention of rain moisture, etc. It will have a change in the thermal conductivity of the soil in the range from 0.4 to 2 W/(m·°C) and its volumetric heat capacity from 400 to 1000 kJ/(m^3·°C). A further increase in these indicators will not affect the effectiveness of the system.

3. The correct choice of type and model of the heat pump [9]. Currently, the cost of heat pump systems is high, as according to the author, the Russian market for the production of heat pumps is still at an initial stage of development, there is no high competitive environment and the dominant position is occupied by foreign manufacturers, whose products are designed in most cases for the use of systems in other climatic conditions. But despite the high cost, it is possible to choose the domestic-made heat pump, which will pay off for the 6th year.

Further, the author conducts a brief review of various heat pump systems [10], analyzes their advantages and disadvantages, and proposes an acceptable option for effective use in the climate of the Moscow region.

To begin with, a schematic diagram of the heat pump operation is outlined in Fig. 2.

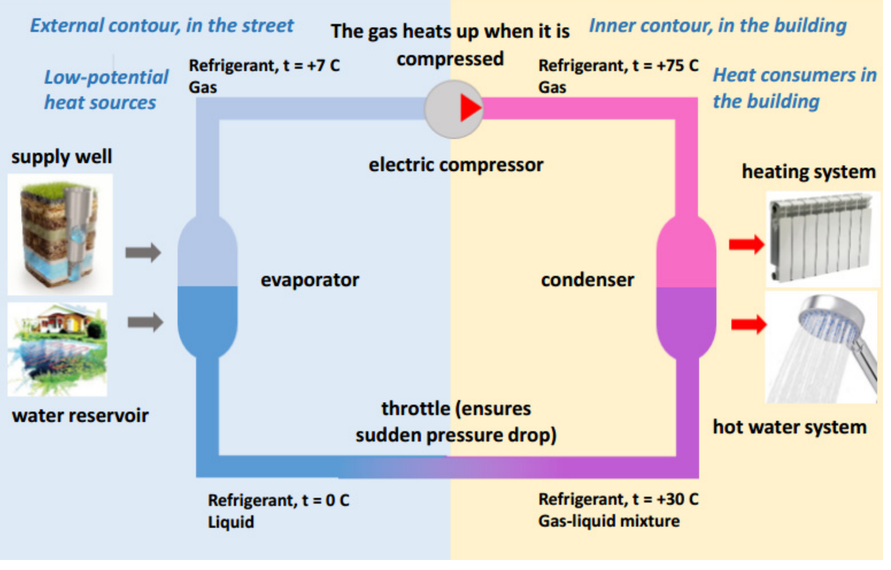

Fig. 2. A schematic diagram of the heat pump operation.

The principle of operation of the compression heat pump consists of two physical phenomena:

1. The absorption and release of heat by a substance when the state of aggregation changes;

2. Change in evaporation and condensation temperature when pressure changes.

The system uses liquids that have a low boiling point. The main elements of the vapor compression circuit are the heat exchanger, evaporator, condenser-heat exchanger, compressor and throttle. The heat pump consists of three circuits:

1). The external circuit is partially installed in the external environment (water, soil, air) and in the room, consists of a heat exchanger through which the heat carrier circulates – a liquid having a low freezing point.

2). The internal circuit consisting of an evaporator and a condenser is installed in a room through which the refrigerant circulates. The refrigerant converts the low-potential energy obtained from the external circuit and transfers it to the heating circuit.

3). The heating circuit also installed in the room ensures the delivery of the heat carrier to the heating system. It is also installed in the room.

The heat carrier, passing on an external contour, heats up on some degrees, taking away heat from a low-potential heat source and arrives in the evaporator where gives this heat to the refrigerant which circulates in an internal contour [11]. The refrigerant, having a low boiling point, passing through the evaporator, due to the low pressure created, boils, changing the aggregate state from liquid to gaseous. From the evaporator, the refrigerant gas enters the compressor, where it is compressed to a high pressure and its temperature rises [12]. Further, the heated refrigerant in a gaseous state enters the second heat exchanger, a condenser. In the condenser, heat exchange occurs between the hot refrigerant and the heat carrier in the heating circuit and then the heat carrier enters the heating devices through the piping systems.

Depending on the combination of the type of source of low-grade heat and the heated medium of the heating circuit, heat pumps are divided into six types [14]:

- water-to-water
- air-to-water
- ground-to-water
- air-to-air
- ground-to-air
- water-to-air

These types differ in the design of the heat exchange part and temperature regimes realized by means of thermodynamic cycles [15].

Heat pump "water-to-water". It consists of a closed thermal circuit, placed in water (lake, pond, river) to a depth of at least 2 meters. The pipeline is placed wavy or rings with the installation of goods in order to avoid surfacing circuit. Disadvantages: the presence in close proximity to the house of the reservoir with the required depth. In practice, this is very rare. There is also a risk of mechanical damage to the circuit, as it is laid in an open way.

Heat pump "air-to-water". This type of heat pump is designed to extract heat from atmospheric air. It does not require the installation of a thermal circuit in the ground or water, as low-potential heat is removed from the air. Externally, this system looks like an air conditioner; it also consists of two units – external and internal. Disadvantages: limited temperature range of use, at -15°C the COP coefficient tends to 1. Also, when used in the cold season, the freezing of the external heat exchanger occurs, therefore the system periodically switches to defrosting mode with the release of heat into the external environment, and this also reduces the COP and the system becomes effective as a conventional electric heater.

The principle of operation of heat pumps, “air-to-air”, “water-to-air” and “ground-to-air” is that the houses use “air heating” by installing air ducts and fans that take heat from the internal circuits of the heat pumps and distribute warm air on the premises. At the same time, heating radiators and heated floors are not used.

Heat pump "ground-to-water". In this scheme, the heat removal comes from the soil, in which the temperature at a depth of 2 meters does not change during the year and is about 6 degrees. The primary heat exchanger can be installed both vertically and horizontally and can be closed or opened. In the closed circuit there is a circulation of the heat carrier on the pipes placed in the ground.

In the open circuit, heat exchange occurs through the circulation of groundwater from specially prepared wells. From the receiving well there is a selection of water for the heat exchanger and for economic needs, followed by the return of water to the second well. An important feature is the construction of wells taking into account the underground flow to prevent water mixing.

Horizontal circuit. Consisting of plastic pipes and placed in the ground a heat exchanger is laid in rings below the freezing depth (for the Moscow region – below 1.5 meters). The necessary condition is the availability of a suitable land plot.

Vertical contour. This method involves drilling one or more wells to a depth of 50 to 140 meters. At the bottom of each well a U-shaped load is lowered with two plastic tubes making up this circuit. The tubes are filled with antifreeze, consisting of a 30% solution of ethyl alcohol.

Disadvantages. With an open circuit, the heat carrier is water, which significantly limits the amount of heat removal, when you try to remove more heat, water freezes and the entire system fails. Additionally, with an allowable heat removal, a high intensity of water circulation is required due to powerful pumps, which reduces the efficiency and can lead to failure of the wells.

The closed circuit with a vertical heat exchanger also has a number of disadvantages, as it is the most expensive in installation and maintenance, there is also a need to install high-power circulation pumps capable of circulating the heat carrier at depths up to 140 meters.

Only a closed-type system with a horizontal arrangement of the circuit has the least drawbacks. The low cost of land work at a depth of not more than two meters, it is also possible to combine the placement of the geocontour by installing the foundation, thereby reducing the total cost of the work. In the absence of clay soil, the cost of preparing the soil composition, ensuring soil moisture due to the designed spillway and drainage systems, are comparable to the cost of gardening and landscaping.

3 Results

Based on the analysis of foreign construction of frame houses, the author identified key criteria for energy efficiency. Based on the results of a study of the model range and types of heat pumps, the composition of the equipment and the necessary starting conditions for creating an “energy-efficient” house with the climatic environment of the Moscow region were determined.

Next, we will calculate the payback of installing a heat pump using the example of a country house with an area of 100 sq.m. In addition, the author proposed the modernization of the existing soil-water heat pump operation scheme through heat recovery from sewage and double recovery of supply and exhaust ventilation using an enthalpy heat exchanger. According to the author, the proposed scheme will create a comfortable indoor microclimate to ensure air exchange and humidification, as well as increase the COP, which will lead to a reduction in electricity costs.

Table presents a comparison of the main characteristics of an electric boiler with a heat pump, as well as one-time and monthly costs. The author has taken as a basis the most common criteria for suburban real estate in the Moscow region - this is a plot of 6 acres, a house of 100 sq.m. Materials and manufacturing techniques of the house are not significant, a key indicator is thermal conductivity not higher than $0.17 W/m^2K$.

Table. 1 Comparison of the costs of installing and operating a heat pump and an electric boiler

Type of equipment	Heat pump 10kW "Ground-to-water" with the COP = 5	Electric boiler 10 kW
The average market price = cost of materials work with the use of domestic equipment	500 000 RUB (with VAT), including the cost of materials, earthworks and installation works for placement of geoconture and installation of equipment	500 000 RUB (with VAT)
Average annual electricity consumption (kW per year)	4 000 kW	20 000 kW
Electricity costs (RUB per year, at a cost of 1 kW = 5 RUB.)	20 000 RUB	100 000 RUB
Payback	(500000–50000)/(10000 –20000)= 5,63 years	

As can be seen from the calculations, if the above energy efficiency criteria are met, including the preparation of the soil mass, it is possible to achieve the COP =5, the payback of such a system will be 5 years and 7.5 months.

The presence of a warm house equipped with a modern heating system is not the last step in creating an energy-efficient and comfortable space for people to live, but it makes it easy to solve the problems of ventilation and humidification of premises. The author proposes to use a ventilation system with an enthalpy recuperator in such “insulated” houses, this will save humidity in the rooms, and this type of recuperator is acceptable for use at low temperatures due to the lack of condensate. Additionally, it is proposed to implement a scheme in which the supply air after passing through the recuperator enters the secondary heat pump heat exchanger. Thus, even at low temperatures, air will enter the premises with temperatures above 17°C. The scheme proposed by the author will also allow for fine-tuning of the temperature in the rooms, regulating the flow of the heat carrier into the warm floors, which is impossible, for example, with only air heating. In the summer period, it is possible to provide for the work of cooling the premises by using the passage of the supply air through the primary circuit with a temperature of +7°C with condensate drain. In this case, only the primary circulation pump will be activated on the heat pump. Also, to increase the COP, the author proposes to use the thermal energy of sewage discharged into the primary tank for subsequent treatment. The primary tank must be insulated from the outside, create a buffer tank in it and pass through it the thermal circuit pipes emerging from the soil. After passing through this heat exchanger, the pipes are connected to the supply to the heat pump. This will increase the input temperature at the primary heat exchanger, even a slight increase in it can significantly affect the COP in the direction of increase.

4 Discussion

At present, in Russia there is a huge selection of climatic equipment that can solve, as a rule, only one problem. If there are several problems, then sometimes it is required to purchase several systems. Moreover, these problems are usually the result of failure to meet the key criteria for energy efficiency described above. For example, in an insufficiently insulated house, as a rule, radiators with a coolant temperature of 65°C and higher are installed. The high temperature of the radiators leads to reduced humidity in the rooms and requires the installation, for example, of an adiabatic humidification system. With this system, cold air is sprayed through nozzles at a pressure of 70 atm, this leads to cooling of the room and requires more heating system performance. The use of heat pumps in insufficiently insulated rooms is irrational, because requires a backup heating source (electric boiler, pilot, or solid fuel boiler), which will be used at extremely low temperatures. The additional cost of equipment increases the payback period to 20 years or more.

5 Conclusion

Based on the analysis, the author lists the main criteria for energy efficiency:

1. The design of the house and the build quality should ensure the thermal conductivity is not higher than 0.17 W/m^2K.

2. The presence on the land of the soil massif with high thermal conductivity and heat capacity, or special soil preparation.

3. The right choice of type and model of the heat pump. The most acceptable heat pump option is "ground-to-water".

4. The use of two constructive solutions:

- double supply air recuperation scheme, the first recuperation takes place using an enthalpy recuperator, the second recuperation occurs due to the supply air passing through the internal heat exchanger of the heat pump
- creation of a buffer tank in the primary storage tank of sewage and organization of recovery by passing the geothermal circuit through the tank, followed by connecting to the input of the heat pump.

Subject to these rules, it is enough to use only one heating system without expensive equipment reserving from low atmospheric temperatures, and living in such a house will be comfortable and healthy.

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