O. P. Ostapenko, Cand. Sc. (Eng.), Assist. Prof.; O. V. Bakum

ECONOMIC EFFICIENCY OF HEAT-PUMPING STATIONS ON THE CONDITIONS OF FUEL AND ENERGY RESOURCES COST CHANGE AND VARIABLE OPERATION MODES

Economic efficiency of heat pumping station (HPS) with various sources of low temperature heat for industrial and municipal heat power branch on conditions of fuel and energy resources cost change and variable operation modes has been analyzed. The suggested recommendations can be applied for the forecast of the conditions of efficient HPS integration in heat supply systems of industrial enterprises and municipal heat power branch.

***Key words**: economic efficiency, heat pumping station, heat pumping plant, cost of fuel and energy resources.*

Introduction

Considerable potential of possible economy of fuel and energy resources as a result of heat pumps application in Ukraine and ecological advantages promote the introduction of heat pumping stations in industry and municipal energy sector. For economically efficient operation of HPS favorable price ratio for fuel and electric energy is required, that is true only for heat pumps with electric drive. Economic efficiency and recoupment of HPS with the drive from gas-piston engine does not depend on the cost of electric energy but it depends only on the cost of fuel.

At the energy market of Ukraine there exists considerable price difference for natural gas for industrial enterprises and enterprises of municipal heat power branch. This causes considerable difference concerning economic efficiency as a result of introduction of heat pumping stations in industry and municipal heat power branch and necessity to realize such assessment.

Recently, a number of investigations have been carried out, aimed at efficient application of heat-pumping plants (HPP) in thermal circuits of energy supply sources. In [1], the authors performed investigations aimed at enhancement of energy efficiency of energy supply sources by means of using HPP, taking into account the impact of circuits and operation modes. Evaluation of HPS efficiency was performed, applying the following criteria: fuel economy as compared with the existing scheme, annual expenditures for fuel and electric energy, investments, thermal unit cost, pay-back term, annual expenditures and profit.

In [2], economic indices of heat supply systems with HPP for the conditions of Russian Federation economy were determined. Calculations were performed for various relationships of fuel prices (gas, coal) and electric energy. In the research [2] such criteria of economic efficiency evaluation are suggested: integral effect (net profit), profitability index (efficiency) and term of recoupment of capital investments. In [3] schemes of HPP application at industrial power plants are considered. In research [4], the efficiency of HPS with electric drive and gas-turbine drive and waste-heat boiler is analyzed.

Authors [5] carried out the comparative studies of three energy supply systems according to heat cost (on the base of gas-fired boiler, heat pump and cogeneration unit with heat pump) on condition of electric energy and gas price change for various groups of consumers. Cost of gas and electric energy was taken into account only for social-budgetary sphere and housing and communal services. The suggested results are obtained only for available prices for electric energy and do not allow to evaluate the efficiency of HPU application in case of price change for fuel-energy resources.

In [6] evaluation of the efficiency of four sources of heat supply rated for 3 MW on the base of electric boiler, fuel boiler (gas, liquid fuel) and heat pumping plant is carried out. Average indices of fuel-energy resources of Ukraine cost were the base for economic models. In [7] evaluation of energy efficiency of small power heat pumping plant as compared with conventional sources of heat supply, based on electric and gas-fired boiler was performed.

In research [8] evaluation of economic efficiency of HPS, rated for 1 MW, used for heat supply systems, taking into consideration complex impact of low temperature heat sources, type of HPP compressor drive and energy resources price, was performed. Economic efficiency and simple recoupment of HPS variants with different sources of low temperature heat and types of HPP compressor drive was investigated. Estimation of economic efficiency of HPS at current prices of energy resources and forecast growth of their price was performed. The research [8] did not take into account the impact of variable operation modes of HPS on the indices of economic efficiency.

In publications [1, 8, 9] energy and economic preconditions of efficient integration of HPS in heat supply systems of industrial enterprises and enterprises of municipal power generation of Ukraine are determined.

In [10] energy, ecological and economic efficiency of HPS with various types of compressor drive, operating on natural and industrial sources of low temperature heat, taking into account variable operation modes of heat supply systems in wide range of HPP power change is evaluated. In research [10], the impact of fuel energy resources price variations on indices of economic efficiency of HPS are not taken into account.

In research [1 – 10] the authors did not perform the evaluation of the economic efficiency of HPS, with various types of drive in heat supply systems of industrial enterprises and enterprises of municipal heat power industry on conditions of fuel and electric energy cost change for variable operation modes of HPS.

The aim of the research is the evaluation of economic efficiency of heat pumping stations in Ukraine on conditions of fuel-energy resources price change and variable operation modes of HPS; analysis of economic efficiency of HPS in industry and municipal heat power branch, carrying out of optimization technical economic research, aimed at determination of optimal economic conditions of HPS application in the systems of heat supply of industrial enterprises and enterprises of municipal heat power industry.

Main part

The study was performed, applying the method of mathematical modeling of HPS operation using the program in Excel environment. Economic efficiency of HPS, with maximum rated power 10 MW in heating season was investigated, maximum power of HPS, operating in hot water supply mode was 2 MW. Variant of operation of hot water boiler house of the same power was taken as the comparative variant. Economic efficiency of HPS with electric drive and compressor drive from gas-piston engine (GPE) was studied. The diagrams of these HPS are shown in [1].

The sources of low temperature heat for HPS were: surface waters, circulating water, ground waters, geothermal waters, air, secondary energy resources, sewage and heat of the soil. Characteristic of low temperature heat sources is given in the paper [10].

Energy and economic efficiency of HPS is greatly determined by optimal distribution of loading between heat pumping plant and hot water boiler of HPS. Such distribution is characterized by a share of HPP loading within HPS β, which is defined as a relation of HPP capacitor power to the power of $\beta = \dfrac{Q_{HPP}}{Q_{HPS}}$.

Proceeding from the analysis of the research, carried out, optimal values of β index for HPS, operating at various sources of heat, with different types of HPP compressor drive, at variable operating modes of heating system are determined. Each of these modes corresponds certain value of thermal capacity of HPS, HPP and share of HPP β loading. The results of the research of HPS energy efficiency, on condition of variable operating modes are shown in the paper [11].

Saving of equivalent and operating fuel as a result of HPS introduction is greatly determined by optimally selected operating modes of HPS, rational distribution of loading between hot-water boiler and HPP, hence – by optimal value of HPP loading share within HPS β. On the basis of determined values of HPP β loading share, the economy of equivalent and operating fuel of HPS is determined for certain operating mode of heat supply system.

Economic efficiency as a result of HPS introduction is defined as the difference of operating expenses of substituting hot-water boiler house and HPS. Operating expenses of hot water boiler house or HPS comprise: fuel cost, electric energy, water costs, depreciation costs, running repair cost, earnings and other expenses. Fuel costs (for boiler houses and HPS with gas piston engine drive) and electric energy costs (for HPS with electric drive) are most important components in the structure of operating expenses. Besides, operation modes of HPS and temperature level of the chosen source of low temperature heat influence greatly energy and as a result, economic efficiency of HPS.

For the cases of variable operation modes and variable heat loading of HPS during a year, average annual value of relative economic efficiency of HPS (in percent) can be determined in the following way:

$$\Delta E_{av.annual.} = \frac{\sum_i \Delta E_i \cdot \tau_i}{\tau_{annual.}}, \tag{1}$$

where ΔE_i – relative economic efficiency of HPS for i^{th} operation mode of HPS, %; τ_i – duration of i^{th} mode of HPS operation, hr/yr; $\tau_{annual.}$ – annual duration of HPS operation, hr./yr.

Relative economic efficiency of HPS (in percent) for i^{th} operation mode can be determined as:

$$\Delta E_i = \frac{(E_{b.h.})_i - (E_{HPS})_i}{(E_{b.h.})_i} \cdot 100, \tag{2}$$

where $(E_{b.h.})_i$ – operating expenses for i^{th} mode of substituting boiler house operation, UAH/yr;
$(E_{HPS})_i$ – operating expenses for i^{th} operation mode of HPS, UAH/yr.

Studies of economic efficiency were carried out by consolidated indices. For various sources of heat in HPS expenses for construction of heat extraction systems from low temperature source.

Application of heat pumps causes the decrease of environmental contamination and reduction of pollutant emissions. Attraction of financial resources as a result of selling quotas for CO_2 emissions according to Kioto protocol, will allow to improve economic efficiency of HPS introduction and reduce their recoupment term. The research takes into account that additional costs, obtained from selling CO_2 emissions quotas, are 20 \$/t of emission.

Taking into consideration present-day situation in fuel-energy complex of the country and the trend of fuel process growth, investigations of HPS economic efficiency were carried out for current values of energy resources in industry and municipal heat power branch and forecast growth of natural gas price for industrial enterprises in the nearest period. Cost values of fuel and energy resources, for which the study was carried out, are shown in Table. 1.

Table 1

Cost of fuel and energy resources

Value of fuel-energy resources cost	Sphere of HPS introduction		
	Municipal heat power industry (prices as of 01.03.14) [12]	Industry (prices as of 01.03.14) [12]	Industry (prices as of 01.12.13) [12], (forecast for 2014 p.)
Electric energy price, UAH/(KW·h)	1.239	1.239	1.239
Natural gas price, UAH/thous. m^3	2296.32	4201.512	4876.08

Table 1 contains cost values of fuel and energy resources in industry and municipal heat power branch as of 01.03.14. Here, for the comparison, the cost of natural gas for industrial enterprises is shown as of 01.12.13, because, according to the forecast, in the second quarter of 2014 the new price for natural gas may be fixed at the level of the price of 2013.

We performed the evaluation of relative economic efficiency of HPS, with various types of drive and sources of low temperature heat on conditions of fuel and energy resources cost change and variable operation modes of HPS.

Table 2 contains values of relative economic efficiency for HPS with electric drive, operating on the heat of sewage, depending on the share of HPS loading, on condition of variable operation mode and cost of fuel and energy resources. From Table 2 it is seen, that if the price of natural gas is 2296.3 UAH/thous. m^3, for enterprises of municipal heat power industry this variant of HPS is unprofitable, that is shown by negative values of relative economic efficiency. At the price of natural gas in industry from 4201.512 till 4876.08 UAH/thous. m^3 (forecast estimation), relative economic efficiency of such variant of HPS is provided.

Table 3 contains values of relative economic efficiency for HPS with electric drive, operating on the heat of circulating water, depending on the share of HPP loading, on conditions of variable operation modes and cost of fuel and energy resources. Here we record the character of HPS relative economic efficiency indices change; analog to previous results, shown in Table 2. For this variant of HPS essential values of relative economic efficiency are provided, if the price of natural gas is from 4201.512 UAH./thous. m^3 and higher. Hence, this variant of HPS will be economically efficient only in industry.

Table 2

Values of relative economic efficiency of HPS, operating on the heat of sewage with electric drive, depending on the share of HPP loading, %

Share of HPI loading β	Relative economic efficiency of HPS ΔE_i, %		
	Municipal heat power industry	Industry	Industry (forecast)
0.158	-5.442	2.413	3.722
0.187	-8.122	3.568	5.517
0.217	-10.802	4.724	7.312
0.246	-13.482	5.879	9.107
0.315	-10.885	4.825	7.445
0.344	-13.565	5.981	9.240
0.374	-16.244	7.136	11.035
0.472	-16.327	7.238	11.167
0.502	-19.007	8.393	12.962
0.629	-21.769	9.651	14.890

Table 3

Values of the relative economic efficiency of HPS, operating on the heat of circulating water, with electric drive, depending on the share of HPP loading, %

Share of HPP loading β	Relative economic efficiency of HPS ΔE_i, %		
	Municipal heat power industry	Industry	Industry (forecast)
0.158	0.119	5.452	6.341
0.187	-0.190	7.903	9.253
0.217	-0.499	10.355	12.165
0.246	-0.808	12.806	15.076
0.315	0.237	10.904	12.683
0.344	-0.071	13.355	15.594
0.374	-0.380	15.807	18.506
0.472	0.356	16.356	19.024
0.502	0.047	18.807	21.936
0.629	0.475	21.808	25.365

Table 4 contains values of relative economic efficiency for HPS with electric drive, operating on the heat of ground, depending on the share of HPP loading, on conditions of variable operation modes and cost of fuel and energy resources. From Table 4 it is seen, that if natural gas price is 2296.3 UAH./thous. m^3, for the enterprises of municipal heat power industry, this variant of HPS is unprofitable, this is shown by negative values of relative economic efficiency. At the price of natural gas in industry from 4201.512 to 4876.08 UAH/thous. m^3 (price projection) insignificant relative economic efficiency of such variant of HPS is provided, that could increase in case of further growth of natural gas cost.

Table 4

Values of HPS, operating on the heat of the ground, with electric drive, depending on the share of HPP loading, %

Share of HPP loading β	Relative economic efficiency of HPS ΔE_i, %		
	Municipal heat power industry	Industry	Industry (forecast)
0.158	-8.994	0.472	2.050
0.187	-13.967	0.374	2.765
0.217	-18.939	0.276	3.480
0.246	-23.912	0.178	4.195
0.315	-17.987	0.943	4.100
0.344	-22.960	0.846	4.815
0.374	-27.933	0.748	5.530
0.472	-26.981	1.415	6.150
0.502	-31.954	1.317	6.865
0.629	-35.974	1.887	8.200

Table 5 contains values of relative economic efficiency for HPS with electric drive, operating on the heat of the air, depending on the share of HPP loading, on condition of variable operation modes and cost of fuel and energy resources. We note the character of change of relative economic efficiency indices of HPS, analogous to previous results, shown in Table 4. For this variant of HPS essential values of relative economic efficiency of HPS will be provided if the price of natural gas is more than 4876.08 UAH/thous. m^3. Such variant of HPS will be economically efficient only in industry, on condition of further growth of fuel cost. In such case it would be more expedient to select another variant of HPS (with other source of low temperature heat and other type of the drive), that will provide high economic efficiency.

Table 5

Values of HPS operating on the heat of theair, with electric drive, depending on the share of HPP loading, %

Share of HPP loading β	Relative economic efficiency of HPS ΔE_i, %		
	Municipal heat power industry	Industry	Industry (forecast)
0.158	-7.803	1.122	2.611
0.187	-12.776	1.025	3.326
0.217	-17.749	0.927	4.041
0.246	-22.722	0.829	4.756
0.315	-15.606	2.245	5.221
0.344	-20.579	2.147	5.936
0.374	-25.552	2.049	6.652
0.472	-23.409	3.367	7.832
0.502	-28.382	3.269	8.547
0.629	-31.212	4.490	10.443

Table 6 contains values of relative economic efficiency for HPS with electric drive, operating on the heat of surface water, depending on the share of HPP loading, on condition of variable operation modes and cost of fuel and energy resources. For this variant of HPS analogous to previous results character of the indices of relative economic efficiency change of HPS is provided (see Table 5). But relative economic efficiency of such HPS variant in case of high price for natural gas in industry (from 4876.08 UAH/thous. m^3) is more essential than in previous variant. The given variant of HPS will be more efficient economically only in industry, on condition that the price of natural gas starts from 4876.08 UAH/thous. m^3.

Table 7 contains values of relative economic efficiency for HPS with electric drive, operating on the heat of ground waters, depending on the share of HPP loading, on condition of variable operation modes and cost of fuel and energy resources. Here we note the character of indices of relative economic efficiency change of HPS, analogous to previous results, shown in Table 6. As in the previous case, this variant of HPS will be economically efficient only in industry, on condition that the price of natural gas will start from 4876.08 UAH/thous. m^3.

Table 6

Values of HPS, operating of the heat of surface water, with electric drive, depending on the share of HPP loading, %

Share of HPP loading β	Relative economic efficiency of HPS ΔE_i, %		
	Municipal heat power industry	Industry	Industry (forecast)
0.158	-5.467	2.517	3.849
0.187	-8.485	3.480	5.476
0.217	-11.502	4.443	7.102
0.246	-14.520	5.407	8.729
0.315	-11.268	4.718	7.384
0.344	-14.285	5.681	9.011
0.374	-17.303	6.645	10.638
0.472	-17.068	6.919	10.919
0.502	-20.086	7.882	12.546
0.629	-22.868	9.120	14.454

Table 7

Values of HPS, operating on the heat of ground waters, with electric drive, depending on the share of HPP loading, %

Share of HPP loading β	Relative economic efficiency of HPS ΔE_i, %		
	Municipal heat power industry	Industry	Industry (forecast)
0.158	-5.828	2.202	3.541
0.187	-8.827	3.183	5.186
0.217	-11.825	4.164	6.831
0.246	-14.824	5.146	8.476
0.315	-11.657	4.403	7.081
0.344	-14.655	5.385	8.726
0.374	-17.654	6.366	10.371
0.472	-17.485	6.605	10.622
0.502	-20.484	7.586	12.267
0.629	-23.314	8.806	14.162

Table 8 contains values of relative economic efficiency for HPS with electric drive, operating of the heat of geothermal waters, depending on the share of HPP loading, on conditions of variable operation modes and cost of fuel and energy resources. For this variant of HPS substantial values of relative economic efficiency are provided in the whole range of natural gas cost variation. Hence, such variant of HPS will be economically efficient in municipal heat power branch and in industry.

Table 8

Values of HPS, operating on the heat of geothermal waters, with electric drive, depending on the share of HPP loading, %

Share of HPP loading β	Relative economic efficiency of HPS ΔE_i, %		
	Municipal heat power industry	Industry	Industry (forecast)
0.158	6.580	8.984	9.384
0.187	9.131	12.998	13.643
0.217	11.682	17.012	17.901
0.246	14.232	21.026	22.159
0.315	13.161	17.967	18.769
0.344	15.711	21.981	23.027
0.374	18.262	25.996	27.285
0.472	19.741	26.951	28.153
0.502	22.292	30.965	32.411
0.629	26.321	35.934	37.537

Table 9 contains values of relative economic efficiency for HPS with electric drive, operating on the heat of secondary energy resources, depending on the share of HPP loading, on conditions of variable operation modes and cost of fuel and energy resources. Here we note high values of relative economic efficiency of HPS within the whole range of natural gas price change in industry and municipal heat power branch on conditions of variable operation modes.

Table 10 contains values of relative economic efficiency for HPS with the drive from gas-piston engine, operating of the heat of sewage, depending on the share of HPP loading, on conditions of variable operation modes and fuel and energy resources cost. As it is seen from the Table 10, for different values of natural gas cost considerable relative economic efficiency of the variant of HPS is provided. It should be noted, that relative economic efficiency of HPS variants relative economic efficiency of HPS variants with the drive from GPE does not change greatly depending on the cost of the fuel.

Table 9

Values of HPS, operating on the heat of secondary energy resources, with electric drive, depending on the share of HPP loading, %

Share of HPP loading β	Relative economic efficiency of HPS ΔE_i, %		
	Municipal heat power industry	Industry	Industry (forecast)
0.158	11.456	13.059	13.326
0.187	10.759	13.888	14.409
0.217	13.564	18.041	18.787
0.246	16.370	22.194	23.165
0.315	15.908	19.469	20.062
0.344	18.713	23.622	24.441
0.374	21.518	27.775	28.819
0.472	23.862	29.203	30.094
0.502	26.667	33.356	34.472

0.629	31.816	38.937	40.125

Table 10

Values of HPS, operating on the sewage, with gas piston engine drive, depending on the share of HPP loading, %

Share of HPP loading β	Relative economic efficiency of HPS ΔE_i, %		
	Municipal heat power industry	Industry	Industry (forecast)
0.158	4.190	4.575	3.942
0.187	7.217	7.879	6.789
0.217	10.613	11.587	9.984
0.246	14.450	15.777	13.595
0.315	10.431	11.389	9.813
0.344	13.827	15.096	13.008
0.374	17.664	19.287	16.618
0.472	17.658	19.279	16.612
0.502	21.495	23.469	20.222
0.629	26.276	28.689	24.720

Table 11 contains values of relative economic efficiency for HPS with the drive from GPE, operating on the heat of circulating water, depending on the share of HPP loading, on conditions of variable operation modes and the cost of fuel and energy resources. Here, we note high values of relative economic efficiency of HPS in the whole range of natural gas cost change in industry and municipal heat power sector on conditions of variable operation modes.

Table 11

Values of HPS, operating on the heat of circulating water, with gas-piston engine drive, depending on the share of HPP loading, %

Share of HPP loading β	Relative economic efficiency of HPS ΔE_i, %		
	Municipal heat power industry	Industry	Industry (forecast)
0.158	5.953	5.651	5.600
0.187	9.711	9.218	9.136
0.217	13.194	12.524	12.412
0.246	18.067	17.150	16.997
0.315	13.749	13.051	12.935
0.344	17.232	16.357	16.211
0.374	22.105	20.983	20.796
0.472	21.704	20.602	20.419
0.502	26.577	25.228	25.003
0.629	31.715	30.106	29.837

Table 12 contains values of relative economic efficiency for HPS with the drive from GPE, operating on the heat of the ground, depending on the share of HPP loading, on the conditions of variable operation modes and cost of fuel and energy resources. For this variant lower, than for two previous variants of HPS with GPE drive (see Table 10 and 11), values of relative economic efficiency in the whole range of natural gas cost change in industry and municipal heat power branch, are provided.

Table 12

Values of HPS, operating on the heat of ground with gas piston engine drive, depending on the share of HPP loading, %

Share of HPIP loading β	Relative economic efficiency of HPS ΔE_i, %		
	Municipal heat power industry	Industry	Industry (forecast)
0.158	2.524	2.396	2.374
0.187	4.703	4.464	4.425
0.217	7.382	7.008	6.945
0.246	10.641	10.101	10.011
0.315	7.301	6.930	6.868
0.344	9.980	9.473	9.389
0.374	13.238	12.566	12.454
0.472	13.332	12.655	12.543
0.502	16.591	15.748	15.608
0.629	21.102	20.031	19.852

For the variants of HPS with GPE drive for the rest of heat sources analogous values of relative economic efficiency on conditions of variable operation modes and fuel-energy resources cost change are obtained. It should be noted, that relative economic efficiency is provided for all HPS variants with GPE drive, in the whole range of natural gas cost change and operation modes and does not change greatly depending on the cost of fuel.

Conclusions

Assessment of relative economic efficiency of HPS with different types of compressor drive and sources of low temperature heat is performed for industry and municipal heat power sector, on conditions of fuel-energy resources price change and variable operation modes.

High values of relative economic efficiency of HPS with GPE drive are provided for all sources of low temperature heat, at variable operation modes in the whole range of natural gas cost change in industry and municipal heat power sector and do not change greatly, depending on the price of fuel.

For HPS with electric drive, on conditions of variable operation modes:

– relative economic efficiency of HPS, operating on the heat of sewage and circulating water, is provided for the price of natural gas (in industry) from 4201.512 to 4876.08 UAH/thous. m^3 (forecast estimations). For the price of natural gas 2296.3 UAH/thous. m^3 (for enterprises of municipal heat power sector) such variants of HPS are unprofitable, it is seen from negative values of relative economic efficiency. HPS, operating on the heat of circulating water, provides higher values of relative economic efficiency, than HPS, operating on the heat of sewage;

– substantial values of relative economic efficiency of HPS, operating on the heat of the air will be provided, if natural gas price is more than 4876.08 UAH/thous. m^3. Such variant of HPS is considered to be ineffective and inexpedient;

– HPS, operating on the heat of surface water, ground and ground waters will be economically efficient only in industry, if the cost of natural gas starts from 4876.08 UAH/thous. m^3 and higher. For enterprises of municipal heat power industry, if the cost of natural gas is 2296.3 UAH/thos. m^3, these variants of HPS will be unprofitable, it is proved by negative values of relative economic efficiency;

– high values of relative economic efficiency of HPS in the whole range of natural gas cost change in industry and municipal heat power branch, on conditions of variable operation modes, are registered for HPS, operating on the heat of geothermal waters and secondary energy resources.

The results of research allow to evaluate economic efficiency of HPS, on conditions of fuel and energy resources cost change in industry and municipal heat power branch, at variable operation modes, types of drive and sources of low temperature heat.

The suggested recommendations can be used for the forecast of the conditions of HPS efficient integration in heat supply systems of industrial enterprises and municipal heat power branch.

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Ostapenko Olga – Cand. Sc. (Eng.), Assistant Professor with the Department of Heat Power Engineering.

Bakum Olena – Student, with the Institute of Civil Engineering, Heat Power Engineering and Gas Supply.
Vinnytsia National Technical University.