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ENERGY, ECOLOGY AND ECONOMY ASPECTS OF THE EFFICIENCY OF HEAT POWER STATIONS OPERATING ON NATURAL AND INDUSTRIAL HEAT SOURCES

The paper estimates energy, eco0lgic and economic efficiencies of heat power stations (HPS) with different types of compressor drive, which operate on natural and industrial sources of low-temperature heat (surface water, water of recycling water supply systems, soil water, geothermal water, air, secondary energy resources, sewage wastewater and heat of the soil) taking into account variable operation modes with wide-range power variations in the heat power plant (HPP). Methods are proposed for complex evaluation of HPS efficiency in variable operation modes according to energy, ecology and economy indicators. Research results make it possible to choose HPS operation modes in order to achieve the desired values of the indicators of energy, ecologic and economic efficiencies for HPS year-round operation.

Keywords: *heat power station, low-temperature heat source, energy efficiency, ecologic efficiency, economic efficiency, fuel consumption, conventional fuel savings, working fuel savings, reduction of carbon dioxide emission.*

Introduction

Implementation of heat-pump technologies for heat generation in Ukraine is one of the efficient energy-saving measures that provide organic fuel economy and reduction of environment pollution. In accordance with "Energy Strategy of Ukraine till 2030" (approved by the Cabinet of Ministers of Ukraine № 145-p of March 15, 2006), development of heat supply system is planned to be implemented by means of gradual growth of heat generation on the basis of electric heat generators (mostly, heat pumps) [1].

The highest energy-saving effect is provided by introduction of heat pump stations where a heat pump is combined with an additional peak power source. One of the conditions for rational use of heat pump stations is availability of natural or industrial sources of low-temperature heat with sufficiently high temperature throughout the year, which do not require considerable expenses for pumping and do not cause corrosion of the equipment. Heat, generated by heat pump stations, could be used for heating and hot water supply for residential, industrial and public buildings as well as for technological needs [2 – 3].

Shortage of fuel and energy resources in Ukraine and environmental advantages of heat pumps stimulate introduction of heat pump stations into the industry and municipal power supply system. Building heat pump stations with natural or industrial sources of low-temperature heat on the basis of boiler houses will male it possible to reduce natural gas consumption, the cost of heat power and relieve the technogenic impact on the environment.

Over recent years a number of studies on the efficiency of heat pump stations in heat networks of power supply sources have been conducted [1, 3–13]. In particular, in [3] the authors have conducted research on improving energy efficiency of energy-supply sources using HPS and taking into account the influence of circuit solutions and operating modes. The circuits of said HPS are presented in [3].

Paper [4] presents investigation and analysis of 108 projects of heat pump stations for 21 region of Ukraine where heat of the air, sea water, river water, soil, water reservoirs, mining water, thermal water, sewage wastewater and secondary energy resources (SER) of metallurgical plants are used. HPS using the heat of wastewater, river water, the heat of soil and soil water are the most widespread in Ukraine. Usage of the heat of sea water, geothermal water, mining water, SER of metallurgical plants in HPS is possible only in certain regions of Ukraine but can be justified by significant volumes of fuel economy. Maximal fuel-saving values are provided by HPS using the heat of thermal and sewage wastewater (58.17 % and 56.09 % respectively). HPS utilizing the heat of air are characterized by the lowest fuel economy (20.41 %).

Introduction of HPS with the total power of 909.48 MW with the application of low-power heat sources, available in the regions of m Ukraine, will enable annual natural gas economy of 614.650 mln. tons. This would provide CO_2 emission reduction in Ukraine in the amount of 732.263 thousand tons per year, which would make it possible to relieve technogenic load on the environment (especially, in large industrial cities) and to increase economic efficiency of HPS implementation attracting the costs from selling the quotes for CO_2 emission in accordance with the Kyoto Protocol.

Heat of the sewage wastewater and river water is planned to be widely used in Ukraine, which will enable annual natural gas savings of 235.864 and 164.920 mln. m^3 respectively. Implementation of HPS using the heat of sea water would provide annual natural gas economy totaling to 96.350 mln. m^3 [4].

The greatest amounts of energy savings in Ukraine from the usage of HPS are achieved in Dniepropetrovsk region (19.36 %), Luhansk region (15.70 %) and Kyiv region (15.32 %). This is due to the availability of considerable natural gas resources and technogenic sources of low-temperature heat in these regions. Essential energy savings from HPS application (11.19 %) could be achieved in the Crimea by using rich natural low-temperature heat sources in the region. Amounts of energy savings from HPS application are very small in the western regions of Ukraine due to the absence of low-temperature heat sources of technogenic origin in these regions. However, HPS using natural heat sources could become the basis for heat supply in these regions as they provide reduction of environment pollution and of harmful emission in the atmosphere [4].

A number of studies have been conducted on estimating economic efficiency from the application of heat pump plants in heat networks of power supply sources [7 – 13].

In [11] economic efficiency of HPS with the power of 1 MW for heat supply systems is estimated taking into account complex influence of low-temperature heat sources, the type of HPP compressor drive and prices for energy carriers. Economic efficiency of HPS with the following natural low-temperature heat sources and the heat of industrial origin was investigated: sea water, water reservoirs, thermal water, air, river water, sewage wastewater, secondary energy resources of metallurgical plants, mining water, soil water. These low-temperature heat sources are quite widespread in the territory of Ukraine. In [11] economic efficiency of HPS with electrically-driven HPP compressor and with gas-piston engine (GPE) is investigated. Circuits of the above HPS are presented in [3].

In [11] it is estimated that with current level of prices for energy carriers and the predicted 10 -15 % growth of natural gas prices, all the investigated variants of GPE-driven HPS are cost-efficient.

According to [11], for electrically-driven HPS it is estimated that:

– with current level of prices for energy carriers and the predicted 10 - 15 % growth of electric energy cost, the variants which make use of the heat of mining and thermal water, of water reservoirs, sewage wastewater and SER of metallurgical plants are cost-efficient ones. Under the condition of more than 20 % growth of prices for electric energy, HPS variants where the heat of water reservoirs and of SER of metallurgical plants are not cost-efficient ones;

– with current level of prices for energy carriers and the predicted 10 - 15 % growth of natural gas prices, the variants which make use of the heat of mining and thermal water, of water reservoirs, sewage wastewater, SER of metallurgical plants and sea water will be cost-efficient ones.

In this case there is almost double reduction of the simple payback of HPS variants.

– under current level of prices for energy carriers and in case of simultaneous 10 – 50 % increase of electrical energy and natural gas costs the variants, where the heat of mining and thermal water, water reservoirs, sewage wastewater and SER of metallurgical plants is used, are cost-efficient ones. In this case simple payback of these HPS variants is reduced almost by half.

The presented results of the research [3, 4, 11] determine the energy and economic prerequisites for effective integration of HPS in the heat supply systems of industrial enterprises and municipal power engineering sector in Ukraine.

Main part

In the papers analyzed [1 – 13] the authors have not estimated energy, ecologic and economic efficiencies of HPS having different types of drive for variable operation modes for natural and industrial sources of low-temperature heat.

The aim of this paper is to determine energy, ecologic and economic advantages of using HPS with different types of drive in Ukraine for variable operation modes taking into account the available sources of natural and industrial low-temperature heat; to analyze energy, ecology and economic efficiencies of HPS for different low-temperature heat sources and types of HPP compressor drive.

The research was conducted by the method of mathematical modeling with the application of software in Excel environment. Energy, ecology and economic efficiencies of HPS with maximal power of 10 MW were investigated for heating season. Maximal power of HPS in the hot water supply mode was 2 MW. For comparison, a variant of boiler house operation with the same power was used. The efficiencies of electrically-driven HPS and of HPS with GPE-driven compressor were investigated. The power of the heat pump condenser varied from 500 to 2000 kW in accordance with the brands of heat pump equipment, produced by the industry. Low-temperature heat sources for HPS were: surface water, water recycling systems, ground water, geothermal water, air, secondary energy resources, sewage wastewater and the heat of soil. Characteristics of the low-temperature heat sources are given in Table. 1. The study was conducted for the following temperature profiles of the heat network operation: 150/70, 130/70, 95/70.

Efficiency of HPS operation is, to a great extent, determined by the optimal distribution of the load between the heat pump plant and the boiler of HPS. This distribution is characterized by the proportion β of the load of HPP as a part of HPS which is defined as the ratio of HPP condenser power to the power of HPS: $\beta = \frac{Q_{HPP}}{Q_{HPS}}$.

Table 1

Characteristics of the sources of low-temperature heat [14]

Low-temperature heat source	Temperature level of the source, ºC
Air	-5…+15
Soil	5…10
Soil water	8…15
Surface water	4…17
Sewage wastewater	10…17
Recycled water	25…40
Geothermal water	40...65
Secondary energy resources	40...70

Table 2 gives the range of the investigated TPP power values for heating (HM) and interheating (IHM) modes as well as the values of the proportion of TPP load for heating, interheating modes and annual average values.

Table 2

The values of power of heat pumps and the proportion of heat power of HPP in HPS

Power of HPP, KW		The proportion of heat power of HPP in HPS		
HM	IHP	HM	IHM	Annual average
500	500	0.061	0.25	0.158
1000	500	0.121	0.25	0.187
1500	500	0.182	0.25	0.217
2000	500	0.243	0.25	0.246
1000	1000	0.121	0.5	0.315
1500	1000	0.182	0.5	0.344
2000	1000	0.243	0.5	0.374
1500	1500	0.182	0.75	0.472
2000	1500	0.243	0.75	0.502
2000	2000	0.243	1	0.629

Proceeding from the analysis of the research results, the optimal value of β indicator have been determined for HPS with different heat sources and different types of HPP compressor drive for variable modes of the heat network operation. A definite value of heating power of HPS, HPP and proportion β of HPP load corresponds to each of these modes

Table 3

The values of savings of reference fuel, working fuel and CO_2 emission reduction for electrically-driven HPS, working on wastewater, depending on the proportion of HPP load

HPP load proportion β	Savings, %		
	Reference fuel	Working fuel	Emission reduction
0.158	-8.390	15.416	1.010
0.187	-4.550	19.266	1.481
0.2165	-0.690	23.115	1.953
0.246	3.150	26.964	2.425
0.315	-2.120	31.713	2.019
0.344	1.720	35.562	2.491
0.374	5.570	39.411	2.963
0.472	4.190	48.008	3.029
0.502	8.000	51.857	3.501
0.629	10.410	64.306	4.038

However, analysis of the efficiency of HPS variants and its operation modes should not be limited only to the energy efficiency indicators. Application of heat pumps provides reduction of environmental pollution and of harmful emission into the atmosphere. Employment of resources from the sale of quotas for CO_2 emissions, in accordance with the Kyoto Protocol, will increase the cost-effectiveness of implementing HPS and reduce the payback period of the latter. The study takes into account that additional funds from the sale of quotas for CO_2 emissions are $ 20 / tone of emissions.

Tables 3 and 4 give the energy and environmental efficiency indicators of electrically- and GPE-driven HPS using the heat of wastewater for variable modes of HPS operation. Here the values of savings of reference and working fuel are presented as well as the values of CO_2 emission depending on the proportion of HPP load. Similar results are obtained for HPS with other sources of heat.

Table 4

Values of savings of reference fuel, working fuel, CO_2 emission reduction for GPE-driven HPS, working on wastewater, depending on HPP load proportion, %

HPP load proportion β	Savings, %		
	Reference fuel	Working fuel	Emission reduction
0.158	6.71	5.85	1.01
0.187	8.73	7.61	1.48
0.217	10.99	9.59	1.95
0.246	13.55	11.82	2.43
0.315	15.38	13.41	2.02
0.344	17.64	15.39	2.49
0.374	20.20	17.62	2.96
0.472	25.56	22.30	3.03
0.502	28.12	24.53	3.50
0.629	38.00	33.16	4.04

As it is evident from Table 3, CO_2 emission reduction is observed for all modes of HPS operation, although savings of reference and working fuel for these modes have contradictory values. For GPE-driven HPS, operating on waste water (Table 4), savings of working and reference fuel as well as harmful emission reduction are registered for all operating modes.

Table 5

Values of savings on FER for electrically-driven HPS depending on HPP load proportion, %

HPP load proportion β	Low temperature heat source							
	Air	Soil	Soil water	Surface water	Wastewater	Recycling water	Secondary energy resources	Geothermal water
0.158	3.058	2.562	3.881	4.169	4.041	6.358	12.731	9.049
0.187	4.055	3.559	5.700	5.972	5.993	9.297	13.858	13.180
0.217	5.052	4.556	7.519	7.774	7.945	12.237	18.094	17.310
0.246	6.048	5.553	9.338	9.576	9.897	15.176	22.331	21.441
0.315	6.116	5.124	7.761	8.043	8.083	12.715	19.242	18.098
0.344	7.113	6.121	9.580	9.845	10.035	15.655	23.479	22.229
0.374	8.110	7.118	11.399	11.647	11.986	18.594	27.715	26.359
0.472	9.174	7.687	11.642	11.917	12.124	19.073	28.863	27.147
0.502	10.171	8.683	13.461	13.719	14.076	22.012	33.100	31.278
0.629	12.232	10.249	15.522	15.790	16.165	25.431	38.485	36.196

Preliminary analysis shows that the efficiency of heat pump stations should be assessed comprehensively, using the energy, environmental and economic criteria since the use of only energy criteria or both energy and environmental criteria do not give unambiguous estimation of HPS efficiency.

Tables 5 and 6 give economic indicators of electrically- and GPE-driven HPS respectively for different sources of low-temperature heat. Here (see tables 6 and 7) the values of savings of energy and fuel resources (FER) are presented (as a percentage) for HPS depending on HPP load proportion.

As it is evident from Tables 5 and 6, saving on fuel and energy resources is provided for all sources of heat, types of drives and operating modes of HPS. GPE-driven HPS gives higher economy on FER than electrically-driven HPS for most modes of HPS operation.

Table 6

Values of savings of FER for GPE-driven HPS depending on the proportion of HPP load, %

HPP load proportion β	Low-temperature heat source							
	Air	Soil	Soil water	Surface water	Wastewater	Recycling water	Secondary energy resources	Geothermal water
0.158	2.241	3.011	3.343	3.663	3.721	5.29	8.557	9.777
0.187	4.177	5.358	5.980	6.299	6.409	8.62	13.341	14.394
0.217	6.556	8.078	8.957	9.277	9.425	11.72	18.158	19.069
0.246	9.450	11.242	12.327	12.646	12.833	16.04	23.026	23.827
0.315	6.483	7.936	8.560	9.154	9.263	12.21	18.384	16.444
0.344	8.863	10.657	11.537	12.131	12.279	15.30	23.201	21.119
0.374	11.756	13.820	14.907	15.501	15.687	19.63	28.069	25.878
0.472	11.840	14.416	14.723	15.533	15.681	19.27	28.307	25.638
0.502	14.733	17.579	18.092	18.903	19.089	23.60	33.175	30.397
0.629	18.740	21.133	22.219	23.148	23.335	28.17	38.378	35.273

Tables 7 and 8 give values of savings on FER and emission (as a percentage) for electrically – driven and GPE-driven HPS using the wastewater heat. As Table 7 and 8 show, for GPE-driven HPS a more considerable economy on fuel and emission is achieved as compared with electrically-driven HPS.

Table 7

Values of savings on FER and emission (as a percentage) for electrically-driven HPS using the heat of wastewater, %

HPP load proportion, β	Savings, %		
	On emission	On FER	Overall economy
0.158	0.062	4.041	4.104
0.187	0.091	5.993	6.085
0.217	0.121	7.945	8.066
0.246	0.150	9.897	10.047
0.315	0.125	8.083	8.207
0.344	0.154	10.035	10.188
0.374	0.183	11.986	12.169
0.472	0.187	12.124	12.311
0.502	0.216	14.076	14.292
0.629	0.269	16.165	16.415

Table 8

Values of savings on FER and emission (as a percentage) for GPE-driven HPS using the heat wastewater, %

HPP load proportion, β	Savings, %		
	On emission	On FER	Overall economy
0.158	0.230	3.721	3.951
0.187	0.396	6.409	6.805
0.217	0.582	9.425	10.007
0.246	0.792	12.833	13.625
0.315	0.572	9.263	9.835
0.344	0.758	12.279	13.037
0.374	0.969	15.687	16.656
0.472	0.968	15.681	16.649
0.502	1.179	19.089	20.268
0.629	1.441	23.335	24.776

Table 9 presents the values of indicators of energy, ecology and economic efficiencies for electrically-driven HPS, operating on the heat of wastewater, depending on HPP load proportion. It should be noted that overall savings on FER and CO_2 emission reduction are provided for all HPS operation modes including even those where excess reference fuel consumption is observed.

Table 9

Values of the indicators of energy, ecologic and economic efficiencies for electrically-driven HPS operating on wastewater heat, %

HPP load proportion, β	Savings, %			
	Reference fuel	Working fuel	Emission reduction	Overall economy
0.158	-8.390	15.416	1.010	4.104
0.187	-4.550	19.266	1.481	6.085
0.217	-0.690	23.115	1.953	8.066
0.246	3.150	26.964	2.425	10.047
0.315	-2.120	31.713	2.019	8.207
0.344	1.720	35.562	2.491	10.188
0.374	5.570	39.411	2.963	12.169
0.472	4.190	48.008	3.029	12.311
0.502	8.000	51.857	3.501	14.292
0.629	10.410	64.306	4.038	16.415

Table 10 presents the values of indicators of energy, ecology and economic efficiencies for GPE-driven HPS, operating on the heat of wastewater, depending on HPP load proportion. Here we observe positive values of all indicators for all investigated operation modes.

Table 10

Values of the indicators of energy, ecology and economic efficiencies for GPE-driven HPS operating on the heat of wastewater, %

HPP load proportion, β	Savings, %			
	Reference fuel	Working fuel	Emission reduction	Overall economy
0.158	6.71	5.85	1.01	3.95
0.187	8.73	7.61	1.48	6.80
0.2165	10.99	9.59	1.95	10.01
0.246	13.55	11.82	2.43	13.63
0.315	15.38	13.41	2.02	9.84
0.344	17.64	15.39	2.49	13.04
0.374	20.20	17.62	2.96	16.66
0.472	25.56	22.30	3.03	16.65
0.502	28.12	24.53	3.50	20.27
0.629	38.00	33.16	4.04	24.78

Tables 11, 12 present the values of the same indicators of energy, ecology and economic efficiencies of electrically-driven and GPE-driven HPP, using the heat of recycled water, depending on HPP load proportion. Here we observe the character of the variations of HPP efficiency indicators that is analogous to the previous cases (Tables 9 and 10).

Table 11

Values of the indicators of energy, ecologic and economic efficiencies for electrically-driven HPS operating on the heat of recycled water, %

HPP load proportion, β	Savings, %			
	Reference fuel	Working fuel	Emission reduction	Overall economy
0.158	-1.7	15.416	4.222	6.618
0.187	2.15	19.266	6.063	9.672
0.2165	6	23.115	7.905	12.725
0.246	9.85	26.964	9.746	15.778
0.315	7.53	31.713	8.443	13.237
0.344	11.38	35.562	10.285	16.290
0.374	15.23	39.411	12.126	19.343
0.472	16.76	48.008	12.665	19.855
0.502	20.61	51.857	14.507	22.908
0.629	26	64.306	16.887	26.473

Table 12

Values of the indicators of energy, ecologic and economic efficiencies for GPE-driven HPS operating on the heat of recycled water, %

HPP load proportion, β	Savings, %			
	Reference fuel	Working fuel	Emission reduction	Overall economy
0.158	9.21	8.03	5.29	5.61
0.187	11.72	10.22	8.62	9.16
0.2165	14.40	12.25	11.72	12.44
0.246	17.29	15.08	16.04	17.04
0.315	20.07	17.50	12.21	12.96
0.344	22.85	19.53	15.30	16.25
0.374	25.64	22.37	19.63	20.84
0.472	31.99	27.60	19.27	20.46
0.502	34.88	30.44	23.60	25.06
0.629	45.52	39.71	28.17	29.90

For all investigated sources of natural and industrial heat for HPS the values of indicators of HPS energy, ecology and economic efficiencies have been determined (see Tables 9 -12) for variable operation modes and different types of HPP compressor drive.

The set of HPS efficiency indicators, proposed in Tables (9 – 12), makes it possible to estimate energy, ecology and economic efficiencies of HPS for variable operation modes and to make a conclusion concerning efficiency of the investigated HPS variant and its operation modes.

Conclusions

The paper has analyzed energy and economic prerequisites for effective integration of heat pump stations into the heat supply systems of industrial enterprises and enterprises of municipal power engineering sector of Ukraine.

Energy, ecologic and economic efficiencies of HPS with different types of compressor drive and operating on different sources of low-temperature heat (surface water, water of recycling water supply system, soil water, geothermal water, air, secondary energy resources, sewage wastewater, soil heat) have been estimated taking into account variable operation modes of water supply systems in the wide range of HPP power variations.

For all of the investigated natural and industrial heat sources, the values of indicators of HPS energy, ecologic and economic efficiencies have been determined for variable operation modes and different types of HPP compressor drives.

It has been determined that there should be complex evaluation of the efficiency of heat pump stations with the application of energy, environmental and economic criteria. The use of only energy criteria or both energy and ecologic criteria do not provide unambiguous HPS efficiency estimation.

The proposed set of HPS efficiency indicators makes it possible to estimate energy, ecologic and economic efficiencies of HPS for variable operating modes and to make a final conclusion concerning efficiency of the investigated HPS variant and its operation modes.

Research results make it possible to make a choice of HPS operation modes in order to obtain the required values of the indicators of energy, ecologic and economic efficiencies for HPS round-year operation.

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