O. P. Ostapenko, Cand. Sc. (Eng.), Assist. Professor

METHODICAL FUNDAMENTALS OF COMPLEX ASSESSMENT OF ENERGY-ECOLOGICAL-ECONOMIC EFFICIENCY OF ENERGY SUPPLY SYSTEMS WITH COGENERATION HEAT PUMP INSTALLATIONS AND PEAK SOURCES OF HEAT

Methodical fundamentals of complex assessment of energy-ecological-economic efficiency of energy supply systems (ESS) with cogeneration heat pump installations (CHPI) of various power levels and peak sources of heat (PSH) with the account of complex impact of variable operation modes of ESS, peak sources of heat in ESS, sources of CHPI drive energy and with the account of energy losses in the process of generation, supply and conversion of electric energy are suggested.

***Key words**: methodical fundamentals, energy-ecological-economic efficiency, energy supply system, cogeneration heat pump installation, peak source of heat.*

Introduction

Taking into consideration the importance of energy and resource saving and increase of energy usage efficiency in heat and power supply systems, in recent years a number of papers was devoted to the problems, studying energy and economic efficiency of ESS with CHPI [1 – 11], numerous studies, aimed at development of the methods of energy and energy-economic efficiency of combined CHPI application in thermal schemes of energy supply systems were carried out. In [6 – 11] the number of investigation of assessment of energy and economic efficiency of energy supply systems on the base of steam compressor heat pump installations (HPI) and cogeneration heat pump installations were carried out.

In [6 – 11] high energy efficiency of energy supply systems with CHPI has been proved. In research [7, 11] methodical fundamentals of energy-economic efficiency assessment of energy supply systems with CHPI of different power levels and peak sources of heat, with the account of complex impact of variable operation modes of ESS, peak sources of heat in ESS, sources of CHPI drive energy and with the account of energy losses in the process of generation, supply and conversion of electric energy, are suggested. In [1 – 11], the authors did not suggested methodical fundamentals of complex assessment of energy-ecological-economic efficiency of energy supply systems with cogeneration heat pump installations of various power levels and peak sources of heat, with the account of complex impact of variable operation modes of ESS, peak sources of heat in ESS, sources of CHPI drive energy and with the account of energy losses in the process of generation, supply and conversion of electric energy.

Aim of the research is the development of methodical fundamentals for complex assessment of energy-ecological-economic efficiency of energy supply systems with cogeneration heat pump installations of various power levels and peak sources of heat, with the account of complex impact of variable operation modes of ESS, peak sources of heat in ESS, sources of drive energy of CHPI with the account of energy losses in the process of generation, supply and conversion of electric energy.

Main part

In our research methodical fundamentals for complex assessment of energy-ecological-economic efficiency of ESS with CHPI (with the drive from gas-piston engine (GPE)) of various power levels and peak sources of heat (for instance, hot-water fuel-fired boiler, electric boiler, solar collectors, etc.) are suggested. Schemes of the studied ESS with CHPI are presented in [1, 12]. Application of the above-mentioned ESS has a number of energy advantages, as it is mentioned in the publications [6, 10]. Besides energy advantages, application of ESS with CHPI stipulates the reduction of environmental pollution (including thermal) and decrease of harmful emissions in the atmosphere. Cogeneration drive of HPI compressors in ESS can be provided on the base of gas engine-generators, manufactured by Ukrainian enterprises: «Pervomayskdizelmash» and SE «V. O. Malyshev plant». Methodical fundamentals for assessment of energy and energy-economic efficiency of ESS with CHPI and PSH are suggested in the research [6 – 7, 11].

In [7] indices of energy-economic efficiency of ESS on the base of combined CHPI and PSH are substantiated in order to determine energy efficient and economically substantiated operation modes of ESS on the base of combined CHPI and PSH, with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI, with the account of energy losses in the process of generation, supply and conversion of electric energy.

As it is noted in the papers [6 – 7, 11], energy efficiency of ESS is greater determined by optimal distribution of loading among ESS elements: cogeneration heat pump installation and peak source of heat (for instance, hot-water fuel-fired boiler, electric boiler, solar collectors, etc.) within ESS and energy efficiency levels of these elements of ESS. Optimal distribution of heat loading among ESS elements can be determined by the loading share of CHPI within ESS β [6 – 7, 11], it equals the ratio of CHPI thermal power (with the account of the capacity of waste treating equipment of CHPI cogeneration drive on the base of the study [6]) and ESS.

In our studies [6 – 7, 11] energy efficiency of the system «Source of drive energy of ESS – ESS – heat consumer from ESS» is analyzed on the example of ESS based on steam compressor HPI with cogeneration drive and peak sources of heat, with the account of energy losses in the process of generation, supply and conversion of electric energy to HPI and PSH in order to determine energy efficiency and economically substantiated ESS operation modes. In [6 – 7, 11] it is suggested to perform comprehensive assessment of energy efficiency of ESS with CHPI and PSH according to complex dimensionless criterion of ESS K_{ESS} energy efficiency, that takes into consideration dimensionless criteria of energy efficiency of CHPI K_{CHPI} and PSH K_{PSH} and distribution of heat loading among these elements of ESS. Dimensionless criterion of energy efficiency of steam compressor CHPI K_{CHPI}, suggested and substantiated in [6, 8], was obtained on the base of energy balance equation for the system «Source of drive energy of CHPI – CHPI – heat consumer from CHPI» with the account of the impact of drive energy sources of steam compressor CHPI and with the account of energy losses in the process of generation, supply and conversion of electric energy to CHPI.

Dimensionless criterion of energy efficiency of electric boiler as peak source of heat within ESS K_{PSH}, suggested in the research [6], was obtained on the base of energy balance equation for the systems «Source of electric energy – electric boiler – heat consumer from ESS» with the account of the impact of energy sources for peak electric boiler and with the account of energy losses in the process of generation and supply of electric energy to electric boiler. Dimensionless criterion of energy efficiency of hot-water fuel-fired boiler as peak source of heat within ESS K_{PSH}, suggested in the research [6], was determined on the base of energy balance equation for the systems «Sources of electric energy and fuel – fuel-fired boiler – heat consumer from ESS» with the account of the impact of energy sources for peak fuel-fired boiler and with the account of energy losses in the process of generation and supply of electric energy to the boiler. According to the research [6], for the cases of alternative peak sources of heat usage in ESS (for instance, solar collectors for ESS with CHPI of small capacity) the value of dimensionless criterion of PSH energy efficiency in ESS K_{PSH} will equal the efficiency factor of alternative peak source of heat η_{APSH} or the efficiency factor of supplementary system with alternative peak source of heat η^{s}_{APSH}.

Complex dimensionless criterion of ESS energy efficiency K_{ESS}, suggested in the research [6 –7], is used for the selection of the most efficient PSH for certain kind of ESS with CHPI. In the research [6] it is noted that complex dimensionless criterion of ESS energy efficiency K_{ESS} is used for the selection of the most efficient PSH for certain kind of ESS with CHPI. In [6] it is noted that complex dimensionless criterion of ESS energy efficiency K_{ESS} is used for the selection of the most efficient peak source of heat for certain kind of ESS with CHPI and energy efficient operation modes of the given ESS on condition $K_{ESS}>1$.

In the research [7] it is suggested to perform the comprehensive assessment of ESS energy-economic efficiency on the base of CHPI and PSH by complex generalized dimensionless criterion of energy-economic efficiency of ESS with CHPI and PSH that has the form:

$$K_{ESS}^{en.ec.} = K_{ESS} + \Delta E_i^{ESS} = (1-\beta)\cdot K_{PSH} + \beta \cdot K_{CHPI} + \Delta E_i^{ESS}, \quad (1)$$

where ΔE_i^{ESS} – is relative economic efficiency (in shares) for ESS on the base of CHPI and PSH for *i*-th operation mode of ESS, that is determined in the following manner:

$$\Delta E_i^{ESS} = \frac{(E_{SH})_i - (E_{ESS})_i}{(E_{SH})_i}, \quad (2)$$

where $(E_{SH})_i$ – are operation costs for *i*-th operation mode of the substituted source of heat (SH), $(E_{ESS})_i$ – are operation costs for *i*-th operation mode of ESS.

As it is noted in [7, 11], economically efficient operation modes of ESS with CHPI will be provided on condition $\Delta E_i^{ESS} > 0$. Energy efficient and economically substantiated operation modes of ESS with combined CHPI and PSH will be provided on condition $K_{ESS}^{en.ec.} > 1$. The greater is the value of $K_{ESS}^{en.ec.}$ index, the more energy efficient, economically efficient and competitive ESS with CHPI and PSH will be.

Methodical fundamentals for energy efficiency assessment of ESS with CHPI and PSH are presented in the studies [6, 8 – 10, 13 – 16]. Methodical fundamentals for energy-economic efficiency assessment of ESS with CHPI and PSH are presented in the studies [7, 11]. Methodical fundamentals for assessment of energy-ecological efficiency of ESS with CHPI and PSH (specific case of ESS with CHPI – heat pump plant) on natural and industrial sources of heat on condition of variable operation modes are presented in the study [17]. Methodical fundamentals for assessment of energy, ecological and economic aspects of ESS with CHPI and PSH efficiency (specific case of ESS with CHPI – heat pump plant) on natural and industrial sources of heat are suggested in the research [18 – 19].

It should be noted that in the studies [17 – 19] comprehensive investigations, aimed at assessment of energy-ecological-economic efficiency of ESS with CHPI of various power levels and PSH, with the account of complex impact of variable operation modes of ESS, peak sources of heat in ESS, sources of drive energy of CHPI and with the account of energy losses in the process of generation, supply and conversion of electric energy, have not been performed.

In our study it is suggested to perform the comprehensive assessment of energy-ecological-economic efficiency of ESS on the base of CHPI and PSH according to complex generalized dimensionless criterion of energy-ecological-economic efficiency of ESS with CHPI and PSH:

$$K_{ESS}^{compl.} = K_{ESS} + \Delta E_i^{ESS} + \Delta EC_i^{ESS} = (1-\beta)\cdot K_{PSH} + \beta \cdot K_{CHPI} + \Delta E_i^{ESS} + \Delta EC_i^{ESS}, \quad (3)$$

where ΔEC_i^{ESS} – is relative ecologic efficiency (in shares) for ESS on the base of CHPI and PSH for *i*-th operation modes of ESS, that is determined in the following manner:

$$\Delta EC_i^{ESS} = \frac{(EC_{SH})_i - (EC_{ESS})_i}{(EC_{SH})_i}, \quad (4)$$

where $(EC_{SH})_i$ – is the amount of harmful emission in the atmosphere for *i*-th operation mode of the substituted source of heat (SH), $(EC_{ESS})_i$ – is the amount of harmful emission in the atmosphere for *i*-th operation mode of ESS with CHPI and PSH.

The index of relative ecological efficiency of ESS with CHPI and PSH ΔEC_i^{ESS} assesses the decrease of harmful emissions in the atmosphere (in shares) as a result of application of ESS with CHPI and PSH for *i*-th operation mode of ESS as compared with the operation of alternative substituted source of heat energy. Harmful emissions in the atmosphere during burning of fuel in boilers as well as harmful emissions during the generation of electric energy at power plants or in the source of CHPI drive energy were taken into account.

As it is noted in the study [6], energy efficient operation modes of ESS with CHPI and PSH will be provided if K_{ESS}>1. As it is noted in studies [7, 11] economically efficient operation modes of ESS with CHPI and PSH will be provided if $\Delta E_i^{ESS} > 0$. In our research it is determined that ecologically safe and efficient operation modes of ESS with CHPI and PSH will be provided if $\Delta EC_i^{ESS} > 0$. The above-mentioned indices of various aspects of the efficiency of ESS with CHPI and PSH are also used for the selection of the most efficient peak source of heat for certain kind of ESS with CHPI and energy-ecologically-economic efficient operation modes of the above-mentioned ESS if K_{ESS}>1.

Ecologically safe, energy efficient and economically substantiated operation modes of ESS with combined CHPI and PSH will be provided on condition $K_{ESS}^{compl.} > 1$. The greater is the value of $K_{ESS}^{compl.}$ index, the more energy efficient, ecologically safe, economically efficient and competitive ESS with CHPI and PSH will be.

The suggested methodical fundamentals for comprehensive assessment of energy-ecological-economical efficiency of ESS with CHPI and PSH have a number of advantages:

— it take into account energy efficiency and power levels of ESS elements;

— they take into account operation modes of steam compressor HPI;

— take into account energy efficiency of PSH in ESS and the kind of the consumed energy, with the account of energy losses in the process of generation and supply of energy to PSH and ESS;

— take into account ecological efficiency of PSH in ESS and the kind of the consumed energy, with the account of energy losses in the process of generation and supply of energy to PSH and ESS;

— take into account energy efficiency of variable operation modes of ESS with the change of load distribution between steam compressor CHPI and PSH in ESS;

— these methods enable to assess the comprehensive impact on energy, ecological and economic efficiency of ESS with CHPI and PSH of such factors: variable operation modes of ESS, peak sources of ESS heat, sources of drive energy of steam compressor CHPI with the account of energy losses in the process of generation, supply and conversion of electric energy in CHPI and ESS;

— enable to assess comprehensively energy-ecological-economic efficiency of the greater part of variants of ESS with CHPI and PSH on conditions of variable operation modes;

— they can be used for the selection of the most energy efficient, ecologically safe and economically substantiated PSH for certain type of ESS;

— suggested methodical fundamentals can be used for comprehensive assessment of energy-ecological-economic efficiency of ESS with PSH and CHPI with different refrigerants, sources of low temperature heat and scheme solutions of HPI.

Application of the suggested methodical fundamentals for comprehensive assessment of energy-ecological-economic efficiency of ESS with CHPI and PSH will be demonstrated on the specific examples.

Fig. 1 and 2 show the results of assessment of energy-ecological-economic efficiency of ESS variants with CHPI and PSH. In our research the values of the dimensionless criterion of energy-ecological-economic efficiency of ESS with of CHPI and PSH are determined on conditions of CHPI loading share change in the range of β = 0,1…1,0. The study was carried out for energy efficient operation modes of CHPI with K_{CHPI} =1,1…2,1 (on conditions of maximum efficiency of GPE) and with K_{CHPI} =1,1…1,6 (on conditions of minimum efficiency of GPE), on the base of the research results [6, 8].

Fig. 1 shows the area of energy-economical efficient and ecologically safe ESS operation, using ground heat, with CHPI of small power and peak electric boiler with the consumption of electric energy from CHPI. This area is determined by the index of energy-ecological-economic efficiency of ESS with CHPI and PSH from the formula (3) on conditions of minimal efficiency of GPE and peak electric boiler. In our research, according to [6, 8], the following values are taken into account: value of GPE efficiency factor η_{EM} = 0,31, value of electric motor efficiency with the account of energy losses in the control unit of the motor η_{ED} = 0,8. Electric boiler house with η_{EB} = 0,9 is provided to be peak source of heat in ESS. The value of dimensionless criterion of electric boiler energy efficiency in case of electric energy consumption from CHPI, according to [6], is $K_{PSH}^{EB} = 0{,}223$. In order to assess the relative ecological efficiency of ESS with CHPI and PSH as the alternative source of heat the electric boiler house of corresponding power was provided.

Fig. 2 shows the area of energy-economical efficient and ecologically safe operation of ESS, using the heat of sewage water, with CHPI of large power and peak gas-fired boiler. This area is defined by the index of energy-ecological-economic efficiency of ESS with CHPI and PSH from the formula (3) on conditions of maximum efficiency of GPE and peak fuel-fired boiler. In our research, according to [6, 8], the following values are taken into account: value of GPE efficiency factor η_{EM} = 0,42 and value of electric motor efficiency with the account of energy losses in the control unit of the motor η_{ED} = 0,9. Fuel-fired boiler house with η_{FB} = 0,9 is provided by peak source of heat in ESS. The value of dimensionless criterion of fuel-fired boiler energy efficiency, according to [6], is $K_{PSH}^{FB} = 0{,}9$. In order to assess the relative ecological efficiency of ESS with CHPI and PSH the gas-fired boiler house of corresponding power was provided as the alternative source of heat.

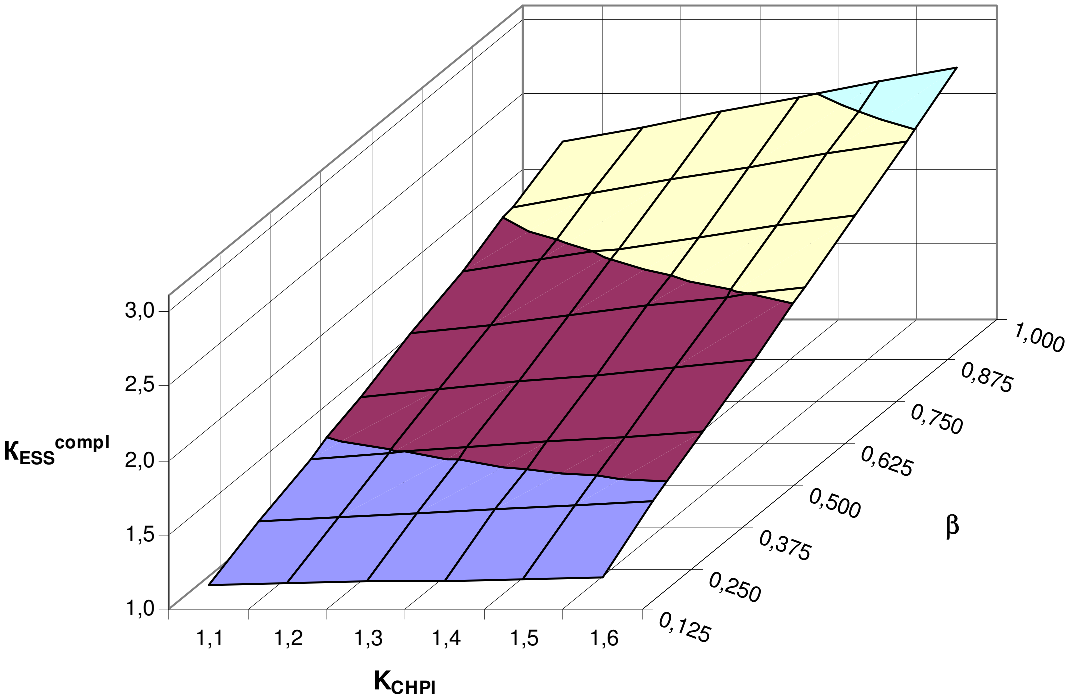

Fig. 1. Area of energy-economical efficient and ecologically safe operation of ESS, using heat of the ground, with CHPI of small power and peak electric boiler, on conditions of minimal efficiency of GPE and peak electric boiler and consumption of electric energy from CHPI

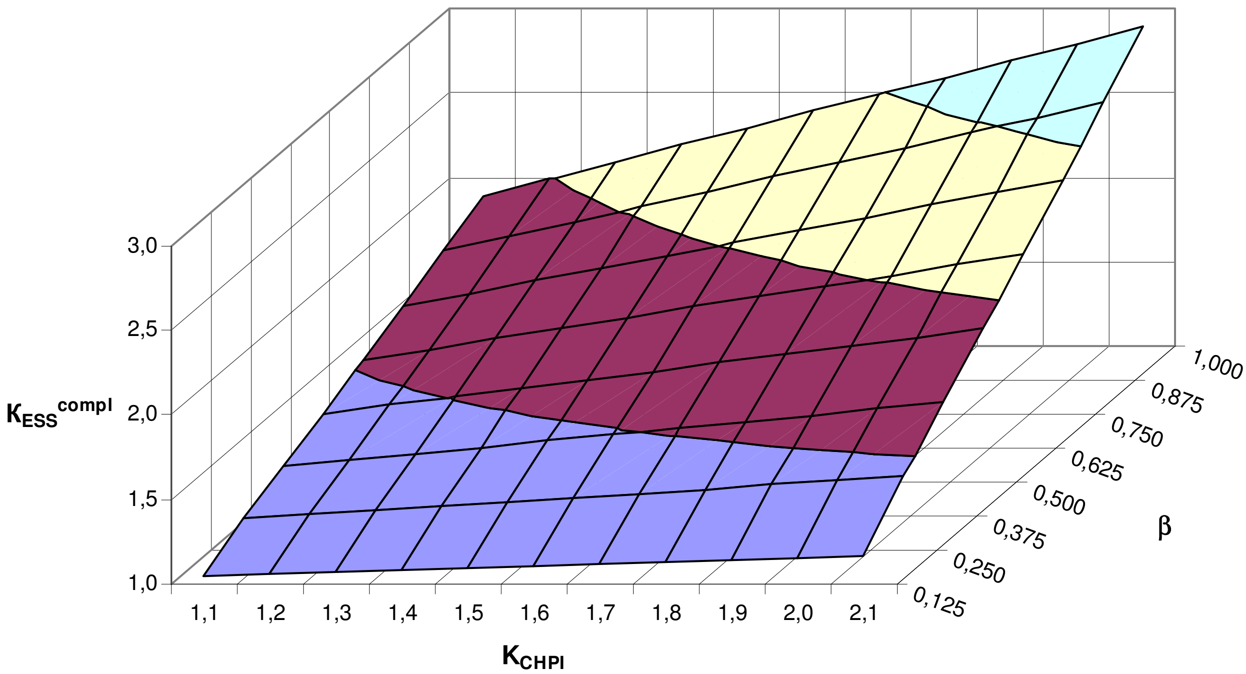

Fig. 2. Area of energy-economical efficient and ecologically safe operation of ESS, using sewage water heat, with CHPI of large power and peak fuel-fired boiler, on conditions of maximum efficiency of GPE and peak fuel-fired boiler

The suggested methodical fundamentals allow to determine the areas of high energy-economic efficiency and ecologically safe operation of ESS with CHPI and PSH and develop recommendations of high efficient operation of ESS with CHPI and PSH.

For practical application of the suggested methodical fundamentals for comprehensive assessment of energy-ecological-economic efficiency of different variants of ESS with CHPI and PSH, we propose to use the results, obtained in the research [6 – 11, 13 – 19].

Conclusions

Methodical fundamentals for comprehensive assessment of energy-ecological-economic efficiency of energy supply systems with cogeneration heat pump installations of various power levels and peak sources of heat, with the account of complex impact of ESS variable operation modes, peak sources of heat in ESS, sources of CHPI drive energy and with the account of energy losses in the process of generation, supply and conversion of electric energy are suggested in the paper.

The suggested methodical fundamentals for comprehensive assessment of energy-ecological-economical efficiency of ESS with CHPI and PSH have a number of advantages:

— they take into account energy efficiency and power levels of ESS elements;

— take into account operation modes of steam compressor HPI;

— take into account energy efficiency of PSH in ESS and type of the consumed energy, with the account of energy losses in the process of generation and supply of energy to PSH and ESS;

— take into account ecological efficiency of PSH in ESS and type of the consumed energy, with the account of energy losses in the process of generation and supply of energy to PSH and ESS;

— take into account energy efficiency of variable operation modes of ESS with the change of load distribution between steam compressor CHPI and PSH in ESS;

— enable to assess the comprehensive impact on energy, ecological and economic efficiency of ESS with CHPI and PSH of such factors: variable operation modes of ESS, peak sources of heat of ESS, sources of drive energy of steam compressor CHPI with the account of energy losses in the process of generation, supply and conversion of electric energy in CHPI and ESS;

— enable to assess comprehensively energy-ecological-economic efficiency of numerous variants of ESS with CHPI and PSH on conditions of variable operation modes;

— they can be used for the selection of the most energy efficient, ecologically safe and economically substantiated PSH for certain type of ESS;

— the suggested methodical fundamentals can be used for comprehensive assessment of energy-ecological-economic efficiency of ESS with PSH and CHPI with different refrigerants, sources of low temperature heat and scheme solutions of HPI.

The suggested methodical fundamentals allow to determine the areas of high energy-economic efficiency and ecologically safe operation of ESS with CHPI and PSH and develop recommendations, concerning high efficient operation of ESS with CHPI and PSH.

For practical application of the suggested methodical fundamentals for comprehensive assessment of energy-ecological-economic efficiency of different variants of ESS with CHPI and PSH, we propose to use the results, obtained in the studies [6 – 11, 13 – 19].

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Ostapenko Olga – Cand. Sc. (Eng.), Assistant Professor with the Department of Heat Power Engineering, e-mail: ostapenko1208@gmail.com.

Vinnytsia National Technical University.