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SPHERES OF ENERGY EFFICIENT OPERATION OF ENERGY SUPPLY SYSTEMS WITH COGENERATION-HEAT PUMP INSTALLATIONS AND PEAK SOURCES OF HEAT IN HEAT SUPPLY SYSTEMS

The approach, aimed at determination of the spheres of energy efficient operation of energy supply systems (ESS) with cogeneration heat pump installations (CHPI) and peak sources of heat (PSH) in heat supply systems, on conditions of optimal operation modes of CHPI, with the account of complex impact of variable operation modes, sources of drive energy for steam compressor heat pump installations (HPI) of different power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy, is suggested.

Key words*: sphere of energy efficient operation, energy efficiency, energy supply system, cogeneration heat pump installation, peak source of heat, heat supply system, dimensionless criterion of energy efficiency.*

Introduction

Studies of energy efficient operation modes of energy supply systems with cogeneration heat pump installations are carried out in numerous publications [1 – 13]. In research [8 – 9] comprehensive assessment of energy efficiency of steam compressor heat pump plants (HPP) with cogeneration drive with the account of complex impact of variable operation modes of HPP, peak sources of HPP heat, sources of drive energy of steam compressor HPP of different power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy, is performed on the developed scientific fundamentals. Energy efficiency of ESS, based of combined CHPI is studied and evaluated in [10], efficient operation modes of ESS are determined with the account of complex impact of variable operation modes, sources of drive energy of steam compressor HPI of different power levels, with the account of energy losses in the processes of generation, supply and conversion of electric energy. Study and assessment of ESS energy efficiency on the basis on combined CHPI and PSH are carried out in [11], efficient operation modes of these ESS with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI of different power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy are determined. In research [12], on the base of the developed methodical fundamentals, the assessment of energy efficiency of energy supply systems with combined CHPI and PSH, on conditions of optimal operation modes of CHPI for heat supply systems is performed, energy efficient operation modes of ESS with CHPI and PSH, with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI of different power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy are determined. In research [13] methodical fundamentals are developed, spheres of energy efficient operation of ESS with CHPI and PSH, on conditions of CHPI optimal operation modes are determined, energy efficient operation modes of ESS with CHPI and PSH are determined, with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI of different power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy.

In accordance with [11, 13], optimal distribution of loading between CHPI and PSH (for instance, hot-water fuel-fired boiler, electric boiler, solar collectors, etc.) within the frame of ESS largely determines energy efficiency of the above-mentioned ESS. Such distribution is characterized by the share of CHPI loading within the frame of ESS β, that is determined as the ratio of thermal capacity of CHPI to thermal capacity of ESS $\beta = Q_{CHPI}/Q_{ESS}$. Optimal values of β index for ESS with different sources of heat for CHPI during variable operation modes of heating network were determined, proceeding from the analysis of the results of research, carried out [14 – 16].

In [11] it is suggested to perform the comprehensive assessment of ESS with CHPI and PSH energy efficiency by complex dimensionless criterion of energy efficiency:

$$K_{ESS} = (1-\beta)\cdot K_{PSH} + \beta \cdot K_{CHPI}, \qquad (1)$$

where K_{PSH} – dimensionless criterion of energy efficiency of peak source of heat within ESS (hot-water fuel-fired boiler (FB), electric boiler (EB), solar collectors, etc.), K_{CHPI} – dimensionless criterion of energy efficiency of combined CHPI within ESS.

In research [5, 10 – 11] dimensionless criterion of steam compressor HPI with cogeneration drive energy efficiency K_{CHPI} was suggested. This criterion is obtained on the base of energy balance equation for «Source of drive energy of HPI – HPI – heat consumer from HPI» system, with the account of the impact of drive energy sources of steam compressor HPI and with the account of energy losses in the process of generation, supply and conversion of electric energy to HPI. Taking into account of such approach, dimensionless criterion of combined CHPI energy efficiency, in accordance with [5, 10] has the following form:

$$K_{CHPI} = Q_{CHPI}/Q_h = \eta_{EGPE}\cdot\eta_{ED}\cdot\varphi^{CHPI}\cdot\eta_{hf}, \qquad (2)$$

where Q_h – power, spent by gas-piston engine-generator (GPE) for generation of electric energy for HPI drive, η_{EGPE} – efficient factor of gas-piston engine; η_{ED} – efficiency factor of electric motor with the account energy losses in motor control unit from [5], φ^{CHPI} – real coefficient of performance of CHPI from the research [10], determined as: $\varphi^{CHPI} = (\varphi_t + K_{GPE}^{h})\cdot\eta_{hp}$, where φ_t – theoretical value of the coefficient of performance of HPI, without the account of the power of utilization equipment of GPE; K_{GPE}^{h} –thermal coefficient of GPE, that equals the ratio of thermal utilization capacity of GPE to its electric power; η_{hp} – energy efficiency of HPI, that takes into account all losses of energy in heat pump from [5 – 6]; η_{hf} – efficiency factor of the heat flow, that takes into consideration losses of energy and working substance in pipe lines and equipment of HPI.

On condition $K_{CHPI} = 1$ combined CHPI transfers to ESS the same thermal power that was used for generation of electric energy for HPI drive. The greater is the value of this index, the more efficient and competitive ESS with CHPI will be.

In research [11] spheres of energy efficiency operation of CHPI of various power levels, obtained on the base of the research [10] and determined by dimensionless criterion of CHPI energy efficiency K_{CHPI}, depending on real values of HPI coefficient of performance φ_r and efficient factor of GPE η_{EGPE}. Energy efficient operation modes of CHPI correspond to the condition $K_{CHPI} > 1$. High values of dimensionless criterion of energy efficiency for ESS with CHPI, obtained in [11], prove high energy efficiency of such combined energy supply systems.

Dimensionless criterion of energy efficiency of peak source of heat – electric boiler –within ESS K_{PSH}, according to [11], 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 the 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. In research [11], assessment of peak electric boiler energy efficiency in ESS, in case of electric energy usage from CHPI and for the cases of electric energy consumption from energy system, based on conventional or alternative sources of electric energy on the base of steam-gas installations, gas-turbine installations, solar power plants of thermodynamic cycle, wind energy plants is carried out.

Dimensionless criterion of peak source of heat energy efficiency– hot-water fuel-fired boiler – within ESS K_{PSH}, according to [11], obtained 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 the 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 (boiler house). In this case, consumption of electric energy by peak source of heat in ESS – fuel-fired boiler – is not directly connected with the process of heat generation in the boiler and the share of electric energy consumption for auxiliary needs is not great, that is why, it does not greatly influence the value of K_{PSH} index.

In research [11], it is noted, that in case of usage of the alternative peak sources of heat in ESS (for instance, solar collectors for small power ESS) the value of dimensionless criterion of peak source of heat energy efficiency for ESS $\mathrm{K}_{\mathrm{PSH}}$ will equal the efficiency of the alternative peak source of heat η_{APSH} or the efficiency of additional system with alternative peak source of heat η^{s}_{APSH}.

From the research [11], it is determined, that for the cases of $K_{CHPI} < K_{PSH}$ the value of dimensionless criterion of ESS energy efficiency K_{ESS} will decrease with the increase of the share of CHPI β load. For other cases the value of dimensionless criterion of ESS energy efficiency K_{ESS} will increase with the increase of CHPI β load share. In research [11 – 12], it is noted, that complex dimensionless criterion of ESS energy efficiency K_{ESS} from the formula (1) could be used for the selection of the most efficient peak source of heat for certain type of ESS and efficient operation modes of ESS.

In details methodical fundamentals of energy efficiency assessment of ESS with CHPI and PSH are described in research [11].

ESS with CHPI and peak electric boilers, suggested in [12], will be energy efficient in heat supply systems, if the share of CHPI loading in ESS will be $\beta > 0{,}4$. On such condition, modern high efficient electric and fuel-fired boilers would be inferior by energy efficiency to the above-mentioned ESS. In [12] it is determined that energy efficiency of ESS with CHPI and peak fuel-fired boilers almost two times exceeds the energy efficiency of modern high efficient electric and fuel-fired boilers, intended for operation in heat supply systems. In [13], it is determined, that ESS with CHPI and peak fuel-fired boilers, suggested in the research, will be energy efficient, if the share of CHPI loading in ESS will be $\beta > 0{,}4$. If this condition is realized, modern high efficient electric and fuel-fired boilers would be inferior by energy efficiency to the above-mentioned ESS. On such condition, these ESS could be recommended as high efficient energy supply systems, as their efficiency more than two times exceeds the energy efficiency of modern high efficient electric and fuel-fired boilers. It is determined, that ESS with CHPI and peak electric boilers, suggested in [13], would be energy efficient, if the share of CHPI load in ESS is $\beta > 0{,}7$. On these conditions, the above-mentioned ESS could be recommended as high efficient energy supply systems, as even in case of minimal efficiency of GPE and boiler, energy efficiency of energy supply system almost two times exceeds energy efficiency of high efficient electric and fuel-fired boilers.

In [1 – 13] the authors did not determine the spheres of energy efficient operation of energy supply systems with CHPI and PSH in heat supply systems, on conditions of optimal operation modes of CHPI, with the account of complex impact of variable operation modes, sources of drive energy of steam compressor HPI of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy.

Aim of the research is the determination of the spheres of energy efficient operation of energy supply systems with combined CHPI and PSH in heat supply systems, on conditions of optimal operation modes of CHPI, determination of energy efficient operation modes of ESS with CHPI and PSH with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI of different power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy.

Main part

The research contains the assessment of energy efficient operation modes of energy supply systems with combined cogeneration heat pump installations and peak sources of heat in the process of operation in heat supply systems. Energy efficiency of energy supply systems with steam compressor HPI of small (up to 1 MW) and large capacity with cogeneration drive from gas-piston engine-generator was studied. Electric and fuel-fired boilers were provided to be used as peak sources of heat in ESS (fuel-fired boiler houses large capacity ESS). The investigated ESS with combined CHPI and PSH can completely or partially provide auxiliary needs in electric energy and provide the consumers needs in heating and hot water supply. Schemes of the energy supply systems with combined CHPI and PSH are presented in research [1, 17]. Methodical fundamentals for assessment energy efficiency of ESS with CHPI and PSH for heat sully systems are described in research [11].

In our research the energy efficiency of the system «Source of drive energy of CHPI – ESS with CHPI and PSH – consumer of the heat from ESS» is analyzed on the example of ESS with steam compressor CHPI and PSH for heat supply systems. The advantage of this approach is the account of energy losses in the process of generation, supply and conversion of electric energy in CHPI and PSH in order to determine energy efficiency of ESS operation modes for heat supply.

In research [11] it is determined that for ESS with CHPI and PSH for the values of load share of CHPI $\beta < 0{,}7$ energy efficiency and competitiveness of ESS greatly determine by the type and efficiency of PSH, on condition of energy efficient operation modes of CHPI. This condition corresponds to optimal values of CHPI loading share in the range of $\beta = 0{,}16\ldots0{,}63$ for heat supply systems operation. That is why, type and efficiency of PSH, on condition of energy efficient operation modes of CHPI in ESS, will greatly determine energy efficiency of ESS for heat supply systems.

In research [11], values of dimensionless index of PSH energy efficiency for ESS are determined; these values are [11]: $K_{PSH}^{ES} = 0{,}302\ldots0{,}318$ for electric boiler on condition of electric energy usage from energy system; $K_{PSH}^{EC} = 0{,}223\ldots0{,}319$ for electric boiler for ESS of small power, on condition of electric energy usage from CHPI; $K_{PSH}^{FB} = 0{,}8\ldots0{,}9$ for peak hot-water fuel-fired boiler within ESS. Proceeding from the analysis of these indices, the conclusion can be made that the usage of fuel-fired boiler as peak source of heat in ESS for the heat supply systems is far more efficient than the usage of peak electric boiler with different variants of electric energy sources.

On conditions $K_{CHPI} > 1$ and $K_{ESS} > \eta_{FB}$ (or $K_{ESS} > \eta_{EB}$) [11], spheres of energy efficient operation of ESS with CHPI and PSH can be determined from the dependences, proposed in the research [11 – 12]. If the above-mentioned conditions are realizes, the studied ESS with CHPI and PSH can be recommended as high efficient energy supply systems that might be competitive with modern high efficient electric and fuel-fired boilers in the systems of heat supply and energy supply.

For energy efficient operation modes of CHPI in ESS and on conditions of $K_{CHPI} > 1$ and $K_{ESS} > \eta_{FB}$ (or $K_{ESS} > \eta_{EB}$) [11], in our research spheres of energy efficient operation and energy efficient operation modes of ESS with CHPI and peak electric and fuel-fired boilers in heat supply systems, for different power levels and energy efficiency of ESS elements are determined. Spheres of energy efficient operation of ESS with combined CHPI and PSH for heat supply systems in our research are determined on conditions of optimal operation modes of CHPI on the base of the research [10 – 13].

The suggested approach, applied for determination of the spheres of energy efficient operation of ESS with CHPI and PSH for heat supply systems has a number of advantages:

— it takes into account variable operation modes of ESS for heat supply during the year with the change of loading share between steam compressor CHPI and peak source of heat in ESS;

— it enables to assess complex impact of 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;

— it takes into account the impact of drive energy sources of steam compressor CHPI of different power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy in CHPI and ESS;

— it takes into account the impact of peak sources of heat for ESS and type of the energy, consumed by them, with the account of energy losses in the process of generation and supply of energy to peak sources of heat;

— as a result of complex approach to ESS energy efficiency assessment the selection of the most efficient PSH for certain type of ESS can be made;

— methodical fundamentals, suggested in [11], and the results of research, presented in this paper can be used for the determination of the areas of energy efficient operation of ESS on the base of steam compressor CHPI with different refrigerants, sources of low temperature heat and scheme solutions in heat supply systems;

— it enables to determine areas and modes of energy efficient operation of ESS with CHPI and PSH for heat supply, at which energy efficiency of the studied ESS exceeds almost two times energy efficiency of modern high energy efficient electric and fuel-fired boilers;

— it enables to evaluate comprehensively energy efficiency of numerous versions of ESS with CHPI and PSH in heat supply systems;

— it enables to develop recommendations on energy efficient operation of ESS with CHPI and PSH with different scheme solutions for heat supply systems.

Application of the suggested approaches, aimed at determination of the areas of ESS with CHPI and PSH energy efficient operation in heat supply systems will be demonstrated on the specific examples.

Figs. 1 – 8 show the results of research, aimed at determination of the areas of energy efficient operation of ESS with CHPI and PSH in heat supply systems for the cases of variable loading of CHPI within ESS and optimal values of CHPI loading share β for energy efficient operation modes of CHPI, based on the results of the research [10 – 13]. The values of the dimensionless criterion of energy efficiency of ESS with CHPI and PSH is studied for the cases of seasonal variable loading of CHPI within ESS for optimal values of CHPI loading share the range of β = 0,16…0,63 [14 – 16], that corresponds to temperature modes of heat supply system operation. The research is performed 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 [10 – 11] results. The above-mentioned values of CHPI K_{CHPI} energy efficiency criteria K_{CHPI} correspond to the values of real coefficient of performance of CHPI within the limits of φ_r = 3,0…5,4 for CHPI of small power and φ_r = 2,7…5,4 for CHPI of large power, according to [11].

Fig. 1 shows the area of energy efficient operation of ESS with CHPI of small power and PSH, on condition of electric energy consumption by peak source of heat (electric boiler) from energy system of Ukraine. In the given research, according to [5], the following values are taken into account: averaged value of the efficiency factor of Ukrainian electric power plants η_{EPP} = 0,383 and efficiency factor value of distributive electric grids in Ukraine η_{DG} = 0,875. Fot these conditions, electric boiler house with η_{EB} = 0,95 is provided to be peak source of heat in ESS. It should be noted, that in case of efficiency factor of electric boiler house change in the range η_{EB} = 0,9…0,95 the value of dimensionless criterion of electric boiler energy efficiency for the cases of electric energy consumption from energy system will be $K_{PSH}^{ES} = 0{,}302...0{,}318$. For the studied operation modes of ESS, values of complex dimensionless criterion of ESS energy efficiency for heat supply systems are $K_{ESS} = 0{,}87...1{,}441$ on condition of β = 0,47…0,63 and may be $K_{ESS} = 2{,}1$ on condition of β = 1.

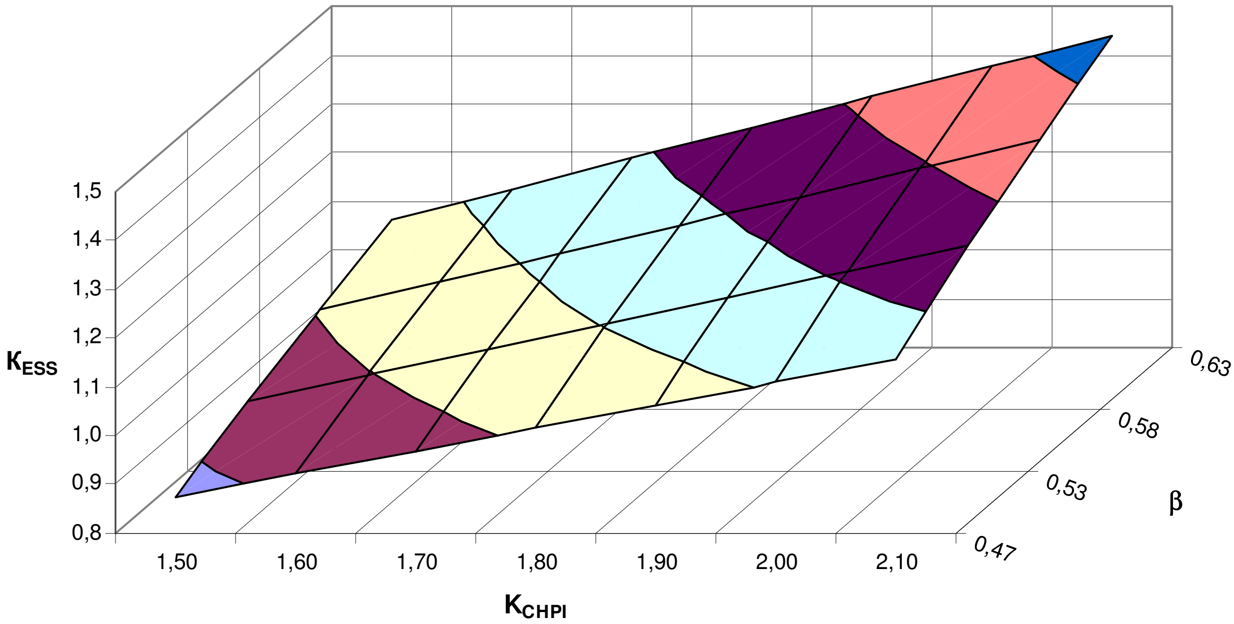

Fig. 1. Area of energy efficient operation of ESS with CHPI of small power for heat supply, on condition of electric energy consumption by peak electric boiler from energy system of Ukraine

As it is seen from Fig. 1, the values of complex dimensionless energy efficiency criterion of ESS are $K_{ESS} = 0{,}87 \ldots 1{,}06$ on condition of minimal value of energy efficient criterion of CHPI K_{CHPI} = 1,5; for operation modes of ESS with K_{CHPI} > 1,5 the values of dimensionless criterion of ESS energy efficiency change in the range of $K_{ESS} = 0{,}92 \ldots 1{,}441$. Energy efficient operation modes of these ESS are provided on conditions of energy efficient operation modes of CHPI with the values of energy efficiency index $K_{CHPI} = 1{,}5 \ldots 2{,}1$.

On conditions of K_{CHPI} > 1 and K_{ESS} > 1 dependences, suggested in the given research, determine the areas of high efficient operation of the studied ESS for heat supply. Fig. 2 shows the area of high efficient operation of ESS with CHPI of small power on condition of electric energy consumption by peak electric boiler from energy system of Ukraine, in the process of operation in heat supply systems.

As it is seen from Fig. 2, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 1{,}02 \ldots 1{,}25$ on condition on minimal value of energy efficiency criterion of CHPI K_{CHPI} = 1,8; for operation modes of ESS with K_{CHPI} > 1,8 the values of dimensionless criterion of ESS energy efficiency change within the limits of $K_{ESS} = 1{,}06 \ldots 1{,}44$. High efficient operation modes of these ESS are provided on conditions of energy efficient operation modes of CHPI with the values of energy efficiency index $K_{CHPI} = 1{,}8 \ldots 2{,}1$. The investigated ESS with CHPI and PSH can be recommended as high efficient energy supply systems, that can be competitive with modern high efficient electric and fuel-fired boilers in heat supply and energy supply systems, as their efficiency almost two times exceeds energy efficiency of modern high efficient electric and fuel-fired boilers.

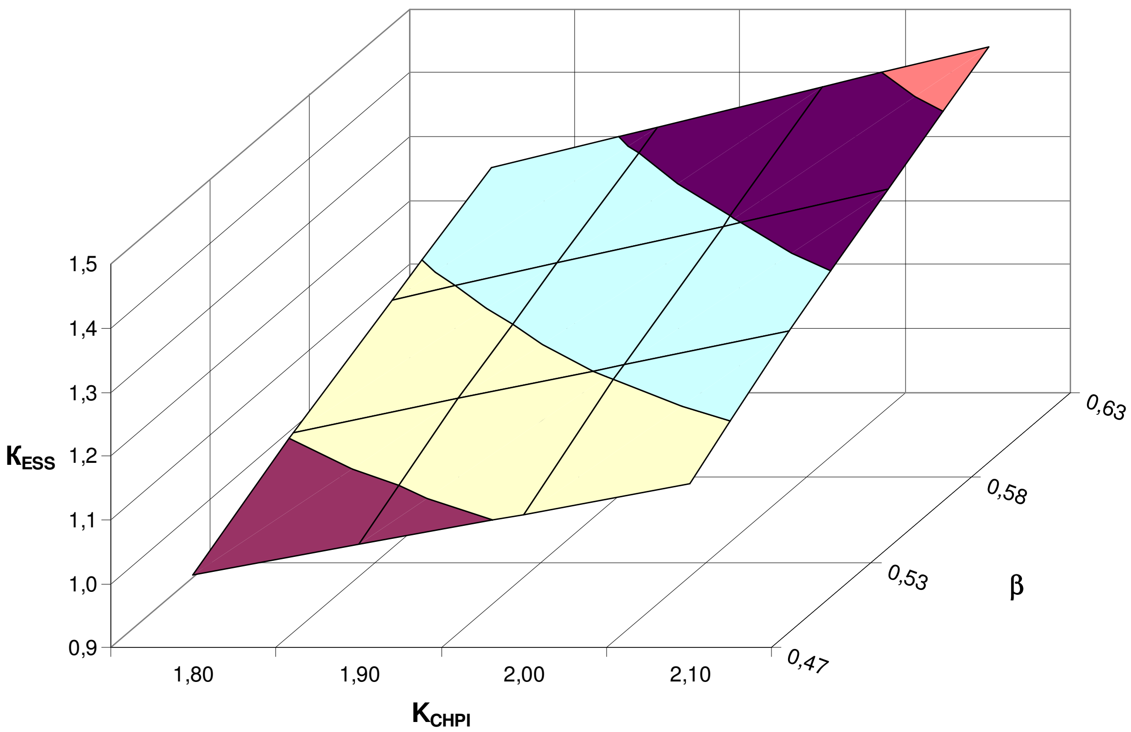

Fig. 2. Area of high efficient operation of ESS with CHPI of small power for heat supply, on condition of electric energy consumption by peak electric boiler from energy system of Ukraine

Fig. 3 shows the area of energy efficient operation of ESS with CHPI of small power for heat supply, on conditions of minimal efficiency of GPE and PSH, with the consumption of electric energy by peak source of heat (electric boiler) from CHPI. In the given research, in accordance with [5, 10], the following values are taken into account: value of GPE efficiency factor η_{EGPE} = 0,31 and value of electric motor efficiency factor with the account of energy losses in the control unit of electric motor η_{ED} = 0,8. Electric boiler house with η_{EB} = 0,9 is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of energy efficiency of electric boiler for the cases of electric energy consumption from CHPI will be $K_{PSH}^{EC} = 0{,}223$. For the investigated operation modes of ESS for heat supply systems the values of the complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}85...1{,}09$ on condition of β = 0,58…0,63 and it can reach the value of $K_{ESS} = 1{,}6$ [12 – 13] on condition of β = 1.

As it is seen from Fig. 3, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}85...0{,}9$ on condition of minimal value of energy efficient criterion of CHPI K_{CHPI} = 1,3; for operation modes of ESS with K_{CHPI} > 1,3 the values of dimensionless criterion of ESS energy efficiency change in the limits $K_{ESS} = 0{,}91...1{,}09$. Energy efficient operation modes of these ESS are provided on conditions of energy efficient modes of CHPI operation with the values of energy efficiency index $K_{CHPI} = 1{,}3...1{,}6$.

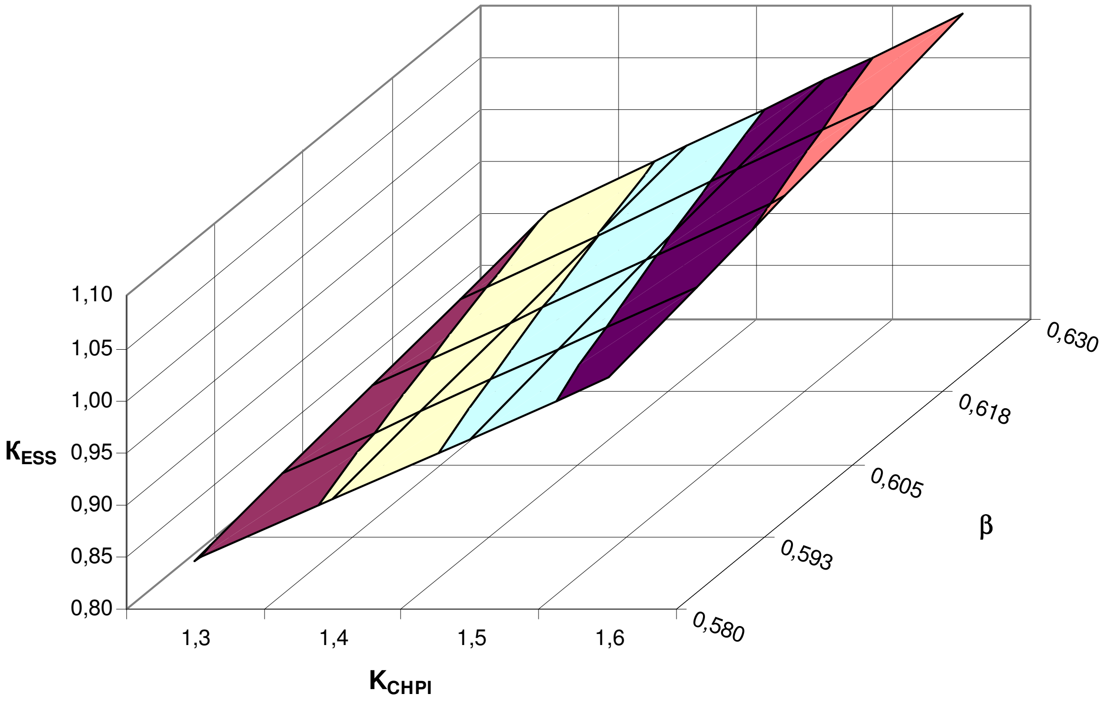

Fig. 3. Area of energy efficient operation of ESS with CHPI of small power for heat supply, on conditions of minimal efficiency of GPE and peak electric boiler with the consumption of electric energy by electric boiler from CHPI

Fig. 4 shows the area of energy efficient operation of ESS with CHPI of small power and peak fuel-fired boiler for heat supply, on conditions of minimal efficiency of GPE and PSH. In the given research, in accordance with [5, 10], the following values are taken into account: value of GPE efficiency factor η_{EGPE} = 0,31 and value of electric motor efficiency with the account of energy losses in the control unit of electric motor η_{ED} = 0,8. Fuel-fired boiler house with η_{FB} = 0,8 is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of fuel-fired boiler energy efficiency will be K_{PSH}^{FB} = 0,8. For the study of ESS operation modes for heat supply systems the values of the complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}91...1{,}304$ on condition of β = 0,37…0,63 and may be $K_{ESS} = 1{,}6$ [12 – 13] on condition of $\beta = 1$.

As it is seen from Fig. 4, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}91...0{,}99$ on condition of minimal value of CHPI energy efficient criterion K_{CHPI} = 1,1; for operation modes of ESS with K_{CHPI} > 1,1 the values of dimensionless criterion of ESS energy efficiency change within the limits $K_{ESS} = 0{,}93...1{,}304$. Energy efficient operation modes of these ESS are provided on the conditions of energy efficient operation modes of CHPI with the values of energy efficiency index of $K_{CHPI} = 1{,}1...1{,}6$.

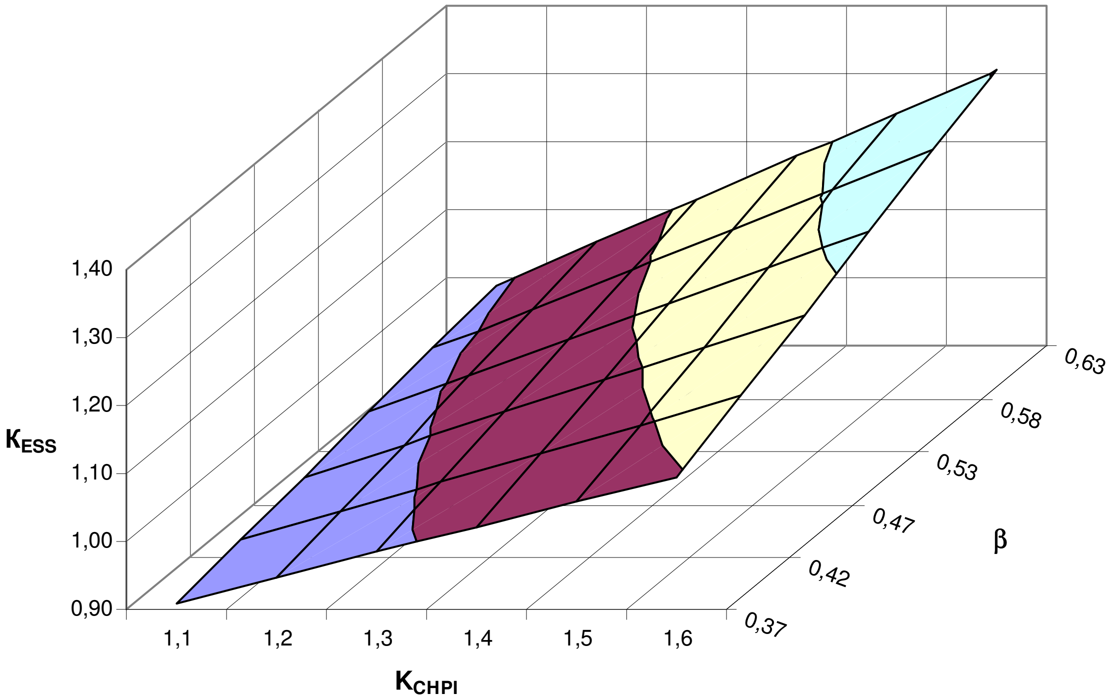

Fig. 4. Area of energy efficient operation of ESS with CHPI of small power for heat supply, on conditions of minimal efficiency of GPE and peak fuel-fired boiler

Fig. 5 shows the area of energy efficient operation of ESS with CHPI of small power for heat supply, on conditions of maximal efficiency of GPE and PSH, with the consumption of electric energy by peak source of heat (electric boiler) from CHPI. In the given research, in accordance with [5, 10], the following values are taken into account: value of GPE efficiency factor η_{EGPE} = 0,42 and value of electric motor efficiency with the account of energy losses in the control unit of electric motor η_{ED} = 0,8. Electric boiler house with η_{EB} = 0,95 is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of electric boiler energy efficiency for the cases of electric energy consumption from CHPI will be $K_{PSH}^{EC} = 0{,}319$. For the studied ESS operation modes for heat supply systems the values of the complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}83...1{,}44$ on condition of β = 0,47…0,63 and may be $K_{ESS} = 2{,}1$ [11] on condition of β = 1.

As it is seen from Fig. 5, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}83...1{,}0$ on condition of minimal value of energy efficiency criterion of CHPI K_{CHPI} = 1,4; for operation modes of ESS with K_{CHPI} > 1,4 the values of dimensionless criterion of ESS energy efficiency change within the limits of $K_{ESS} = 0{,}87...1{,}44$. Energy efficient operation modes of these ESS are provided on the conditions of energy efficient operation modes of CHPI with the values of energy efficiency index of $K_{CHPI} = 1{,}4...2{,}1$.

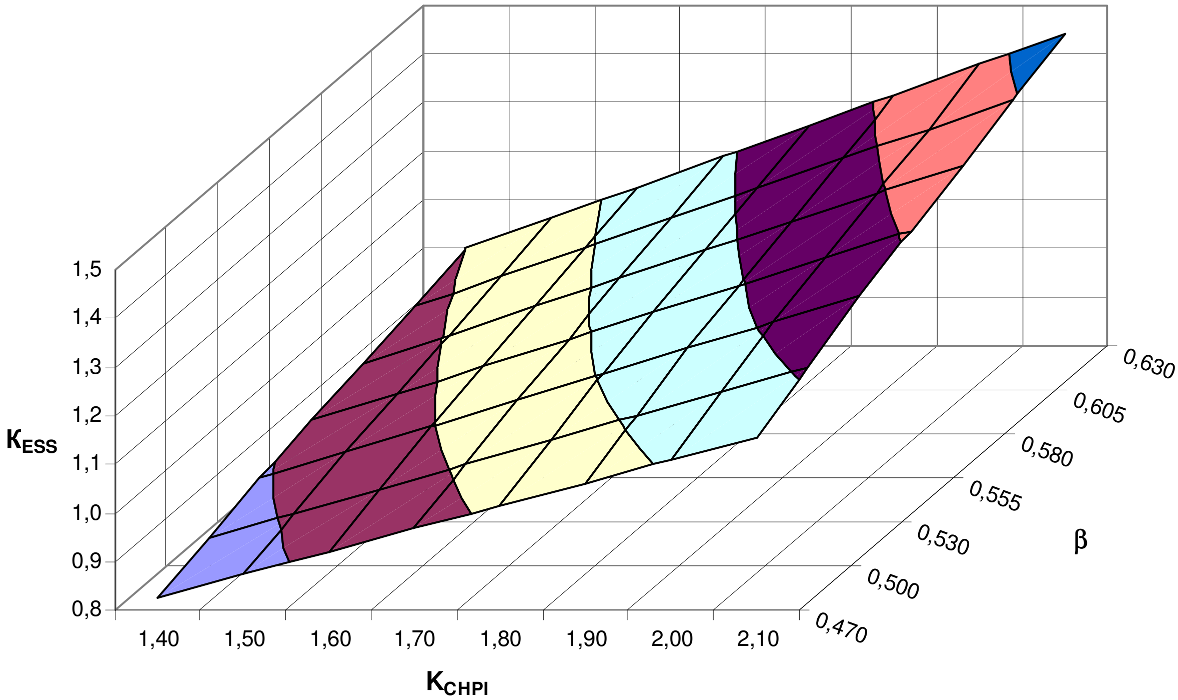

Fig. 5. Area of energy efficient operation of ESS with CHPI of small power for heat supply, on conditions of maximal efficiency of GPE and PSH and electric energy consumption of by the electric boiler from CHPI

Fig. 6 shows the area of energy efficient operation of ESS with CHPI of small power and peak fuel-fired boiler for heat supply, on conditions of maximal efficiency of GPE and PSH. In the given research, according to [5, 10], the following values are taken into account: value of GPE efficiency factor η_{EGPE} = 0,42 and value of electric motor efficiency with the account of energy losses in the control unit of electric motor η_{ED} = 0,8. Fuel-fired boiler house with η_{FB} = 0,9 is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of fuel-fired boiler energy efficiency will be K_{PSH}^{FB} = 0,9. For studied operation modes of ESS for heat supply systems the values of the complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}95...1{,}656$ on condition of β = 0,26…0,63 and may be $K_{ESS} = 2{,}1$ [11] on condition of $\beta = 1$.

As it is seen from Fig. 6, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}95...1{,}03$ on condition of minimal value of energy efficiency criterion of CHPI K_{CHPI} = 1,1; for operation modes of ESS with K_{CHPI} > 1,1 the values of dimensionless criterion of ESS energy efficiency change in the range of $K_{ESS} = 0{,}98...1{,}656$. Energy efficient operation modes of these ESS are provided on the conditions of energy efficient operation modes of CHPI with the values of energy efficiency index of $K_{CHPI} = 1{,}1...2{,}1$.

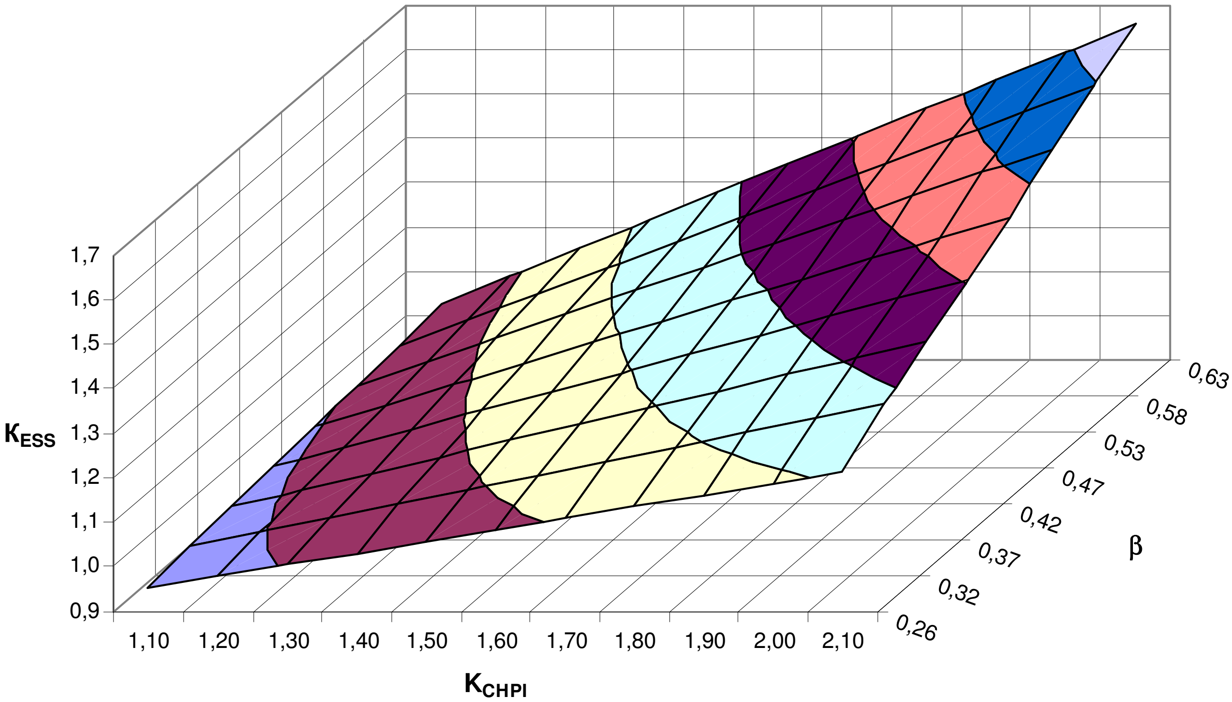

Fig. 6. Area of energy efficient operation of ESS with CHPI of small power for heat supply, on conditions of maximal efficiency of GPE and peak fuel-fired boiler

Fig. 7 shows the area of energy efficient operation of ESS with CHPI of large power and peak fuel-fired boiler house for heat supply, on conditions of minimal efficiency of GPE and PSH. In the given research, in accordance with [5, 10], the following values are taken into account: value of GPE efficiency factor η_{EGPE} = 0,31 and value of electric motor efficiency with the account of energy losses in the control unit of electric motor η_{ED} = 0,9. Fuel-fired boiler house with η_{FB} = 0,8 is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of fuel-fired boiler energy efficiency will be $K_{PSH}^{FB} = \eta_{FB}$ =0,8. For the studied operation modes of ESS for heat supply systems the values of the complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}9 \ldots 1{,}304$ on condition of β = 0,32…0,63 and may be $K_{ESS} = 1{,}6$ [12 – 13] on condition of β = 1.

As it is seen from Fig. 7, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}9 \ldots 0{,}99$ on condition on minimal value of CHPI energy efficient criterion K_{CHPI} = 1,1; for operation modes of ESS with K_{CHPI} > 1,1 the values of dimensionless criterion of ESS energy efficiency change within the limits of $K_{ESS} = 0{,}93 \ldots 1{,}304$. Energy efficient operation modes of these ESS are provided on the conditions of energy efficient operation modes of CHPI with the values of energy efficiency index of $K_{CHPI} = 1{,}1 \ldots 1{,}6$.

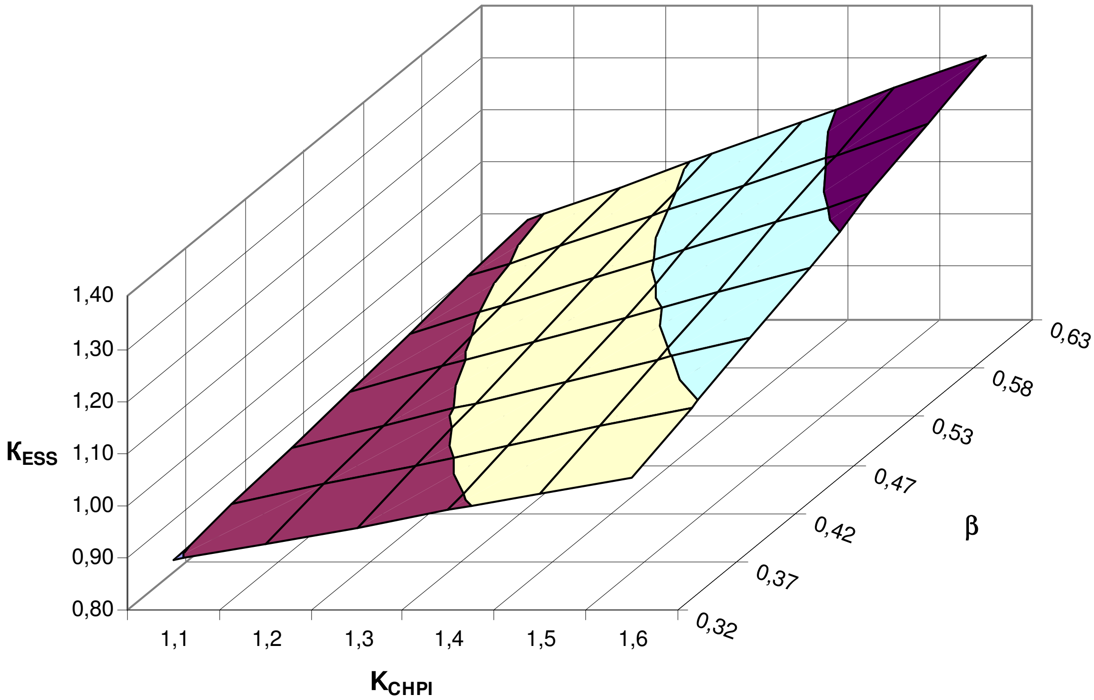

Fig. 7. Area of energy efficient operation of ESS with CHPI of large power for heat supply, on conditions of minimal efficiency of GPE and peak fuel-fired boiler

Fig. 8 shows the area of energy efficient operation of ESS with CHPI of large power and peak fuel-fired boiler for heat supply, on conditions of maximal efficiency of GPE and PSH. In the given research, according to [5, 10], the following values are taken into account: value of GPE efficiency factor η_{EGPE} = 0,42 and value of electric motor efficiency with the account of energy losses in the control unit of electric motor $\eta_{ED} = 0{,}9$. Fuel-fired boiler house with η_{FB} = 0,9 is provided to be peak source of heat in ESS for these conditions. The value of dimensionless criterion of fuel-fired boiler energy efficiency will be K_{PSH}^{FB} = 0,9. For the studied operation modes of ESS for heat supply systems the values of the complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}93...1{,}656$ on condition of β = 0,16…0,63 and may be $K_{ESS} = 2{,}1$ [11] on condition of $\beta = 1$.

As it is seen from Fig. 8, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 0{,}93...1{,}03$ on condition on minimal value of CHPI energy efficiency criterion K_{CHPI} = 1,1; for operation modes of ESS with K_{CHPI} > 1,1 the values of dimensionless criterion of ESS energy efficiency change within the limits of $K_{ESS} = 0{,}95...1{,}656$. Energy efficient operation modes of these ESS are provided on the conditions of energy efficient operation modes of CHPI with the values of energy efficiency index of $K_{CHPI} = 1{,}1...2{,}1$.

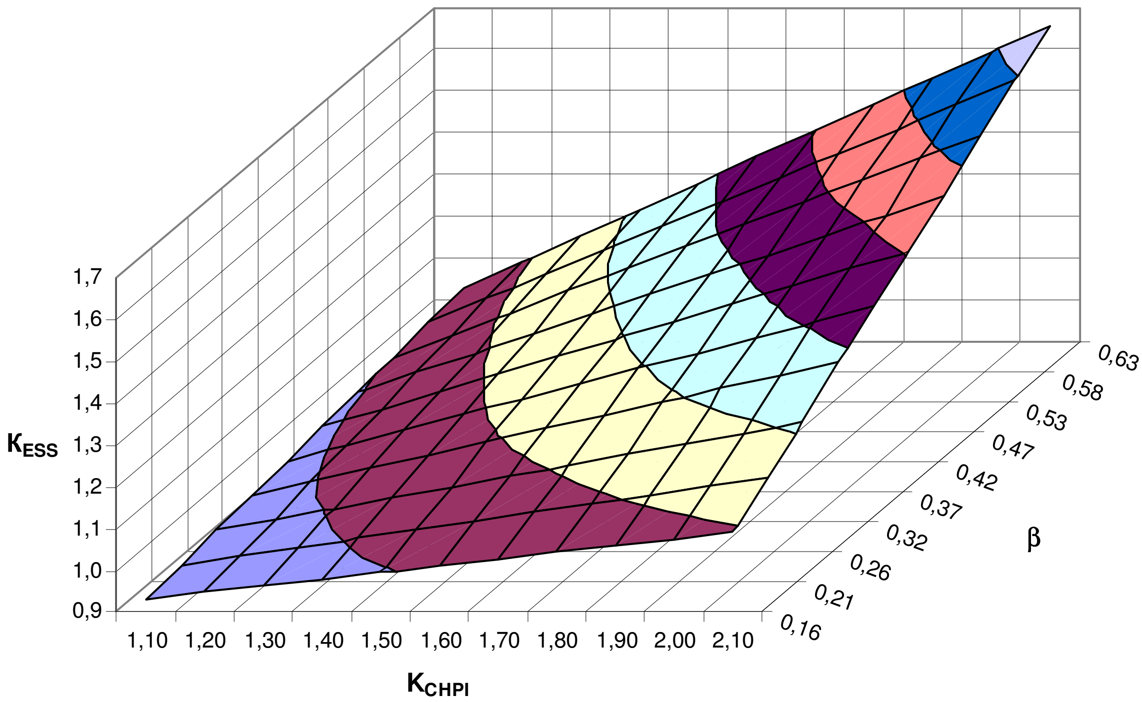

Fig. 8. Area of energy efficient operation of ESS with CHPI of large power for heat supply, on conditions of maximal efficiency of GPE and peak fuel-fired boiler

It should be noted, that the dependences, shown in Figs. 1 – 8, are obtained for energy efficient operation modes of CHPI on the base of the results of the research [10 – 13].

Dependences, shown in Figs. 4 and 7 determine the areas of energy efficient operation of ESS with CHPI of various power levels and peak fuel-fired boiler (boiler house) for heat supply, on conditions of minimal efficiency of GPE and fuel-fired boiler (boiler house). On conditions of $\beta = (0{,}32\ldots0{,}37)\ldots0{,}63$ and $K_{CHPI} = 1{,}1\ldots1{,}6$ these ESS can be recommended as high efficient energy supply systems, as their efficiency almost two times exceeds energy efficiency of high efficient electric and fuel-fired boilers.

Dependences, shown in Figs. 6 and 8 determine areas of energy efficient operation of ESS with CHPI of various power levels and peak fuel-fired boiler (boiler house) for heat supply, on conditions of maximal efficiency of GPE and fuel-fired boiler (boiler house). On conditions of $\beta = (0{,}16\ldots0{,}26)\ldots0{,}63$ and $K_{CHPI} = 1{,}1\ldots2{,}1$ these ESS can be recommended as high efficient energy supply systems, as their efficiency more than two times exceeds energy efficiency of high efficient electric and fuel-fired boilers. The investigated ESS can be competitive with modern high efficient electric and fuel-fired boilers in heat supply and energy supply systems.

In the research [12] it is determined, that the investigated ESS with CHPI and peak fuel-fired boilers will be high efficient in heat supply systems, if the share of CHPI load in ESS will be $\beta > 0{,}4$; that corresponds to the results of research, shown in Figs. 4, 6 – 8. In our research it is determined that on condition of maximal efficiency of GPE and fuel-fired boiler, the investigated ESS with CHPI and fuel-fired boilers will be energy efficient if the share of CHPI load in ESS will be $\beta > 0{,}16\ldots0{,}26$, depending on CHPI power level. On condition of minimal efficiency of GPE and fuel-fired boiler the investigated ESS with CHPI and fuel-fired boilers will be energy efficient, if the share of CHPI load in ESS will be $\beta > 0{,}32\ldots0{,}37$, depending on CHPI power level.

Dependences, shown in Figs. 1 – 3 and 5, determine areas of energy efficient operation of ESS with CHPI and peak electric boiler in heat supply systems, with different versions of electric energy sources for peak electric boiler and on conditions of different energy efficiency of GPE and electric boiler. In the research [12] it is determined, that the investigated ESS with CHPI and peak electric boilers will be energy efficient, if the share of CHPI load in ESS will be $\beta > 0{,}7$. In our research it is determined that ESS with CHPI and peak electric boilers will be energy efficient, if the share of CHPI load in ESS will be $\beta > 0{,}47\ldots0{,}58$, depending on CHPI power level. However, such operation modes of ESS will be provided on condition of high efficient operation of CHPI with energy efficiency index of $K_{CHPI} > 1{,}3\ldots1{,}5$, depending on CHPI power level. These conditions correspond to the results of the research, shown in Figs. 1 – 3 and 5.

The suggested approaches, aimed at determination of the areas of ESS with CHPI and PSH energy efficient operation in heat supply systems enable to determine energy efficient areas and operation modes of the above-mentioned ESS, with the account of complex impact of variable operation modes, sources of drive energy for steam compressor CHPI of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy.

Scientific results, obtained in the research, regarding to determination of energy efficient operation areas of ESS enable to develop recommendations concerning energy efficient operation of ESS with CHPI and PSH with different scheme solutions for operation in heat supply systems. For assessment of energy efficiency of different variants of ESS with CHPI and PSH for heat supply systems, besides the above-mentioned approaches, we suggest to use the results, obtained un the research [1, 5 – 16].

Conclusions

Methodical fundamentals are developed, areas of energy efficient operation of ESS with CHPI and PSH, on conditions of optimal operation modes of CHPI, for heat supply systems are determined; energy efficient operation modes of ESS with CHPI and PSH with the account of complex impact of variable operation modes, sources of drive energy of steam compressor HPI of different power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy are determined.

The suggested approach, aimed at determination of the areas of energy efficient operation of ESS with CHPI and PSH for heat supply systems has a numerous advantages:

— it takes into account variable operation modes of ESS for heat supply during the year with the change of loading share between steam compressor CHPI and peak source of heat in ESS;

— it enables to assess complex impact of 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;

— it takes into account the impact of drive energy sources of steam compressor CHPI of different power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy in CHPI and ESS;

— it takes into account the impact of peak sources of heat for ESS and type of the energy, consumed by them, with the account of energy losses in the process of generation and supply of energy to peak sources of heat;

— as a result of complex approach to ESS energy efficiency assessment the selection of the most efficient PSH for certain type of ESS can be made;

— methodical fundamentals, suggested in [11], and the results of research, presented in this paper can be used for the determination of the areas of energy efficient operation of ESS on the base of steam compressor CHPI with different refrigerants, sources of low temperature heat and scheme solutions in heat supply systems;

— it enables to determine areas and modes of energy efficient operation of ESS with CHPI and PSH for heat supply, at which energy efficiency of the studied ESS exceeds almost two times energy efficiency of modern high energy efficient electric and fuel-fired boilers;

— it enables to evaluate comprehensively energy efficiency of numerous versions of ESS with CHPI and PSH in heat supply systems;

— it enables to develop recommendations on energy efficient operation of ESS with CHPI and PSH with different scheme solutions for heat supply systems.

For energy efficient operation modes of CHPI in ESS and on conditions of K_{CHPI} > 1 and K_{ESS} > η_{FB} (or K_{ESS} > η_{EB}) [11], areas of energy efficient operation and energy efficient operation modes of ESS with CHPI and peak electric and fuel-fired boilers in heat supply systems are determined for various power levels and energy efficiency of ESS elements.

For ESS with CHPI of different power levels and peak fuel-fired boilers the areas of energy efficient operation in heat supply systems, that corresponds to energy efficient operation modes of ESS and CHPI with β = (0,32…0,37)…0,63 and $K_{CHPI} = 1{,}1...1{,}6$ on conditions of minimal efficiency of GPE and fuel-fired boiler (boiler house). Under these conditions energy efficiency of these ESS almost two times exceeds energy efficiency of high efficient electric and fuel-fired boilers.

On conditions of maximal efficiency of GPE and fuel-fired boiler (boiler house), for ESS with CHPI of different power levels and peak fuel-fired boilers the areas of energy efficient operation in heat supply systems, that corresponds to energy efficient operation modes of ESS and CHPI with β = (0,16…0,26)…0,63 and $K_{CHPI} = 1{,}1...2{,}1$ are determined. These ESS can be recommended as high efficient energy supply systems, as their efficiency more than two times exceeds energy efficiency of high efficient electric and fuel-fired boilers. The investigated ESS can be competitive with modern high efficient electric and fuel-fired boilers in heat supply and energy supply systems.

It is determined that on condition of minimal efficiency of GPE and fuel-fired boiler, the investigated ESS with CHPI and fuel-fired boilers will be energy efficient, if the share of CHPI load in ESS will be β > 0,32…0,37, depending on CHPI power level.

It is determined that on condition of maximal efficiency of GPE and fuel-fired boiler, the investigated ESS with CHPI and fuel-fired boilers will be energy efficient if the share of CHPI load in ESS will be β > 0,16…0,26, depending on CHPI power level.

It is determined that ESS with CHPI and peak electric boilers will be energy efficient, if the share of CHPI load in ESS will be β > 0,47…0,58, depending on CHPI power level. However, such operation modes of ESS will be provided on condition of high efficient operation of CHPI with energy efficiency index of K_{CHPI} > 1,3…1,5, depending on CHPI power level.

The approaches, aimed at determination of the areas of energy efficient operation of ESS with CHPI and PSH in heat supply systems are suggested, they enable to determine energy efficient areas and operation modes of the given ESS with the account of complex impact of variable operation modes, sources of drive energy for steam compressor CHPI of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy.

Scientific results, obtained in the research, dealing with the determination of energy efficient areas of ESS operation enable to develop recommendations, concerning energy efficient operation of ESS with CHPI and PSH with different scheme solutions for operation in heat supply systems. For evaluation of energy efficiency of different variants of ESS with CHPI and PSH for heat supply systems, besides the above-mentioned approaches, we suggest to use the results, obtained un the research [1, 5 – 16].

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