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# TECHNOLOGY AND ECONOMICS OF NEAR-SURFACE GEOTHERMAL RESOURCES EXPLOITATION

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The paper presents economic justification for applicability of near-surface geothermal installations in Luga region, based on results of techno-economic calculations as well as integrated technical and economic comparison of different prediction scenarios of heat supply, both conventional and using geothermal heat pumps (GHP).

Construction costs of a near-surface geothermal system can exceed the costs of central heating by 50-100 %. However, operation and maintenance (O&M) costs of heat production for geothermal systems are 50-70 % lower than for conventional sources of heating.

Currently this technology is very important, it is applied in various countries (USA, Germany, Japan, China etc.), and depending on the region both near-surface and deep boreholes are being used. World practice of near-surface geothermal systems application is reviewed in the paper.

***Key words*:** heat supply, near-surface Earth crust, geothermal resources, subsoil, heat pump, energy, economic assessment, heat provision, thermal product

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**Introduction.** Fuel and energy potential of our planet is composed of various energy sources of cosmic and terrestrial origin, first and foremost subsoil fossils (natural gas, oil, coal, oil shale, turf) or separate elements with specific properties (e.g. uranium, thorium), which can release atomic energy in the course of nuclear reactions [8, 11].

The group of renewable energy sources includes hydro energy, solar radiation, geothermal heat, wind energy, biomass energy etc., which are practically inexhaustible, to a great extent renewable and environmentally friendly [1, 9]. It is related to the fact that the energy of natural processes can be used directly, skipping the stage of fuel combustion or production of nuclear reactions in atomic boilers.

Throughout different countries, the most actively used source is the energy of falling water due to the fact that the capacity of hydro power stations situated on large rivers can be quite significant. Other unconventional renewable sources of energy are widely distributed and do not allow to generate capacities, comparable to those of power stations operating on fossil fuel or nuclear energy. Out of all these types of energy, geothermal sources have a certain advantage, as they are widely spread, allow high concentration of heat in the zones of recent volcanism and hydrothermal activity, and most importantly – they are independent from seasonal and daily fluctuations, unlike solar and wind energy [5, 17].

In the latest decade, there has been a visible broadening of options how to use geothermal energy for heat supply due to practical application of low-temperature resources of near-surface Earth crust. This has become possible with the help of new technologies, related to the use of heat pumps and subsurface (borehole) heat exchangers [19, 21].

**Development of near-surface thermal resources.** The use of low-temperature shallow-depth geothermal energy can be regarded as some techno-economic phenomenon or as a real revolution in the system of heat production. Less than in 30 years the world has developed a multiple-option technology and constructed millions of operating heat supply systems. Near-surface (shallow-depth) geothermal systems are used for heating and cooling of various types of private houses (from very cheap to luxurious ones and from individual property to blocks of flats), fuel stations, supermarkets, churches, education offices etc. [3, 18, 20].

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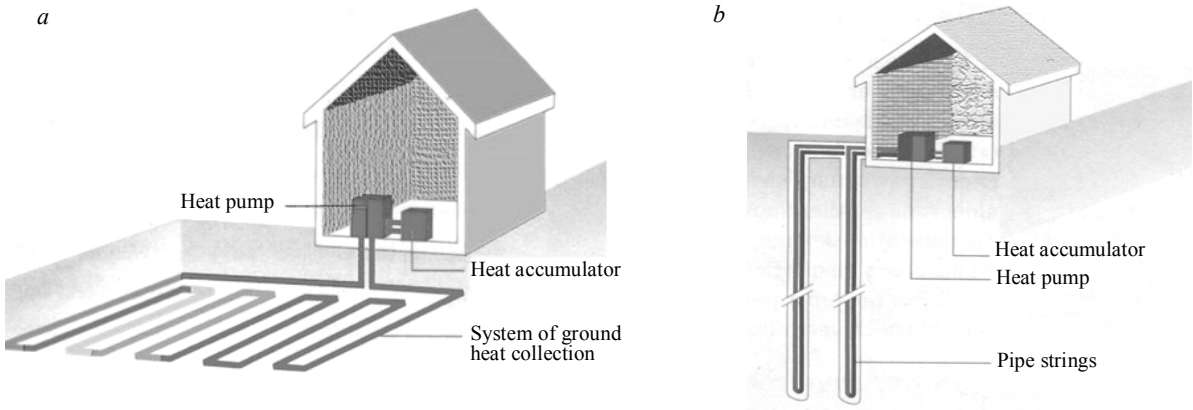



Fig.1. Near-surface (shallow-depth) geothermal system with heat exchange in horizontal tunnels (*a*), in boreholes (*b*)

The idea behind this technology is to create an underground heat exchanger [4], situated at shallow depth of 200-300 m, with a closed or an open loop, connected to a heat pump, located inside the heated space (Fig.1). Temperature of the rocks used for this purpose should be in the interval from –5 to +15 °C.

These systems use not only geothermal energy, accumulated in mineral rocks or water, but also solar radiation. A precise share of various types of energy used by the source depends on the depth of heat exchanger, climate and hydrogeological conditions of the area. It is supposed that for shallow-depth horizontal heat exchangers solar energy will account for the major share. Near-surface systems can provide heat supply for prevailing conditions in any country or its regions, define local economic efficiency and growth rates of the industry.

Many countries have already installed systems that facilitate increasing use of near-surface geothermal resources. Most of them are confined to North America, Europe and China. The number of countries with such installations has risen from 26 in 2000 to 33 in 2005, 43 in 2010 and 48 in 2015. Capacity of these installations varies from 5.5 kW for private houses to 150 kW for commercial enterprises. The number of 12 kW-installations (typical for private houses in the USA and Western Europe) is approximately 4.16 million [20].

Geothermal heat pumps (GHP) have been recognized as an efficient source of renewable heat generation, but even more important is their role in combating climate change. This is confirmed by Canadian energy specialists: «We can hardly expect any commercially available technology, other than geothermal heat pumps, to have a greater potential of mitigating negative effects of carbon dioxide emissions and heating of buildings by other sources».

The main areas of application for heat products of near-surface (shallow-depth) geothermal systems (installations), taking into account customer specifics, are:

• heat and hot water supply for individual private houses;

• heating and air conditioning of individual houses; multi-storey apartment houses; schools, hospitals and other municipal buildings; business offices; residential areas or building clusters;

• thawing of snow and ice cover on the sidewalks and driveways.

Two basic technologies are used for GHP construction [2]: closed loop, connected in the subsoil, and ground water (open loop). These systems (Fig.2, 3) can be positioned horizontally, vertically or in water reservoirs (rivers, lakes, seas). It is reasonable to construct heat pumps in near-surface layers either in the areas where hole drilling is economically viable, or where there are boreholes already.

In the closed loop scheme the pipes are oriented either horizontally (at the depth of 1-3 m) or vertically (at the depths from 20 to 300 m). Heat exchange of water anti-freezing agent takes place through plastic pipes, in order to absorb the heat of the subsoil in winter or to give up heat to the subsoil in summer.

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Open loop systems use ground or reservoir water directly in the heat exchanger and then discharge it either into the subsoil or for irrigation purposes. GHP efficiency is characterized by the energy conversion coefficient (ECC), which is a ratio between the energy produced and the input (electricity for the compressor); for the equipment in place it varies from 3 to 6 (the greater the value, the higher the efficiency). Thus, ECC = 4 shows that one unit of electricity equals four units of heat.

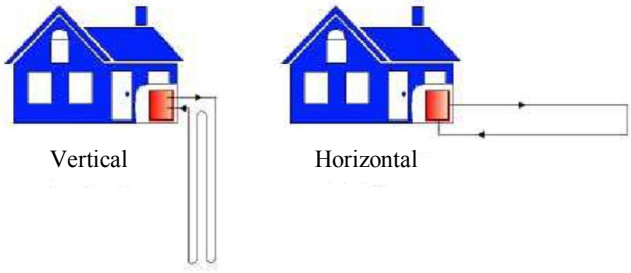
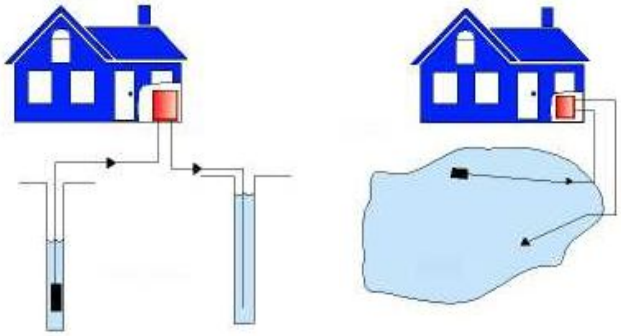


Fig.2. GHP scheme «closed loop»


Fig.3. GHP scheme «open loop»

Estimating how the use of geothermal heat pumps can change the world economy in terms of fossil fuel consumption in tons of oil equivalent (toe) and in terms of $CO_2$ flow, the following assumptions have been made. E.g., comparison between annual use of geothermal energy – 28,000 TJ (7,800 GWh) – and heat production by oil power plants operating at 30 % efficiency demonstrates saving of 15.4 million oil barrels or 2.3 million toe. This prevents approximately 7 million tons of $CO_2$ from being emitted into the atmosphere [20]. In particular, reduction of $CO_2$ emissions through GHP application is absolutely evident. E.g., connection of underground heat pumps to the regular heating system of Great Britain can lead to a cut in $CO_2$ emissions of more than 50 %, as compared to conventional heating technologies based on fossil fuels.

A classification of geothermal heat pumps technologies has been proposed (Fig.4).

**Experience of the USA in using geothermal heat pumps.** The majority of GHP units in the USA have been built for cooling purposes and to a lesser extent for heating, the load of which is on the average only 1,000 hours per year [14].

In Europe most units are installed for heating purposes, and frequently they only cover base-load demand with the support of fossil fuels for peak hours. For this reason European systems can function from 2,000 to 6,000 hours per year, on the average around 2,300 hours of maximum load.

Even though the cooling process returns the heat to the soil and therefore GHPs are not a fully geothermal source of energy, this non-fossil fuel does contribute to a cleaner environment. In the USA, in 2005 GHPs accounted for approximately 12 % of all heating and cooling operations, mostly in Midwestern and Eastern states from North Dakota to Florida. In this period 50,000 unites were implemented annually, where 46 % are vertical closed loop systems, 38 % – horizontal closed loop systems, 15 % – open loop systems. Over 600 schools have installed these units for heating and air conditioning; they are especially popular in Texas. GHPs for typical private needs have an installed capacity of around 10.5 kW.

One of large GHP constructions in the USA operates in the Galt Hotel in Louisville, Kentucky. The GHP provides heating and air conditioning for 600 guest rooms, 100 apartments, 89,000 $m^2$ of the office area, total 161,650 $m^2$. It pumps 177 l/s into four boreholes at temperature 14 °C, serving 15.8 MW of cooling and 19.6 MW of heating load. Compared to a similar adjacent building, which has no GHP, consumed heat energy allows to save approximately 50,000 USD a month.

**European experience of near-surface geothermal resources exploitation.** Geothermal heat pumps can be applied for heating and cooling practically anywhere and they have enough flexibility

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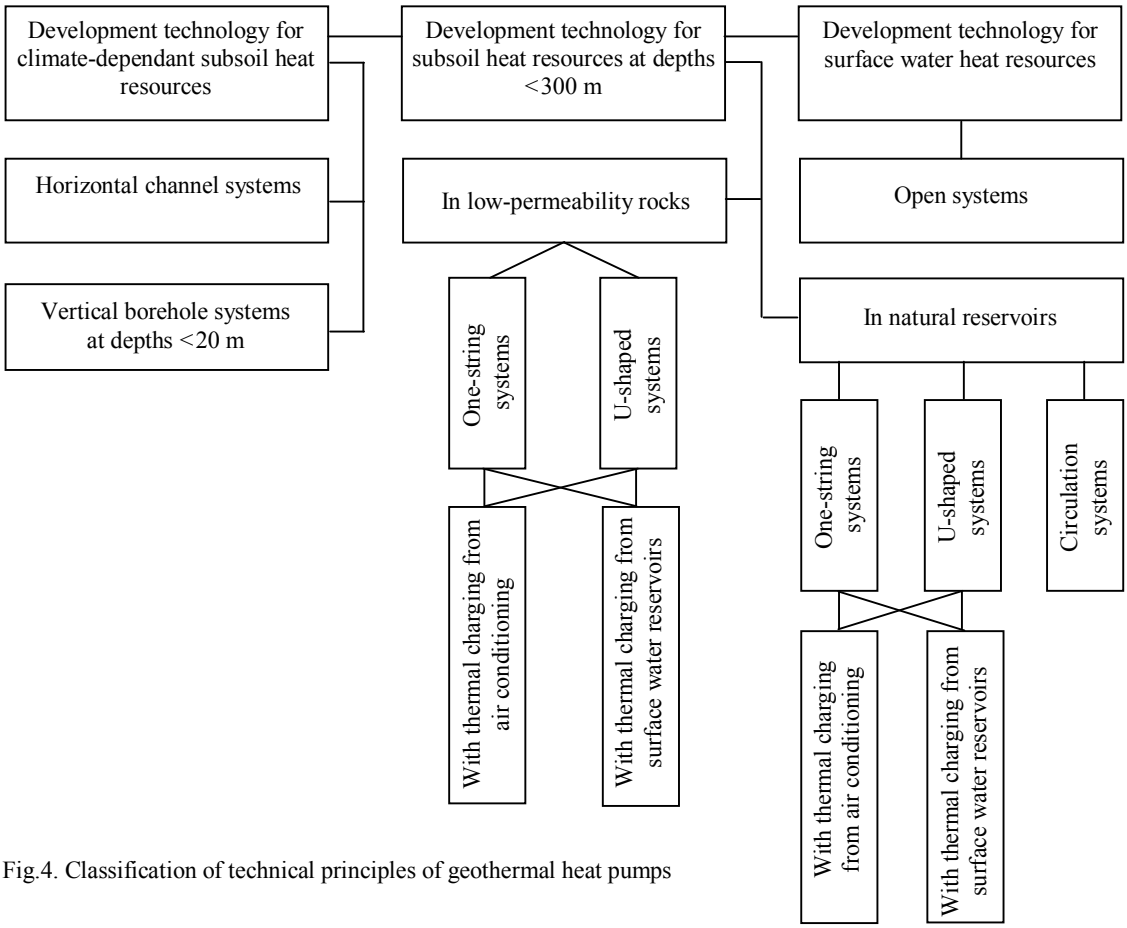



Fig.4. Classification of technical principles of geothermal heat pumps

to satisfy any requirements. In Western and Central Europe, direct use of deep geothermal energy to supply heat to densely-populated regions is currently limited to certain geologic and geometric conditions. In this situation the application of omnipresent near-surface geothermal resources by de-centralized GHPs is a clear choice [15].

The result of this is that such systems actively penetrate the market; the number of commercial enterprises, working in this field, is constantly growing and so does their production. More than 20 years ago in Europe the concept of supporting this technology was approved, together with abovementioned generic project and its installation criteria. A typical borehole GHP of the «vertical loop» type is presented in Fig.5.

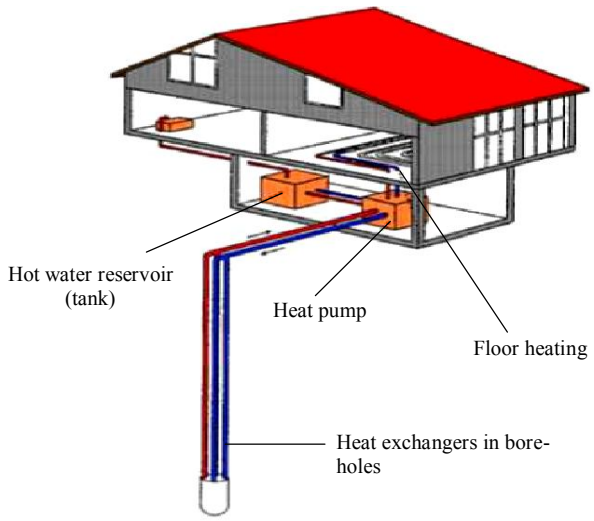



Fig.5. Typical use of a private heat supply system with a geothermal heat pump in Central Europe (borehole depth ≥100 m)

**GHP systems in China.** GHP is based on the original innovative technology of using heat energy of the near-surface Earth crust, which has been invented and developed to supply heat to private houses and commercial buildings. Since its appearance on the market in 2001, the technology has attracted attention of customers and government services of China [24]. GHPs are successfully applied in various provinces of the country and provide service to a wide range of buildings: private houses, office buildings, hotels, hospitals, shopping malls, schools, the National Theater. The systems have also been applied during the Olympic Games in Beijing (2008).

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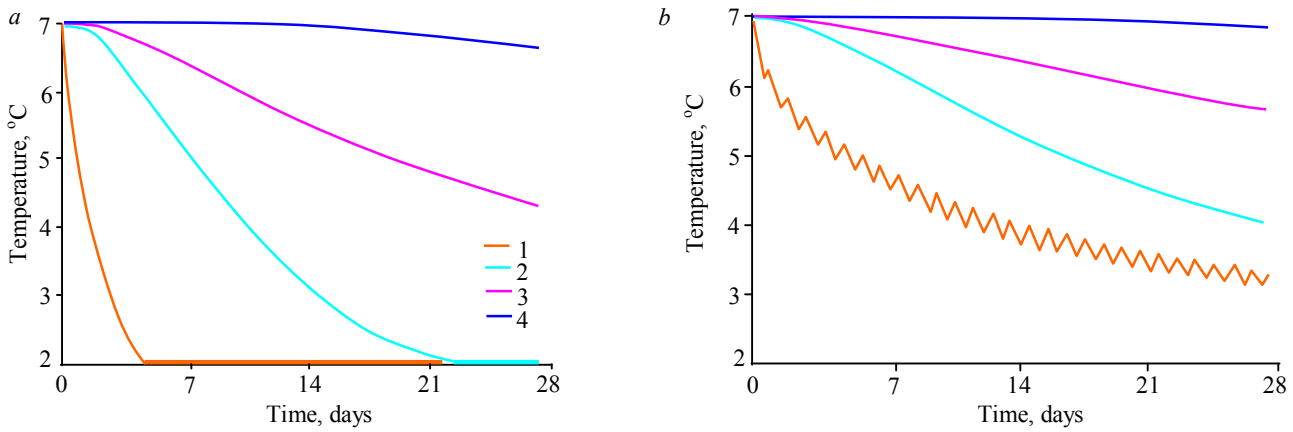



Fig.6. Underground temperature curves for continuous (a) and intermittent (b) heating operations
1 – 3.2 m from the pipe; 2 – 1.2 m; 3 – 0.1 m; 4 – 1 m between two pipes

**Heat pump operation from a shallow-depth underground source in Japan.** By means of experiment on the system of near-surface GHP in the city of Takanashi, rock temperatures in the proximity of a borehole have been identified for both continuous (permanent) and intermittent heating processes [23]. In case of intermittent heating, the system has been operated from 6 h 00 min till 21 h 30 min in the cycle of 30-minute liquid circulation and 30-minute pause. Fig.6 shows temperature changes in near-surface rocks for continuous and intermittent operations.

In case of continuous heating, rock temperature in the proximity of the borehole quickly decreases – in particular, at the distance 0.1 m from the borehole the temperature reaches the level of supplied heat-transfer agent in 6 days.

In the course of intermittent heating, rock temperature decreases at a slower pace. It indicates that rock temperature around the borehole recovers when the circulation is paused.

**Geothermal systems with heat pumps in Russia**. Efficiency of energy use is an indicator of scientific, technical and economic potential of the community, which allows to estimate the level of its development.

Comparison of energy efficiency parameters of different countries shows that in Russian economy energy consumption within gross domestic product (gross national product) is several times higher than in developed countries. Specific energy consumption in Russia is approximately four times higher than in the USA – a country with high capacity of goods production and services provision; 2.5 and 3.6 times higher than in Germany and in Japan respectively. This implies that it is possible to cut energy consumption in Russia by 40-50 % in the least [13, 16, 22].

Generation of high temperatures with the help of heat pumps is one of the most promising fields of energy conservation, and currently it attracts a lot of attraction worldwide.

The energy crisis of 1970s served as a powerful incentive for GHP development. E.g., in the USA in this period the number of produced heat pumps tripled and hit the level of 300,000 a year, with the number of GHP installed around 1 million. In 1980s the rates of GHP application stabilized and then started growing again due to environmental concerns and the initiative of energy conservation. Unfortunately, in Russia only a few individual buildings have been equipped with GHP.

In 1994-1997, in order to demonstrate how non-conventional energy technologies can be applied in buildings with regular operating conditions, a recreation and entertainment park «ECOPARK FILI» was put into operation in Moscow [10]. Demonstration complex consists of support facilities and two office buildings of the «Ulitka» type. Total area of the buildings is 1,000 $m^2$. The complex is situated in the territory of 1 hectare. The buildings of the complex are equipped with automated heat pump systems of heat supply (ATNU), using low-potential heat energy from near-surface layers. GHPs include systems of ground heat collection to extract 40 kWh of

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low-potential heat from the Earth crust. They are connected to four heat pumps ATNU-15 (produced in Russia), which achieve heat productivity of 60 kWh.

Monitoring results for heat pump systems and buildings on the whole are presented below:

| Parameter | Building 1 | Building 2 |
|---|---|---|
| Thermal resistance of external protection, $m^2 \cdot °C/W$ | | |
| Walls | 1.2 | 3.0 |
| Windows | 0.4 | 0.4 |
| Current energy consumption, MWh per year | 143.5 | 49.8 |
| Lighting and household needs | 48.0 | 18.0 |
| Hot water supply | 16.0 | 12.0 |
| Heating | 79.5 | 19.8 |
| Specific consumption of capacity resources , $kWh/m^2$ per year | 478 | 166 |

When assessing energy efficiency of the buildings, all the input energy has been taken into account: for heating purposes, hot water supply, lighting, office equipment and household needs.

In 1998 in Yaroslavl Oblast for the first time in Russia a village school was equipped with a GHP system. Two-storey building of the school is made of brick, total area ~2,000 $m^2$, volume ~6,900 $m^3$, wall thickness 640-680 mm, area of window and door openings ~230 $m^2$ and ~20 $m^2$. The building has an underground facility. The school is situated in Filippovo village, 100 km from Yaroslavl, and is intended for 162 pupils and 20 teachers. The heat pump is located in a separate building, designed for a coal boiler facility.

It should be noted that several mistakes have been made in the process of system design, namely: distance between boreholes has been substantially under-estimated, and very low depth has been selected for them. This was the reason of a relatively low energy conversion coefficient – only 2-3 % [7].

Some monitoring results of the school heating system operation:

| Parameter | 5th October 2001-4th November 2001 | 4th November 2001-23rd March 2002 |
|---|---|---|
| Thermal energy production, kWh | 33,348.8 | 244,878.0 |
| Energy consumption, kWh | 21,465.0 | 183,810.0 |
| Amount of energy from the subsoil, kWh | 18,368.8 | 92,168.0 |
| Energy saving (excluding hot water), % | 45 | 31 |
| Energy conversion coefficient, fraction | 3.23 | 2.16 |
| Average amount of subsoil heat extracted for 1 m of heat exchanger length, W/m | 182 | 126 |

In 2001 a house with an experimental heat supply system was constructed and put into operation in Moscow at Akademika Anokhina Street.

Results of construction are presented in Table 1 in form of comparison between the project design and experimentally obtained actual parameters.

*Table 1*

**Results of comparison between the project design and actual parameters of geothermal heat supply in the house at Akademika Anokhina Street, Moscow**

| Parameters | Reference house | | Energy efficient house | |
|---|---|---|---|---|
| | Design | Experiment | Design | Experiment |
| Thermal capacity consumed, kW | | | | |
| heating | 362.5 | 388.6 | 379 | 370 |
| hot water supply | 453.6 | 723.3 | 90 | 83 |
| Annual consumption by the building, MWh | | | | |
| thermal energy for heating | 1059 | 1008 | 577 | 560 |
| energy for GHP | 182.5 | 27.3 | 384 | 430 |
| Annual consumption for 1 $m^2$ of apartment space, kWh | | | | |
| thermal energy for heating | 162 | 154 | 87.6 | 85.0 |
| electrical energy | 124.5 | 80.1 | 132.4 | 157 |
| Annual fuel consumption for 1 $m^2$, kg o.e./$m^2$ | 55.1 | 40.9 | 27 | 30 |
| Energy saving compared to reference house (design), % | 0 | | 50 | 45.5 |

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Table 2 contains results of integrated technical and economic comparison of prediction scenarios for conventional and GHP heat supply in Moscow by 2020. The comparison has been made using the following assumptions:

1. Cost of 1 ton of oil equivalent (o.e.) – 100 USD.
2. Capital investment into 1 kW of conventional technology (regional heating plant, individual gas boiler in the building etc.) – 100 USD excluding capital investments into the heat network.
3. Capital investment into 1 kW of GHP heating efficiency – 250 USD, modification of the system to use low-potential heat – 50 USD.
4. Fundamental investments into GHP are incurred solely by investors of constructed or restored objects and involve no costs for the city budget.
5. Average annual energy conversion coefficient for GHP technology is set to 3.5.

*Table 2*

**Results of techno-economic comparison of prediction scenarios for conventional and geothermal heat supply in Moscow by 2020**

| Techno-economic parameter | Scenario | |
|---|---|---|
| | Reference | Geothermal |
| Capacity of installed equipment, MW | 66,700 | 66,700 |
| Electricity-generating equipment, MW | 9,500 | 14,500 |
| Heat pumps | – | 5,000 |
| Heating equipment, MW | 57,200 | 57,200 |
| Heat pumps | – | 17,500 |
| Resource saving per year | | |
| million MWh | – | 32.25 |
| million tons of o.e. | – | 3.84 |
| Capital investment into heat pumps, million USD | | 5,605 |
| from city sources | | 1,230 |
| from the budget | | 4,375 |
| Saving of municipal O&M costs on primary fuel procurement, million USD | – | 384 |

Capital investment into construction of near-surface geothermal system (NGS) can be 50-100 % higher than the cost of traditional systems of combined heat production [6]. In the USA it is considered satisfactory if the project pays off in the period of 4-8 years. At the same time, operation and maintenance (O&M) costs of energy production by NGS are 50-70 % lower than the costs of conventional heating, using electricity or oil products. Payback period is shorter in distinctly continental climate, where the system can be used for heating in winter and for cooling in summer. Cost calculation for NGS construction in a private one-family house in Switzerland (in thousands USD) confirms this statement:

| Costs | NGS | Oil heating boiler |
|---|---|---|
| Borehole heat exchanger to the depth 135 m | 8.05 | – |
| Heat pump | 7.35 | – |
| Regulation of heating system | 1.61 | – |
| Materials and installation | 2.94 | – |
| House boiler, low-NO burner | – | 5.6 |
| Plastic container for oil products | – | 4.2 |
| Flue system | – | 4.9 |
| **Total** | **19.55** | **14.7** |

Results of calculations, based on economic-mathematical modeling of geothermal heat supply system for a cottage in Luga region in 2016, are given below. Basing on the developed economic-mathematical model [6], investigations and optimization calculations [12] have been carried out for NGS parameters:

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**Natural, economic conditions and input parameters**

| | |
|---|---|
| Number of residents, persons | 5 |
| Maximum water temperature in the supply pipeline, °C | 70 |
| Maximum water temperature in the return pipeline, °C | 40 |
| Water temperature during summer hot water supply, °C | 50 |
| Cold water temperature in winter, °C | 3 |
| Temperature of water discharged by GHP, °C | 3 |
| Diameter of water-feeding pipe (water column), m | 0.1 |
| Desirable lifespan of the system, years | 15 |
| Length of productive borehole, m | 200 |
| Yield of productive borehole, $m^3/h$ | 3 |
| Rock temperature at bottom hole, °C | 10 |
| Reservoir thickness, m | 180 |
| Distance between boreholes, m | 15 |
| Distance between borehole sets, m | 15 |
| Cost of electricity, rub/Wh | 0.00337 |
| Bank rate, % | 7 |
| Cost of fuel (diesel), rub/toe | 35,800 |
| Maximum thermal load during heating season, MJ/h | 85.29 |
| Total annual thermal load, GJ/year | 244.0 |
| Flow rate of heating water under $Q_{max}$, $m^3/h$ | 0.624 |
| Temperature of water leaving production pipe, °C | 4.79 |
| Flow rate of geothermal heat-transfer agent in the system, $m^3/h$ | 9.60 |
| Borehole diameter, m | 0.250 |
| Maximum number of boreholes, pcs | 4 |
| Borehole lifespan, year | 15.0 |
| Length of heating line, m | 60.0 |
| Diameter of external heating line, m | 0.041 |
| Total maximum injection pressure, MPa | 0.3044 |
| Annual heat production, toe/year | 10.49 |
| Overall maximum power consumption kW | 6.82 |
| Maximum power consumption by the circulation system, kW | 1.32 |
| Maximum power consumption by GHP, kW | 5.50 |
| Overall energy consumption, kWh/year | 14,963 |
| Energy consumption by GHP, kWh/year | 13,928 |

**Economic parameters of the circulation system**

| | |
|---|---|
| Total capital costs, thousands rub | 2,887.78 |
| Capital costs of borehole construction, thousands rub | 1,830.95 |
| Capital costs of borehole pipe columns, thousands rub | 536.77 |
| Capital costs of heating line, thousands rub | 64.55 |
| Capital costs of pumping facility, thousands rub | 88.22 |
| O&M costs (incl. loan payments), thousands rub/year | 300.75 |
| Energy costs, thousands rub/year | 3.49 |
| Working expenses (subsidies), thousands rub/year | 13.89 |
| Loan and interest payments, thousands rub/year | 286.85 |

**Economic parameters of GHP**

| | |
|---|---|
| Capital costs, thousands rub | 855.89 |
| O&M costs (incl. loan payments), thousands rub/year | 132.35 |
| Energy costs, thousands rub/year | 46.94 |
| Working expenses (subsidies), thousands rub/year | 47.33 |
| Loan and interest payments, thousands rub/year | 85.02 |

**Economic parameters of the overall system**

| | |
|---|---|
| Capital costs, thousands rub | 3,743.67 |
| O&M costs (incl. loan payments), thousands rub/year | 433.09 |
| Working expenses (subsidies), thousands rub/year | 61.22 |
| Loan and interest payments, thousands rub/year | 371.87 |

**Economic criteria of the system efficiency**

| | |
|---|---|
| Costs of heat production (loan), rub/MJ | 1.775 |
| Costs of heat production (subsidies), rub/MJ | 0.251 |
| Payback period (subsidies), years | 9.82 |

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## Conclusions

1. Low-temperature geothermal energy from near-surface layers of the Earth crust is a powerful source of heat or frost. Application of near-surface geothermal systems is a significant and a widely-spread resource, which can be used to supply heat for private houses, common facilities, industrial and agricultural objects.

2. GHP system offers a technical solution with low capital and O&M costs.

3. The system reviewed in the paper belongs to the «closed loop» type, without any emissions of gas, liquid or other contaminants.

4. Extensive application of the system will serve as an incentive for enhancing efficiency of geothermal energy use and environmental protection, as well as for reduction of geothermal energy costs.

5. Saving of fossil fuels (coal) for heating the area of 2.5 million $m^2$ is equivalent to the emission reduction of 260 thousand tons of $CO_2$, 2.2 thousand tons of $SO_2$ and 1.6 thousand tons of $NO_2$.

6. The paper briefly summarizes and analyzes state of development and application practice of a relatively new technology of extracting geothermal energy for its use in heat supply – geothermal heat pump installations (systems).

7. A rough estimation of the practicability and efficiency of constructing such system has been carried out for Luga region of Leningrad Oblast.

8. Techno-economic calculations have demonstrated technological and economic feasibility of such solution to heat supply problems in this region.

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