Energy and Economic Efficiency of Gas Turbine Units and Heat Pumps in Power-supply Systems in the Arctic Regions of Russia

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Abstract. Currently, in publications, there is some controversy about the efficiency of various power-supply systems operating in extreme climatic conditions. The need to dispel this controversy explains this study's relevance. The purpose of this study is to evaluate the feasibility of the use of cogeneration gas turbine and microturbine units as the heat-and-power source for a camp-like residential facility in the Arctic regions of Russia. A boiler plant and a heat pump system are analyzed as heat sources for the afore-mentioned camp. The authors used their own mathematical models of the units to do the study. The estimates were based on the annual facility-specific power and heat consumption data, additionally climatic conditions and fuel kind (natural gas) were taken into consideration. The study resulted in defining the plants' limits of equal fuel consumption, depending on the substituted power output efficiency and the power/heat production cost to the price of gas correlation. Another result was the evaluation of the power efficiency (by the natural gas consumption) and economic feasibility, as well as the payback term. We concluded that in case the natural gas was the only fuel available the ground source vapor-compressing heat pump systems were power-wise and economically unsound, provided they were operated under environmental conditions typical for the Russian North and according to the region-specific heat-supply schedule. The outcome of this study can be used when planning/designing the power-supply facilities in extreme climatic conditions, as well as in evaluating/estimating the power-supply systems' efficiency.

Keywords: boiler plant, cogeneration, efficiency, gas turbine unit, heat pump, microturbine unit, payback term, power supply, production cost.

Eficiența energetică și economică a turbinelor cu gaz și a pompelor de căldură în sistemele de alimentare cu energie în regiunile arctice ale Rusiei

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Rezumat. Scopul investigației îl constituie estimarea eficienței energetice și economice de alimentare cu energie a unei tabere de schimb, amplasate în regiunile arctice ale Rusiei cu utilizare în calitate de surse de generare a energiei electrice și termice a instalațiilor cu co-generare cu turbine pe gaze, microturbinei pe gaze, centralei termice pe gaze, pompei de căldură cu compresia de vaporilor de apă. În calculele au fost folosite modelele matematice elaborate de autorii lucrării. Calculele sunt efectuate în curbelor anuale de sarcină pentru energia electrică și termică a obiectului cercetat, ținând cont de cont de condițiile climaterice din zonă în cazul utilizării în calitate de resurse energetice primare ale gazelor naturale. Calculele au determinat indicatorii de performanță a tipurilor de instalații utilizate pentru producerea energiei, utilizând în calitate de criteriu de comparare raporturile costurilor energiei electrice și termice produse, gazelor naturale utilizate. S-a estimat eficiența economică și termenii de rambursare a investițiilor. S-a determinat, că în condițiile de disponibilitate a gazelor naturale pentru transformare în energie pompe subterane de căldură cu compresia vaporilor de apă pentru condițiile caracteristice nordului Rusiei sunt energetic și economic neeficiente. Rezultatele cercetărilor se pot utiliza la elaborarea proiectelor de alimentare cu energie ale obiectelor din zonele de nord, precum și pentru cercetarea eficienței sistemelor de alimentare cu energie electrică.

Cuvinte-cheie: centrală termică, cogenerare, eficiență, instalație cu turbină cu gaz, sistem cu pompă de căldură, microturbina, durata de recuperare, energie, costuri.

Энергетическая и экономическая эффективность применения газотурбинных установок и тепловых насосов для систем энергоснабжения в арктических регионах России

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Аннотация. Неоднозначность имеющихся в литературе данных об эффективности разных вариантов систем энергоснабжения в условиях сурового климата определяет актуальность данного исследования. Целью статьи является оценка энергетической и экономической эффективности энергоснабжения вахтового поселка, расположенного в арктических регионах России, с применением в качестве источников электро- и теплоснабжения когенерационных газотурбинной установки и микрогазотурбинной установки, а в качестве источников теплоснабжения также газовой котельной и парокомпрессионной теплонасосной установки. При расчетах использованы созданные авторами математические модели этих установок. Расчеты проведены по характерным годовым графикам электрических и тепловых нагрузок объекта энергоснабжения с учетом климатических условий при условии использования в качестве топлива природного газа. В результате расчетов выявлены показатели эффективности установок рассмотренных видов в зависимости от эффективности производства замещаемой электроэнергии и соотношения стоимости электроэнергии, тепловой энергии и газа, определен энергетический (по расходу природного газа) и экономический эффект от их применения, а также сроки окупаемости инвестиций. Определено, что при наличии природного газа как основного топливного ресурса грунтовые парокомпрессионные теплонасосные установки в условиях российского Севера при работе по характерным температурным графикам систем теплоснабжения энергетически и экономически неэффективны. Результаты работы могут быть использованы при разработке проектов энергоснабжения объектов в условиях сурового климата, а также при исследовании эффективности систем энергоснабжения.

Ключевые слова: котельная, когенерация, эффективность, газотурбинная установка, теплонасосная установка, микротурбинная установка, срок окупаемости, энергоснабжение, себестоимость.

I. INTRODUCTION

The principle factor in reducing the production cost is the effective use of resources. A promising approach is a more efficient use of natural gas and associated petroleum gas to cover the power demands of industry, public infrastructure and population. The primary task in this approach is to correctly choose a power/heat supply system based on its characteristics. The use of distributed power generation systems (DPGS) for cogeneration purposes to cover the power/heat needs of facilities removed from Russia's unified power grid makes it possible to conserve material and power resources. Due to the increased fuel heat recovery efficiency η_{it} (HREC) it also becomes possible to cut down the emission of green-house gases [1, 2].

The value of HREC is determined as follows:

$$\eta_{it} = \eta_e + \eta_t . \qquad (1)$$

In formula (1), $\eta_e = N_e / Q_f$ is the efficiency of the plant for generating electrical energy (electrical efficiency), which is equal to the ratio of its electrical power N_e to the thermal power released by the combustion of fuel, Q_f.

$\eta_t = Q_t / Q_f$ is the efficiency of the heat energy release unit (heat efficiency), which is equal to the ratio of the power of its external heat load Q_t $\mathrm{Q_t}$ to the thermal power released by the combustion of the fuel, Q_f.

The DPGS-based cogeneration power supply systems available in the market [3] include low-yield gas turbine units (GTU) [4], vapor-compressing heat pump systems (HP) [5-8], microturbine units (MTU) [9], gas-reciprocating and diesel internal combustion engines (ICE), solar- and wind power systems, and conventional gas-burning boiler plants. When choosing from among power supply systems, it is imperative to compare their respective economic and power efficiency characteristics. One should consider, within a framework of boundary conditions, annual schedules of power and heat consumption specifically for the industry in question, as well as climatic conditions of the region the facility is located in. When comparing certain options and computations outside the boundary conditions, the efficiency of some technologies, e.g. heat pump systems, seems exaggerated [5,7,8]. However, once the boundary conditions were strictly observed, international studies proved economic infeasibility of ground source buried-loop vapor compression HP's in regions of moderate to cold climate, e.g. in Canada [10].

The purpose of this study is to evaluate the feasibility of upgrading the power supply systems of a typical camp-like residential facility for a gas-producing company's employees. The facility itself is located in the Arctic regions of Russia, beyond the Arctic Circle. The upgrade calls for the cogeneration GTU and MTU to be used as a combined power/heat source, the heat supply is an underground HP (the heat exchangers are buried 40-50 m below the surface, which well below the permafrost level). The facility is removed from Russia's unified power grid, thus it is a part of power/heat supply system at the core of which is a medium-yield GTU-TPP. However, the TPP is some tens of kilometers away from the camp, which fact prohibits its use as a heat supply source.

This study's main task was to develop a most fuel-efficient heat/power supply system that could meet the local demands (at the rated temperature of ambient air of -46°C it was 3.729 MW in heat, and 2.75 MW in electric power; the fuel was natural gas (97.5% methane content)).

This study's additional objective was to define parameters of energy and economic efficiency of heat pump plant within given borderline conditions, compared to those of a gas-powered boiler plant. Another goal was to compare, within the frameworks of the afore-mentioned parameters, the internally-powered sources (GTU and MTU) against the externally-powered sources (boiler plants and ground source HP).

II. MATERIALS AND METHODS

The authors used mathematical models of GTU, MTU and HP, which were developed in Vyatka State University (their thermal schemes are presented in Fig. 1-3). Those models were based on complete power balance computations of all the plants' elements of these schemes, including GTU and MTU combustion chambers. We used the technical data provided by the manufacturers of MTU and GTU to verify the plants' efficiency in a wide range of loads [11].

Within a year-long span we used our mathematical models to compute annual fuel consumption and power-production characteristics. To do this in the most accurate way we took into consideration seasonal fluctuations of both electric and heat consumption. The use of mathematical models for MTU and GTU makes it possible to more accurately measure the power efficiency in power/heat cogeneration mode, than when using a more simplified approach of analyzing the mode diagrams or manufacturer-provided data on electric power output [12]. Calculations on the models allow to take into account the influence of not only the value of the flow of the working fluid, but also the temperature of the outside air on the electrical and thermal efficiency of the plants.

It is highly worth mentioning the fact that the mode diagrams for MTU and GTU are absent in the documentation, provided by the manufacturers and equipment suppliers. In this case, calculations based on the models constructed by the authors [11] allow one to take into account the influence of the working fluid flow rate and the temperature of the outside air on the efficiencies η_{it}, η_e and η_t. This outside temperature affects the air/fuel ratio in the combustion chamber, which was determined by the iteration process. The construction of mathematical models of turbine units GTU and MTU is similar to the models presented by the authors in previous works [13, 14].

The calculation of a single-stage HP was carried out according to a standard procedure [15] using a cycle of the refrigerant used (Freon R-134a) in the diagram of its state [16]. During the calculation, the compressor efficiency was constant, but the temperature driving forces in the heat exchangers and the temperature dependences of the refrigerant on the temperatures of the ground and the delivery water varying throughout the year were taken into account.

We used the models to compute the electric and heat loads (both daily and annual) of a camp housing approximately 1500 people. The facility was located on the Yamal peninsula [17]. In our computations we included both the industrial and household electric/heat loads. As a substituted electric-power source (to run comparison on economic and power-producing feasibility) we chose the external GTU-TPP power supply (the same source to power the HP); as the substituted and peak-load heat supply source we picked a gas-fueled boiler plant with an efficiency equal to η_k=0.92 EFF.

Petroleum- and gas-producing companies are keen to cut their expenses on power supply [18, 19], to apply cogeneration in power and heat production (gas turbine- and gas-reciprocating mini CHP plants), and the use of heat pump systems [20].

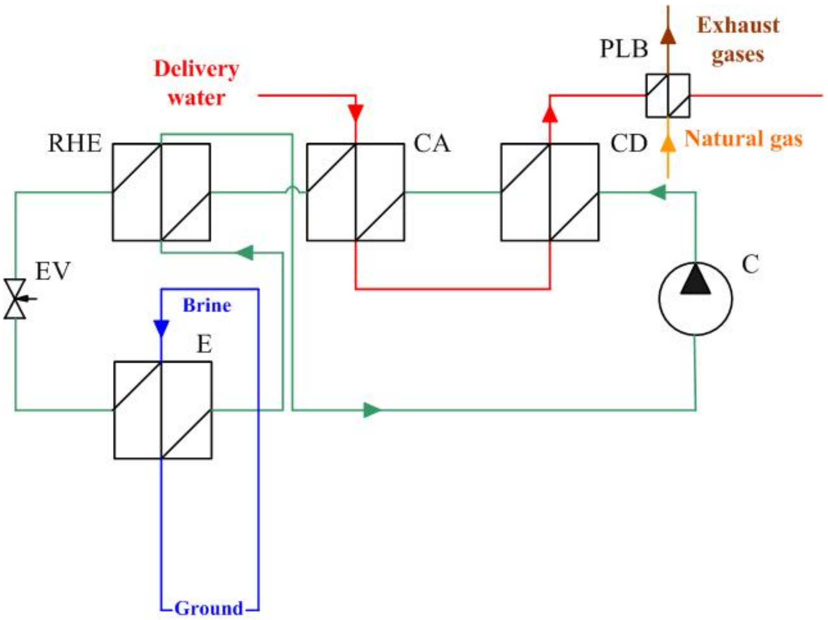
The source data for our computations were aggregate data on the factual monthly heat consumption by the facility. The heating system was designed to be twin-pipe, close-circuit, and direct. With accurate control, the temperature curve of the heating system was set 110/70°C (the rated temperatures of feed and return delivery water respectively). The heating period was 303 days a year [17], while the hot water supply demand was registered all year round. By its power/heat demand and the climatic conditions the camp is representative of such facilities in the Arctic regions of Russia.

The economic efficiency was evaluated through calculation of an average heat/power production cost within a year [21], as well as the payback terms of the upgrading projects [9, 10, 21, 22, 23].

Two versions of the heat/power supply system (employing a gas-burning boiler plant and a ground source HP) meant external electric power supply from the operating GTU-TPP system;

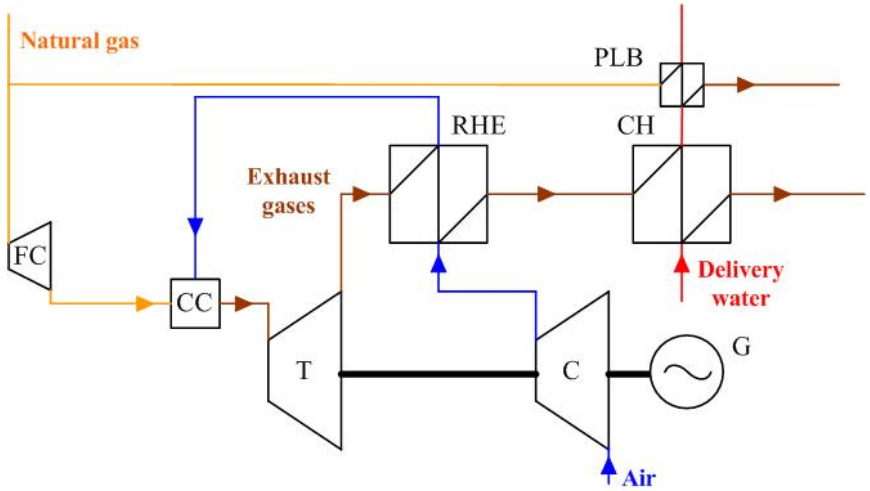
while the other two were meant to generate electric power on their own: to power the GTU that would be the Perm motor-works GTU-2,5P turbine plant (with η_e=22,1% EFF in electric power production under maximum load conditions, and maximum HREC η_{it}=76.9% EFF declared by the manufacturer). To power the MTU it was designed to use a Capstone C200 MTU bloc (η_e=33% and η_{it}=74% respectively). The choice of those plants was explained by their superior characteristics in this price-tag segment for the expected load range.

We used our own mathematical models of the plants whose thermal circuits are demonstrated in Fig. 1-3. Our calculations were founded on heat demand within general ambient air temperature intervals, whose duration was based on the meteorological observations data [17]. The power production efficiency value was kept within the limits set by the GTU and MTU manufacturers for alternating operational modes (Fig. 4, 5). To cover the power demands at the rated load the micro turbine block operated 14 micro turbines 200 kW each. The linearization of monthly average power loads was done through the least squares (along with the thermal load data the information is presented in Fig. 6 as duration diagrams).



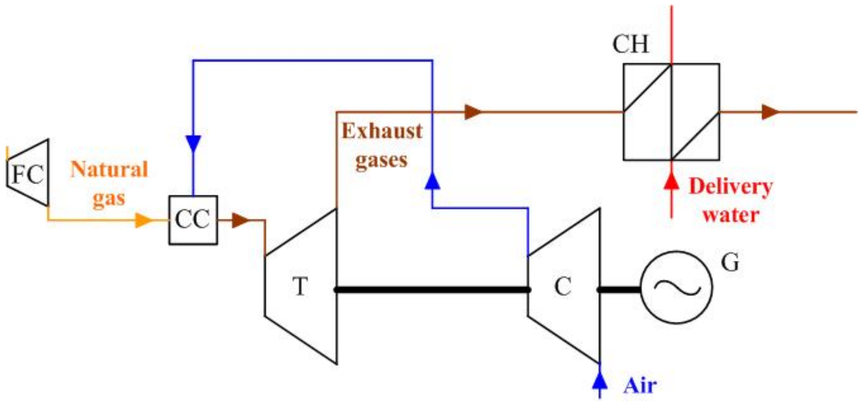
C – compressor, CD – condenser, CA – condensate aftercooler, RHE – regenerative heat exchanger, EV – expansion valve, E – evaporator, PLB – peak load boiler

Fig.1. Heat pump system diagram.



C – compressor, RHE – regenerative heat exchanger, CC – combustion chamber, T – turbine, CH – circuit heater, G – power generator, PLB – peak load boiler, FC – fuel compressor

Fig.2. Microturbine unit diagram.



C – compressor, CC – combustion chamber, T – turbine, CH – circuit heater, G – power generator, FC – fuel compressor

Fig.3. Gas turbine unit diagram.

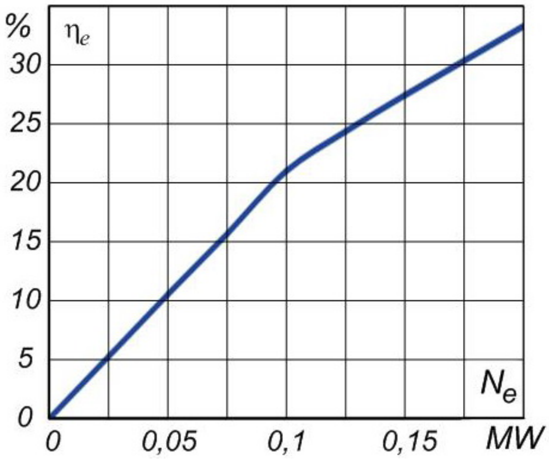


Fig.4. The dependence between the power production efficiency coefficient η_e and the microturbine unit electric load N_e.

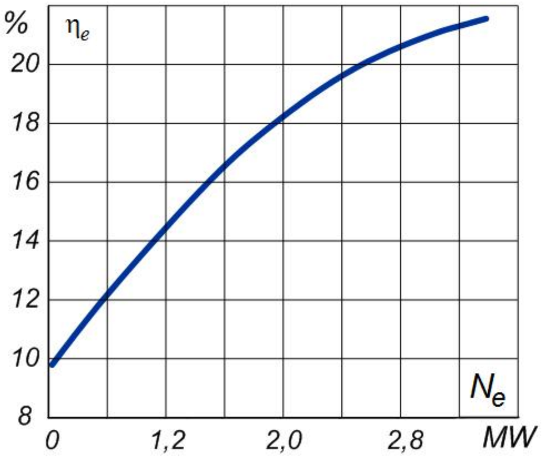


Fig.5. The dependence between the power production efficiency coefficient η_e and the gas turbine unit electric load N_e.

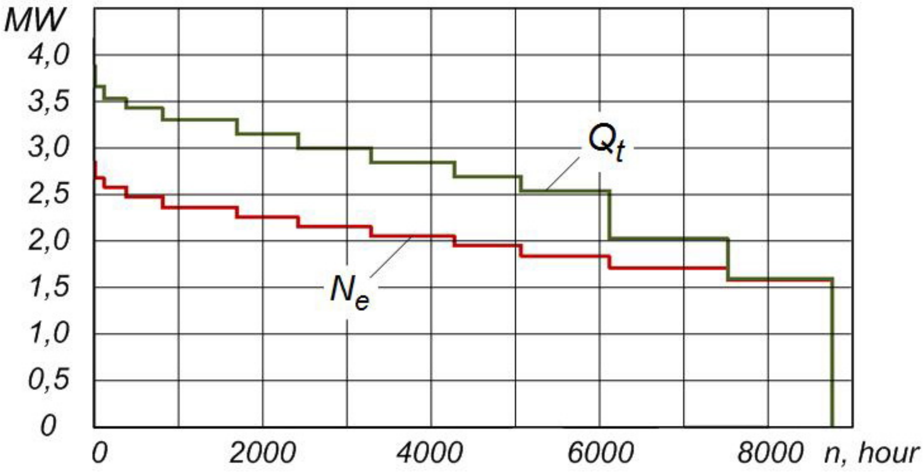


Fig.6. Dependency diagram for heat Q_t and electric N_e loads and the duration of demand periods n within a year.

To do both the heat/power and economic estimates we used the following fixed rates: heat sell price at 2000 RUB/Gcal and the gas procurement price at 5370 RUB per 1000 m^3, in other words the prices were comparable to those at the beginning of 2017. The resource (energy) constituent was derived from three average power rates at: 5.74 RUB/kWh, 4.32 RUB/kWh and 2.88 RUB/kWh, thus the electric power price rates were respectively 11.08, 8.34, and 5.56 times those of gas (per a unit of energy equivalent).

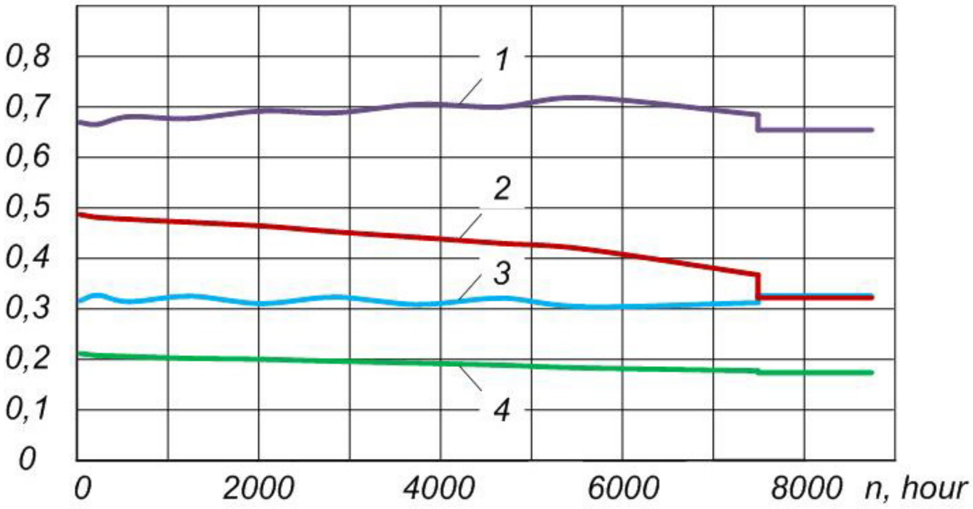
The primary method of evaluating the energy efficiency of competing sources is to limit them to the consumption of a single commodity; in this case it is natural gas. For the TPP being substituted the gas consumption was calculated by multiplying the consumed power value by the given reduced specified efficiency for power production and transportation η, that fluctuated from 0.3 to 0.5 in our calculations.

The parameter η is equal to the multiplication of the efficiency of a replacement plant for generating electricity η_e by the efficiency of electric energy transport from the TPP being substituted to the given consumer η_{tr}, that is,

$$\eta = \eta_e \cdot \eta_{tr} . \tag{2}$$

III. THE STUDY OUTCOME AND DISCUSSION

The computed results on the energy efficiency comparison of competing options are graphically presented in Fig. 7-10. Fig. 7 displays the correlations of yearly fuel heat recovery efficiency coefficient (HREC) η_{it} and power production EFF of both the GTU and MTU η_e.



1 – η_{it} MTU; 2 – η_{it} GTU; 3 – η_e MTU; 4 – η_e GTU

Fig.7. Yearly fuel heat recovery efficiency coefficient (HREC) η_{it} and power production EFF of both the GTU and MTU η_e.

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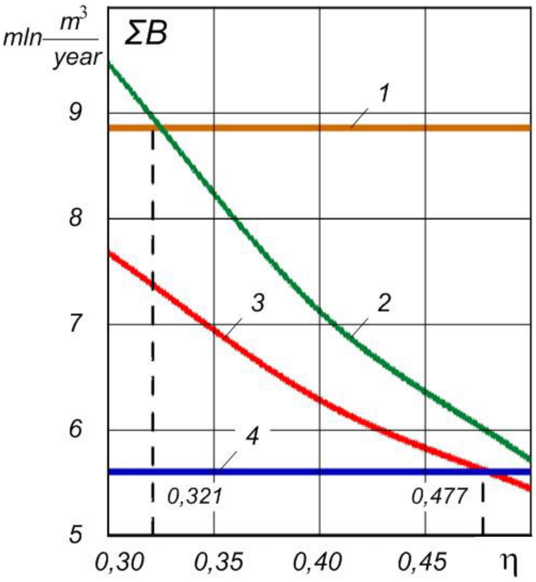
Gas consumption, depending on the electric power production efficiency coefficient of the substituted plant, once directed to power production is presented in Fig. 8. This comparison was done to specify the efficiency limits of various plants in case an external power source (either a gas turbine or a combined-cycle TPP) of equal efficiency was available.

The computations clearly demonstrated that in case the MTU generated both the thermal and electric power per annual demands schedule, there was a significant drop in fuel consumption as compared to the combined operation of GTU-2,5P, boiler plant, and HP, and provided that the efficiency of the substituted GTU-TPP is η<0,4772 EFF. At higher η values it becomes economically more advantageous to use the TPP for electric power production, while the boiler plant was best used as a heat supply source.

The use of MTU within its efficiency limits cuts down both the fuel consumption and greenhouse gases and nitrogen oxides emission. High fuel HREC values (no less than 0.65) prove low heat pollution level.

In case the power supply is switched to electric power production for the entire grid (rated power is 2.75 MW excluding HP, Fig. 6), the externally-powered heat pump system has fuel efficiency equal (or higher) to that of the gas turbine, provided the EFF value of the substituted power source exceeds η=0,32. However, the most feasible option regarding gas consumption is a microturbine plant up to η=0,4772 EFF value, while at higher η-values that would be an externally powered boiler plant. Taking into account the fact the efficiency coefficient value of the substituted GTU-TPP systems is η=0.25-0.28 (power transfer losses included) in the Far North clime conditions, the most energy-efficient of the studied plants is the MTU, then go boiler plants, and, finally, the low-yield GTU. At lower GTU and MTU power output this ratio doesn't change much, the difference is that the efficiency shifts from GTU towards boiler plants.

The HP's precedence over the boiler plant regarding the primary fuel consumption takes place only if the η efficiency coefficient value of the substituted TPP is lower than the borderline value of $\eta \geq \eta_k/\varphi = 0.92/1.8 = 0.51$, where φ=1.8 – derived from the computations (Fig. 9) of the HP's yearly coefficient of performance (COP) at any given load (freon R-134a is the medium, delivery water maximum temperature beyond the HP is 90°C).



1 – GTU; 2 – HP; 3 – boiler plant; 4 – MTU

Fig.8. Dependence between aggregate gas consumption for power production ΣB and the EFF of the substituted GTU-TPP system η.

The coefficient of performance of HP φ is determined by formula:

$$\varphi = Q_t / N_k \tag{3}$$

where Q_t is the heat load of HP, kW (determined by the graph of thermal loads);

N_k is the power consumed by the compressor, kW, and determined by the formula

$$N_k = N_s / (\eta_s \cdot \eta_e \cdot \eta_m) \tag{4}$$

In formula (4), N_s is the adiabatic power of the compressor, kW, determined by calculating the HP mathematical model in the process of adiabatic compression of freon;

η_s is the adiabatic efficiency of the compressor (assumed to be 0.82);

η_e is the efficiency of the electric motor (assumed equal to 0.95);

η_m is the mechanical efficiency of the drive (assumed equal to 0.98).

The relatively low average annual value of COP (φ=1.8) determined because of the calculations (Fig. 9) is due to two factors. The first one is the low (negative Celsius) temperature of the refrigerant in the HP evaporator, resulting from the year-round operation of the HP in the selection of heat below the depth of permafrost soils that have a year-round negative Celsius temperature. The second factor is a rather high average annual temperature of the network delivery water at the outlet from the HP according to the temperature graph of the projected heat supply system, which is about 80°C. Therefore, the difference in temperatures of condensation and evaporation in the HP is very high and ranges from 90°C to 120°C during the year. The difference in the cost of the power delivered to the consumer and the cost of resources used by the system as related to the end-price of the electric power is given in Fig. 10. It is this difference that makes the bulk of the economic effect.

The outcome of this study can be used when planning/designing the power-supply facilities in the Far North regions, as well as in evaluating/estimating the power-supply systems' efficiency.

The comparison of basic economic parameters is given in Table 1, the HP heat-production cost is calculated at 2.88 RUB/kWh electricity rate.

The outcome of this study can be used when planning/designing the power-supply facilities in the Arctic Regions of Russia, as well as in evaluating/estimating the power-supply systems' efficiency.

At the same time, any further DPGS-related research of cogeneration seems to be in the field of evaluating the power-producing and financial efficiency of gas reciprocating mini CHP plants as compared to GTU and MTU depending on both the scale of local power-supplying system and the efficiency of the substituted power production. As for the ground source buried-loop HP, the further research goal is in defining their efficiency as compared to boiler plants depending on the climatic conditions, the kind and price of the substituted fuel, the cost and production efficiency of the consumed electric power, and the temperature schedule of the heat supply system.

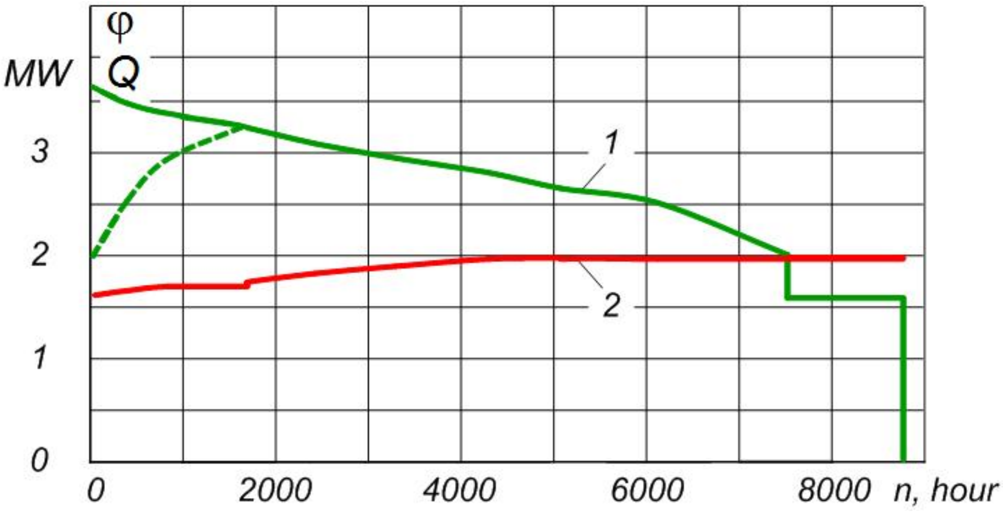
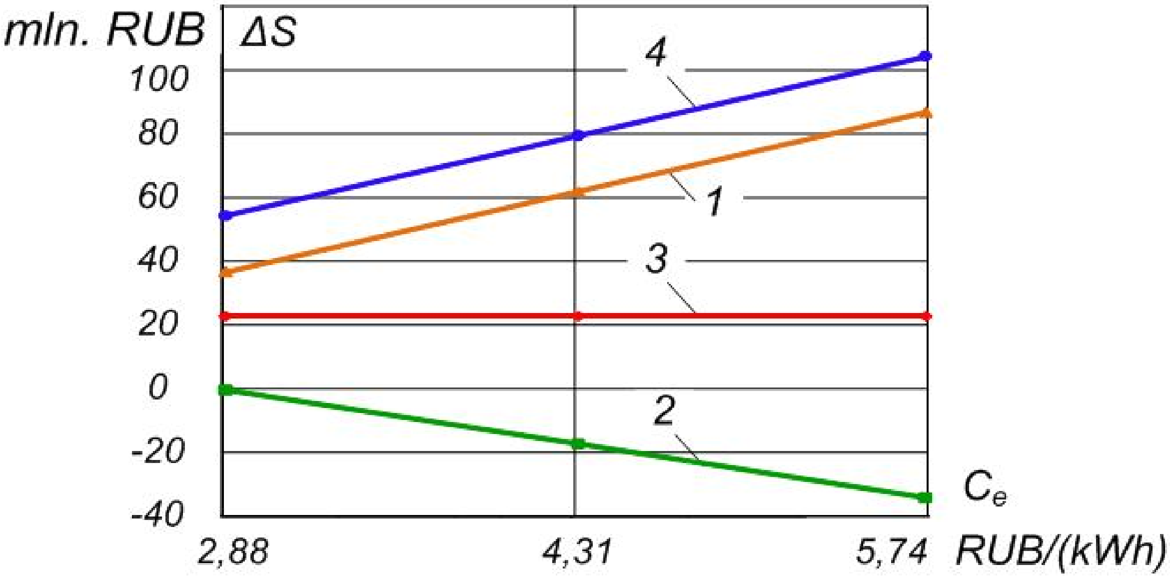


Fig.9. Change of heat demand Q (1), MW, and HP coefficient of performance φ (2) in demand duration n within a year. The dotted line shows the heat load on the HP itself within the operational boundaries of the peak load boiler (PLB).



1 – GTU; 2 – HP; 3 – boiler plant; 4 – MTU

Fig.10. The annual difference between the cost of the provided power and the price of consumed resources ΔS, mln. RUB, at the above-mentioned heat and gas rates, in dependence to the electric power rates C_e.

TABLE I. PROJECTS' ECONOMIC EFFICIENCY AT 10% ANNUAL DISCOUNT RATE

Parameters	**Boiler plant**	**GTU**	**MTU**	**HP**
Capital investments, mln. RUB.	8.2	92.3	259.3	93.0
Heat production cost, RUB/Gcal	1184	1994	1960	6011
Electric power production cost, RUB/kWh	-	1.71	1.68	-
Payback term taking into account the annual discount rate at 2.88 RUB/kWh, years (months)	0.7 (8)	3.57 (43)	5.97 (72)	no payback
Payback term taking into account the annual discount rate at 5.87 RUB/kWh, years (months)	0.7 (8)	1.34 (16)	3.03 (37)	no payback

IV. CONCLUSIONS

1. At the existing and forecasted for Russia gas-to-electricity cost ratio, which is from 5 to 12 (per a energy equivalent unit), the vapor-compressing HP, utilizing the ground heat, in Russia's northern regions, is always inferior to a gas-powered boiler plant in terms of economic efficiency as a heat supply source. The HP is least efficient in heat-supplying systems due to the low coefficient of performance φ, which takes place in case of region-specific temperature schedules with the delivery water temperatures amounted in 90°C and above and at an average annual temperature of the refrigerant in the evaporator about 0°C and below, which situation is typical of the permafrost regions.

2. The electric-power-producing efficiency of gas microturbine plants within 3 MW demand range always surpasses that of low-yield gas turbine plants due to higher power-producing EFF of the former.

3. The energy and ecological effectiveness of MTU electric power production, in cogeneration mode, goes up with the increase of the external heat supply share, in other words, with the rise of the annual HREC value. At η=0.35-0.40, the electric power production and transfer EFF value, the minimal average yearly HREC value, at which the MTU equals the efficiency of external power suppliers, is 0.55-0.60.

4. The MTU's operating in Russia's Far North, where the power production and transfer efficiency coefficient of the substituted power plants doesn't exceed η=0.3, are more efficient when externally powered, than the studied alternative power sources such as low-yield gas turbine units, gas-powered boiler plants, and buried-loop vapor-compressing HP. However, high cost of cogeneration micro gas turbine plants results in higher power-production cost, which, in its turn, calls for high-intensity operational modes to shorten the payback terms.

5. ICE-based gas reciprocating mini CHP plants seem to be even more promising as distributed power generation systems than MTU or GTU in the climatic conditions of Russia's Far North. Yet, estimation of their energy and economic effectiveness, as compared to other options, is outside the scope of this study.

6. The research of GTU-, MTU-, ICE-, and HP-based DPGS efficiency should be continued with the application of adequate mathematical machinery models within a wide range of internal and external boundary conditions, taking into account the existing operating conditions in power supply systems.

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