Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Efficiency of Geothermal Systems for Heat Supply and Electricity Production in Russia

L.A. Ogurechnikov[1], Yu.M. Petin[2]

1Institute of Thermophysics SB RAS, Lavrentiev ave. 1, Novosibirsk, 630090, Russia

E-mail: aleks@itp.nsc.ru

2"Energia", Ltd., Kutateladze str. 18/1, Novosibirsk, 630128, Russia

E-mail: energy@online.nsc.ru

Keywords: geothermal heat, heat pump, electricity productions

ABSTRACT

The main consumption tendencies for geothermal heat with low potential (<130 °C) are heat supply, refrigerating and electricity productions. Technical solutions using low-boiling substances in geothermal systems provide the most efficient conversion of low-potential heat (t<40 °C) into the energy with higher potential and extend possibilities of efficient hot water production for application in low-temperature technological processes, heating, hot water supply and refrigeration. Peculiarities of technological schemes for geothermal heat consumption by electric-driven vapor-compression heat pump systems with various actuating fluids are considered. The coefficient of heat energy conversion, energy supply cost, ratios of prices for electric and heat energies determine economic appropriateness of power saving heat pumps with the electric-driven compressor. The efficiency of a gas drive is shown. The optimal choice of initial and final parameters of Rankine cycle with low-boiling actuating fluids at electricity production is considered together with the effect of external factors on thermodynamic and technical-economical efficiency of heat energy conversion into electricity.

1. INTRODUCTION

Recently, application of power-saving technologies on the basis of electrical technologies instead of direct combustion of coal, oil and gas involving low-potential heat-carriers and ambient heat is welcome in many countries [1]. Construction of vapor-compression heat pump systems for heat supply is one of the most promising ways to substitute fuels by electricity, renewable and recycled energy supplies. The first proposals on application of heat pump installations, whose foundations have been developed in 1824, were made in 1852, when William Thomson has suggested a device, called by him as the heat multiplier, and demonstrated how a refrigerating machine could be used for efficient heating. Works on the use of heat pump equipment in Russia were started in 1971, when a pilot system of geothermal heat supply was built in Kamchatka (Paratunka village) for the residential area of Sredne-Paratunka greenhouse facility [2]. In the system there was a heat plant consisting of four heat pumps NT-25. After field tests of the heat pump system, it was decided that the use of heat pump equipment for the systems of geothermal heat supply at a deficit of low-potential heat is quite rational. However, this experiment was not put in good use by Russian industry and stayed unnoticed due to various reasons. The key of them were as follows: low cost of primary energy resources (in average, trailing expenditures for power-generating coals, fuel oils and gas made up 10 –12 USD/MW·h depending on the object location), no economic interest of developers and producers to development of a single non-standard equipment, and power well-being of industrial enterprises. Therefore, environmentally responsible power-saving technologies did not find industrial application. Nevertheless, "Kamchatka experiment" was a powerful incentive to the following works in Russia. In 1976 a heat pump system on the basis of waste heat of technological processes was put into operation at Samtredia tea factory. Fuel oils were completely displaced from the energy balance of this factory. In 1976 a heat pump station was put into operation for heating and cooling of sanatorium "Druzhba" in Yalta. Independently on resources of energy in the country, without doubt they decrease constantly. High-temperature processes in technical devices are accompanied by incomplete use of power budget of organic fuel. This problem is especially topical at use of primary energy resources for low-temperature processes in local heat and hot water supply systems. Therefore, power-saving low-temperature technologies based on heat energy of geothermal renewable (conditionally) sources are of a particular interest.

2. EFFICIENCY ANALYSIS OF GEOTHERMAL HEAT SUPPLY SYSTEMS

To determine technical efficiency and economic appropriateness of the heat pump equipment for the system of geothermal heat supply the mathematical model based on the condition of constant volume of compressed vapors [3]. This condition is demanded by the use of a standard industrial compressor. Thermal potentials of low-potential geothermal heat sources and heating-system water directed to the heat and hot water supply system are usually known at the stage of initial data accumulation. With consideration of temperature differences between heating and heated media, this allows determination of boundaries for thermodynamic cycle with some restrictions on the pressure of vapors of low-boiling actuating fluid at the compressor outlet and degree of their compression. The final point of adiabatic compression is on isobar of superheated vapors, and with consideration of indicator efficiency of compressor thermodynamic, the parameters of actuating fluid are determined for the real cycle. The problem of technological scheme calculation is to adjust volumetric flow rates, weight characteristics and parameters of actuating fluids of transmitted and converted energy in the elements of heat pump installation depending on temperature parameters of the cycle. At that, the balance equation, which connects the flow rate of actuating fluid in thermopower circuit with the flow rate of low-potential heat carrier, is the main.

Figure 1: Principle technological scheme of the heat pump system and thermodynamic cycle in the *T-S* diagram. Symbols: com-compressor, rhe-regenerative heat exchanger, ev- evaporator, thr-throttle, lc-liquid cooler, con-condenser.

Analysis of the technological scheme shown in Fig. 1 and processes of heat energy transfer allowed us to distinguish at modeling of the heat pump equipment the following typical zones: boiling, superheating and heating of actuating fluid. Mathematical description of the processes of heat energy transfer in each of these zones and corresponding presentation of these calculation regions by the model allow consideration of different technological schemes with various low-boiling actuating fluids with different thermodynamics and technical-economic efficiency by means of assembling and combination of equipment elements. The efficiency criterion of thermodynamic cycle occurring in the technological scheme is the coefficient of energy conversion:

$$\varphi = (Q_{\text{heat.sys.}} + Q_{\text{hws}})/L_{\text{cw}} = 1 + Q_{\text{geot.s.}}/L_{\text{cw}}, \qquad (1)$$

where $Q_{\text{geot.s.}}$ is the amount of heat supplied from a geothermal source to evaporator of the thermopower circuit; L_{cw} is the work of compression; $Q_{\text{heat.sys.}}$, Q_{hws} are the amounts of heat supplied to the systems of heat and hot water, correspondingly.

Independently on the economy type and ownership, determination of technical-economical appropriateness of geothermal power-saving technologies for transformation of the heat energy is connected with calculation of expenses: investments into the technology, operation costs and incomes from selling of produced power (electric, heat and cold). Estimate of investment project efficiency was carried out using net discounted profit (NDP):

$$\text{NDP} = \Sigma(R_t - 3_t^+)\cdot\alpha_t - K, \qquad (2)$$

where R_t is sales, 3_t^+ is expenses without investments, α_t is the discounting coefficient, K is discounted investments.2.1 Efficiency of Heat Energy Conversion in Vapor-Compression Heat Pumps

Coefficients of energy conversion in a heat pump are shown in Fig. 2 depending on a temperature drop between the processes of evaporation and condensation of actuating fluid in the thermopower circuit of the heat pump system.General regularity of dependencies presented follows from thermodynamic analysis of cycles performed. A decrease in the temperature drop between isotherms (isobars) of Rankine cycle causes reduction of the compression work, increase in the amount of heat supplied from a geothermal source and rise of the power conversion coefficient. Relation between conversion coefficients under the modes of heat and hot water supply, shown in Fig. 2, was obtained considering potential possibilities of the cycle. At that, the heat load on condensate cooler makes up 30–35% of the heat load of condenser. This relation may decrease to 8–10% depending of specific operation conditions of heat pump installations.

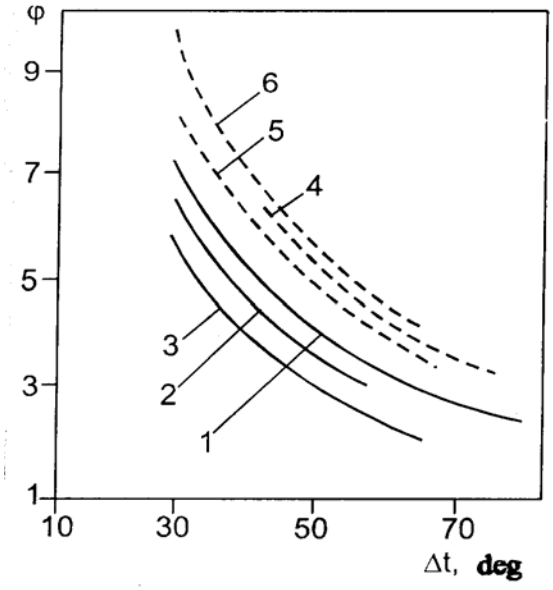


Figure 2: The effect of temperature drop during the cycle on its efficiency for different actuating fluids heating mode; mode of heating and hot water supply during the heating season; 1.4-R134a (R12); 2.5R21; 3.6-R142b.

Subsection headings should be capitalized on the first letter. Avoid using subsections deeper than subsubsections.The section break that follows the last words of the paper will cause the columns to be even. Relationships presented testify that a specific character of thermodynamic properties of low-boiling actuating fluids influences the efficiency of power conversion in the thermopower circuit of the heat pump system. Chladone R134a (R12) provides condensation at a maximal temperature level T3–4≤338–343 K (65 –70 °C). This chladone allows application of heat carriers of low-potential sources as the heating medium (e.g., subterranean waters with the temperature of 279 –281K (6 –9 °C)) and construction of the refrigerating system with a stable level of low (positive in Centigrade scale) temperatures in a cold store. It becomes possible to perform thermodynamic cycle of the heat pump system with multipurpose destination: as a source of heating, hot water supply and cooling. A lower compression degree is typical for chladone R21 (ODP=0.04) at temperature drop Δt fixed for the considered low-boiling substances as well as a possibility for an increase in vapor pressure. This allows achievement of the heat supply mode with water temperatures of 368–393 K (95 –120 °C). Due to alterations of the volume thermodynamic potential, we can estimate a possibility of low-boiling actuating fluids to transfer energy (Fig. 3). At a constant temperature drop between condensation and evaporation processes, an increase in volume energy density of low-boiling actuating fluids with a rise of temperature of heat supplied from a low-potential source attracts attention. Among considered chladones promising for application in vapor-compression heat pump systems, the most preferable ones are R22 (ODP=0.05) and R134a. Chladone R142b (ODP=0.65) has higher volume energy in comparison with R21 despite the lower coefficient of energy conversion. The use of R142b in heat pumps provides the thermodynamic cycle with the temperature of removed heat 363 K (90 °C) in vapor-compression heat pump systems, and this is preferable for Russia, whose main territories are located in moderate and cold temperature zones.

This provides qualitative heat energy for the consumers in correspondence with standards of hot water supply of 95/70 °C depending on the temperature of ambient air.

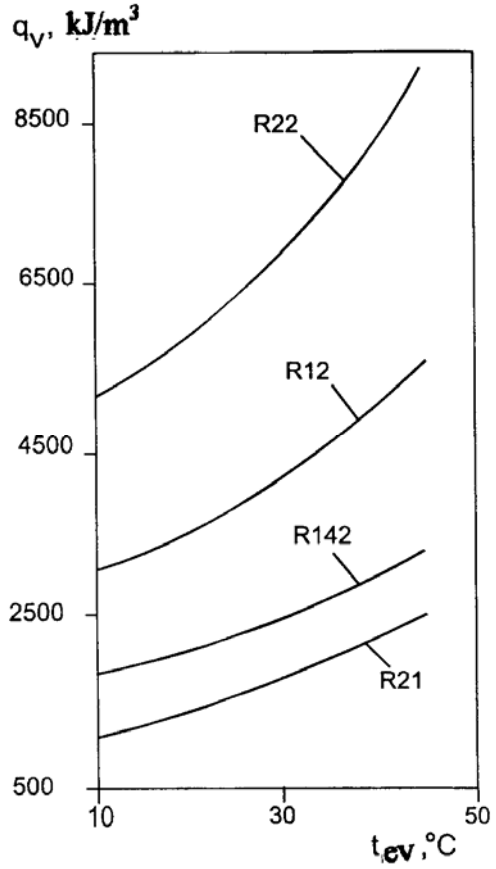


Figure 3: Dependence of volumetric heat productivity of chladones qv on evaporation temperature t_{ev} of chladone during the cycle.

2.2 System Tests

Coefficient of energy conversion φ characterizes the heat pump installation from the point of the amount of heat with high potential, obtained per a unit of vapor compression work in a compressor. These are two different and nonequivalent types of energy. From the positions of system approach, vapor-compression heat pump installations are used by the fuel and energy complex of Russia, and this determines the criterion for the estimate of power-saving technology: fuel consumption.

In heat supply systems with traditional sources of heat energy for heat and hot water supply from boilers and heat power plants (HPP), electricity consumption for a drive of heat pump system compressor should be considered as low-priority type of electricity consumption. Condensing plants are considered as the low-priority electricity generating sources. While analyzing dependency between specific fuel consumption for electricity production by the condensing plants and the capacity of power units over Russia, it became possible to determine the average consumption of standard fuel per a heat unit (produced by vapor-compression heat pump system with a compressor drive from an electric engine) as a function of energy conversion coefficient:

$$в_{hps} = a \cdot в_e \cdot (1 + в_{in.n.})/\varphi, \quad (3)$$

where $в_e$ is the averaged consumption of standard fuel for electricity production (340 –360 g s.f./kW·h); $в_{in.n.}$ is the coefficient of electricity consumption for intrinsic needs; a is the constant of proportionality, considering dimension of assigned values.

At comparative analysis of power efficiency of heat energy production in a vapor-compression heat pump, traditional heat sources (boilers and heating units) are considered. Technical perfection of boilers is determined by the efficiency, and heat source for the heating units is steam from cogenerating turbines of the power plants. Specific consumption of standard fuel per a heat unit (GJ) in a boiler is determined as

$$в_b = 34.2/\eta_b, \quad (4)$$

where η_b is the efficiency of boiler.

Equality of specific consumption of standard fuel for a heat unit production in vapor-compression heat pumps and boilers allowed determination of connection between power efficiencies of considered heat sources:

$$\varphi = a \cdot в_e \cdot (1 + в_{in.n.}) \cdot \eta_b/34.2, \quad (5)$$

In case of cogeneration systems, fuel consumption for heat energy production was assumed considering its values at heat production by vapor-generator of heat and power plant and difference in fuel consumption at condensation and cogeneration production of electricity by turbines (at average production of electricity accompanying heat consumption) [4– 6]. Specific fuel consumption for heat production in cogeneration turbines, using steam for hot water, can be determined as

$$в_{hpp} = в_b - \Delta в_e \cdot Э_h, \quad (6)$$

where $\Delta в_e$ is specific economy of standard fuel for energy cogeneration, i.e., the difference in specific consumption of fuel for condensation production and cogeneration of electricity; $Э_h$ is specific cogeneration of energy on the basis of heat consumption.

Fuel economy at combined generation of electricity covers a wide range of values depending on the turbine type: $\Delta в_e = 0.09 – 0.20$ kg s.f./(kW·h). At the modern level of thermal economy of condensing and heat-and-power plants, we can assume that $\langle \Delta в_e \rangle = 0.175$ kg s.f./(kW·h).

Specific electricity production accompanying heat consumption is determined by initial parameters of steam and parameters of steam in samples of cogeneration turbines. Operation values vary $Э_h = 115–125$ kW·h/GJ, and for turbines of *T*–100 –130 type they reach 120 –170 kW·h/GJ. The average value assumed for different systems of hot water supply in Russia is $Э_h = 116$ kW·h/GJ. For these quantitative relationships, the minimal coefficient of heat energy conversion in the heat pump systems, when specific consumption of standard fuel per a unit of produced heat ($в_{hps} = в_{hpp}$) is:

$$\varphi = a \cdot в_e \cdot (1 + в_{in.n.}) \cdot \eta_b/(34.2 – \Delta в_e \cdot Э_h \cdot \eta_b), \quad (7)$$

should not be lower than $\varphi = 5.8$ with the efficiency of vapor-generator at the heat and power plant of 90%. This relationship proves high power efficiency of the systems for combined energy production.

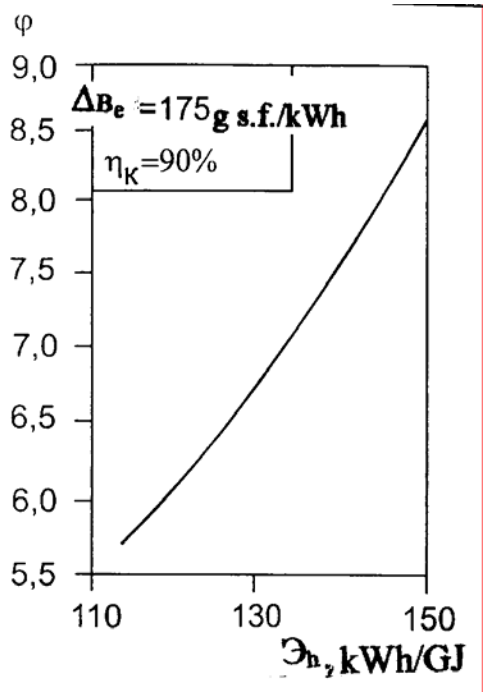


Figure 4: Dependence of energy conversion coefficient at the heat pump system on electricity production accompanying heat consumption

2.3 Peculiarities of Constructed Geothermal Heat Pump Systems

Analysis of investments for boring and construction of geothermal wells demonstrated that average investment for a geothermal source in Novosibirsk region makes up 700–800 USD/m at a boring depth of 1200 m. Under these conditions, construction of a local geothermal heat pump source decreases economic efficiency of all heat supply system. There are no government laws in Russia, which provide breakeven application of power-saving geothermal technologies. Search for possibilities to reduce expenses and increase economic efficiency of geothermal systems suggested an opportunity to use existing wells for water supply of settlements with isolated systems of heat supply from boilers on organic fuel. In 1990, the Institute of Thermophysics SB RAS together with "Energia" company constructed the system of heat supply for the boarding school in Kupino town (Novosibirsk region), using heat pumps 2^x NT80. The source of low-potential heat iseothermal water from the well withwater temperature of 23–27 °C.

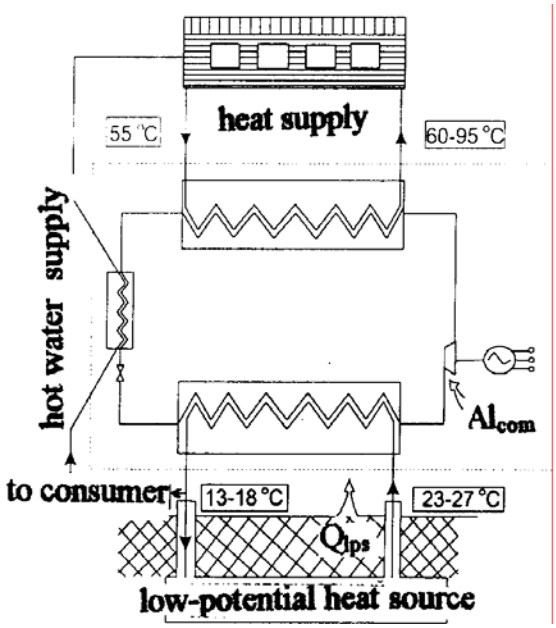


Figure 5: The heat supply system in Kupino town

The peculiarity of technological scheme shown in Fig. 5 is the use of geothermal water with return of cooled water after evaporator of the heat pump system (t_2 = 15–18 °C) to water facilities (geothermal water meets the demands to drinking water), and its back pumping into a re-injection well. Simultaneously, this provides environmental protection and complex use of water from geothermal source with displacement of boiler to the area of maximal heat loads. Similar technological schemes were used at geothermal sources in towns Karasuk and Krasnoozernoe. These settlements are characterized by an absence of a required amount of fresh water. To increase the efficiency of geothermal heat supply systems, accumulating tanks are installed in heat-supplying facilities (Scherbaki, Kozino settlements of Ust-Tarka district of Novosibirsk region) at cyclic compressor operation.

Annual heat energy supply of 5700 Gcal was taken as the initial data for the Table 1. For heat pumps the amount of harmful emissions is determined by electricity spent by them in the region of generating sources (hydroelectric-power plants, cogeneration plants, atomic power plants, etc.). Directly in location of heat pump installation (near low-potential heat sources or close to heat energy consumers) there is no environment contamination. The estimate of economic efficiency of vapor-compression heat pump installations demonstrated the following. The cost of 1 Gcal at a standard heat capacity of the vapor-compression heat pump system of "Energia, Ltd." (Novosibirsk) is 125–140 USD. It is obvious in Fig. 6 that with an increase in coefficient of energy conversion φ (dependencies 1–5), the area of economic efficiency of vapor-compression heat pump systems increases, and this allows higher relation of costs for electric and heat energy ($И_e/И_h$). An interest to heat pump systems in Russia is mainly connected with self-regulating systems, which can be used in settlements far from the systems of district heating independently on estimate criteria. Today these installations are competitive with boiler plants, and consideration of ecological and social factors makes them even more attractive. However, market situation with the tax structure in Russia increases the pay-back period for the new power-saving technology and reduces its economic efficiency.

Three options were considered on the basis of experiments carried out by "Energia, Ltd." on the estimate of application prospects of vapor-compression heat pump systems with a gas drive. I – Heat pump system with the electric drive, II – Heat pump system with the gas drive, III – Heat pump system with the gas drive and heat recuperation under the following initial conditions: 1) cost of natural gas used for the heat pump drive is $Ц_g$ = 56 USD/1000 m^3, 2) gas calorie content Q^p_p = 9000 kcal/m^3, 3) electricity cost $Ц_e$ = 3.25 cent/kWh.

Original position for options 2) and 3) is theoretical amount of energy generated by combustion of 1 m^3 of natural gas. Then

$$Ne_{n.g.} = Q^p_p \cdot \eta_g/860, \quad (8)$$

where η_g is the efficiency of gas engine.

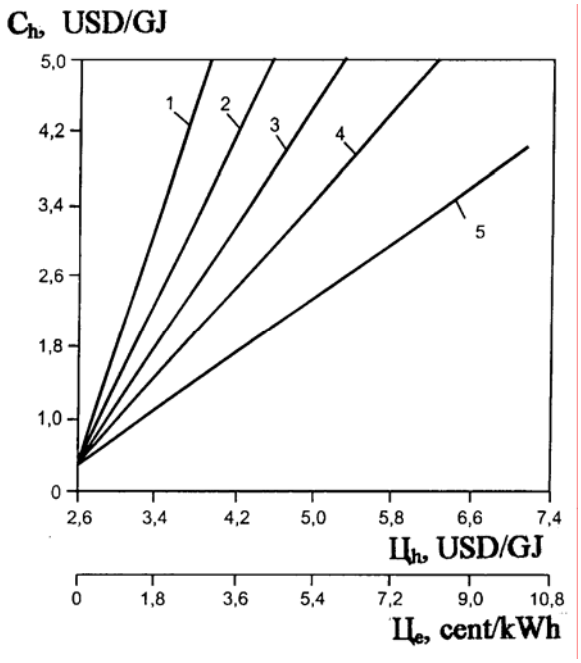


Figure 6: The effect of energy supply cost on the prime cost of heat production by vapor-compression heat pump installations: *1* – φ = 2.5; *2* – φ = 3.0; *3* – φ = 3.9; *4* – φ = 5.0; *5* – φ = 7.5.

Option 3) considers application of waste heat from the gas engine (heat from engine cooling and flue gases). Calculation results are shown in Table 2.

Preliminary estimates of efficiency of vapor-compression heat pump system with a gas drive prove economic appropriateness of this class of heat pumps. Recuperation of waste heat of a gas engine provides useful application of 80% of heat generated at combustion of natural gas.

EFFICIENCY OF BINARY POWER PLANTS

Results of technical-economical optimization of a binary power plant with R12 (substitute of R134a) performed by the method of Gauss-Zeidel are presented in Table 3 for initial A and optimal B versions. Power plant capacity is 1500 kW, it operates on water heating heat carrier with the temperature of 115 °C at the temperature of cooling water of 5 °C, typical for Kamchatka region, where this temperature is stable during the whole year (5 –7 °C).

Optimal version provides minimum expenses for construction and exploitation electric power plant with low-boiling actuating fluid. A specific feature of chladone is relatively high density. It limits the initial pressure because of an increase in electricity consumption for the drive of chladone feed-pump and additional expenses for obtaining of the same power effect in both compared versions and completion of chladone vapor expansion within the area of overheating. Optimization investigations for the choice of parameters of the binary power plant were carried out as assignment of initial information in the form determined dependencies. Actually, information used for the problem solution has a random character, especially for calculations referred to future. Therefore, uncertainty of initial data requires validity of results obtained.

According to analysis of information required for optimization, technical-economical initial data has the highest error from the point of reliability. Since there are no regularities for future alterations of initial technical-economical data, it is reasonable to consider specific capital investments as random values assigned in a certain range of their alteration. Optimization research carried out for the pessimistic version demonstrated that the 20-% increase in the cost of metal of heat exchanging surfaces provided a rise in velocity of a primary heat carrier in the zone of boiling ($W_{boil.}$ = 1.9 m/s), cooling water in the condenser ($W_{cond.}$ = 1.8 m/s) and vice versa. In some optimal parametrical range, versions of a binary power plant will have equal efficiency.

An estimate of economic efficiency of geothermal sources for electricity production on low-boiling actuating fluids was performed for the conditions of Kamchatka region, Russia. Dynamics of a change in the net discounted profit (NDP) during the service life of a binary power plant, including construction, is shown in Fig. 7. For the chosen initial data, all main criteria of discounted estimate system for economic efficiency of the geothermal binary power plant (net discounted profit, profit rate, intrinsic norm, etc.) are sufficient for making a decision on investments to the considered project.

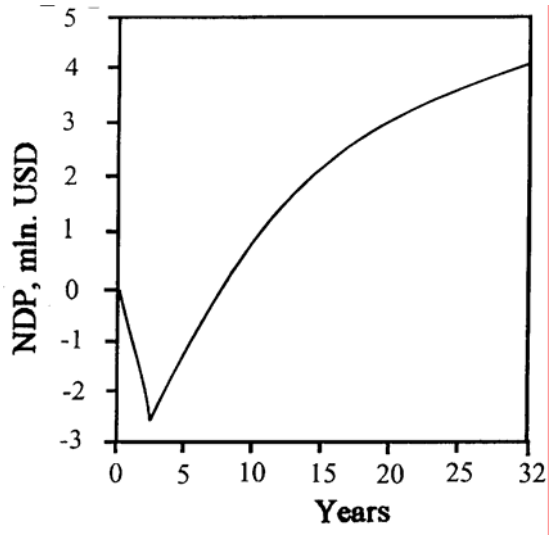


Figure 7: Net discounted profit of the investment project dealt with the binary power plant in Kamchatka region, Russia.

2.5. CONCLUSION

Despite uncertainty of technical development, a future increase in costs on organic fuel and expenses for environment protection is evident. Using geothermal heat sources or waste heat of industrial enterprises, heat pump systems and binary power plants are power-saving and environmentally protective measures. General regularity of considered technologies is the maximal period of their use during a year and location in regions with expensive fuel. Construction of binary power plants in Kamchatka seems to be very promising due to geothermal sources of hot water and water-steam mixture, high electricity cost, and absence of organic fuel with a low temperature of a cold source.

NOMENCLATURE

Q_{hws}– amount of heat sent to the system of hot water supply;

tsf– ton of standard fuel (1 tsf = 7000 kcal/kg);

φ– coefficient of heat energy conversion in a heat pump;

$Q_{geot.s.}$– amount of heat sent from a geothermal source to evaporator;

L_{cw}– work of compression;

$Q_{heat.sys.}$– amount of heat sent to the heating system;

NDP– net discounted profit;

R_t– product sales (heat, electricity);

$З_t^+$– expenses without discounted investments;

α_t– discounting coefficient;

K– discounted investments;

ODP– ozone depletion potential;

Δt– temperature difference between chladone condensation and evaporation;

$в_e$– consumption of standard fuel for electricity production;

$в_{hps}$– consumption of standard fuel per a heat unit produced by the heat pump system with a compressor drive from an electric engine;

$в_{in.n.}$– coefficient of electricity consumption for intrinsic needsof a heat pump;

a– proportionality coefficient considering dimension of accepted values (a = 1 at $Q_{geot.s.}$ [kWh]; a = 278 kWh/GJ at $Q_{geot.s.}$ [GJ]);

η_b– efficiency coefficient of a boiler plant;

$в_{hpp}$– specific fuel consumption for heat production by a cogeneration turbine;

$в_b$– specific fuel consumption for heat production by a boiler plant;

$\Delta в_e$– specific economy of standard fuel at combined electricity production;

$Э_h$– specific combined electricity production by a heat power plant at heat consumption;

$Ц_e$– electricity cost (rate);

$Ц_h$– heat energy cost (rate);

C_h– prime cost of heat generation by a heat pump system;

$Ne_{n.g.}$– theoretical amount of energy produced at combustion of 1 m^3 of natural gas;

η_g– efficiency coefficient of the compressor gas drive;

t_1– temperature of geothermal water at the inlet to evaporator;

q_v– volumetric heat productivity;

t_{ev}– temperature of chladone evaporation

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TABLE 1

Comparative ecological efficiency of the heat pump system with traditional sources for heat supply of Kupino town

Harmful emissions, t/Gcal	Heat pump			Boiler plant (coal)	Electric heating
	φ = 3.0	φ = 5.3	φ = 6.6		
Ashes	no	no	no	15.2	no
SO_2	8.8	5.0	4.5	10.5	25.5
NO_x	5.0	2/5	2.0	6.6	14.2
CO	3.8	2.1	1.5	3.8	12.1
Total	17.6	9.6	8.0	36.1	51.8

TABLE 2.

Efficiency of vapor-compression heat pumps with a gas drive

No.	Factors	Temperature of low-potential heat source		
		t_1 = 25 °C	t_2 = 28 °C	t_3 = 32 °C
1.	1 option Temperature of system water, °C	62		
2.	Conversion coefficient, φ	4.33	4.68	5.22
3.	Electricity consumption for heat production, kWh/Gcal	268.6	262.2	269.5
4.	Cost price of heat energy, USD/Gcal	9.8	9.1	8.1
5.	2 option Natural gas consumption, m^3/Gcal	73	67.5	60.5
6.	Cost price of heat energy produced by heat pump system, USD/Gcal	5	4.6	4.1
7.	3 option Amount of additional heat obtained due to regeneration of waste heat, Gcal	0.299	0.276	0.248
8.	Total amount of heat sent to consumer, Gcal	1.299	1.276	1.248
9.	Cost price of heat energy produced by heat pump system with a gas drive and heat regeneration, USD/Gcal	3.8	3.6	3.3

TABLE 3.

Value of optimal parameters of a chladone power installation of the 1500-kW capacity, operating by Rankine cycle

No.	Parameters and characteristics	A	B
1.	Initial pressure of chladone vapor before turbine P_0, MPa	1.25	1.0
2.	Initial vapor temperature before turbine T, °C	110	109
3.	Final pressure of expansion process P, MPa	0.18	0.14
4.	Velocity of cooling water in tubes of condenser W_{con}, m/s	1.5	1.73
5.	Velocity of initial heat carrier in the zone of boiling W_{boil}, m/s	2.0	1.85
6.	Chladone velocity in the heater W_{heat}, m/s	0.1	0.8