Areas of high energy efficiency of energy supply systems with cogeneration heat pump installations of large power and peak fuel-fired boilers for heat supply systems

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Abstract. The approach, aimed at determination of the areas of high energy efficiency of energy supply systems (ESS) with cogeneration heat pump installations (CHPI) of large power and peak fuel-fired boilers (FB) for heat supply systems (HSS), on conditions of optimal operation modes of CHPI, taking into consideration complex impact of variable operation modes, sources of drive energy for steam compressor heat pump installations (HPI) of large power, with the account of energy losses in the process of generation, supply and conversion of electric energy, is suggested.

Keywords: *area of high energy efficient operation, energy supply system, cogeneration heat pump installation, peak fuel-fired boiler, heat supply system.*

Introduction. In recent years a number of investigations, dealing with the efficiency of usage combined cogeneration heat pump installations in thermal schemes of energy supply sources were carried out [1 – 13]. This technology provides the application of combined cogeneration heat pump installations, that enables to reduce the consumption of natural or alternative gas by 30 – 45 %, as compared with boiler installations of the equivalent capacity [1], and obtain cheaper at cost electric energy, as compared with the grid energy (by 30 – 40 %). Cogeneration drive of HPI compressors can be provided on the base of gas engines-generators, manufactured by Ukrainian enterprises.

Publications review on the subject. In research [2 –3] energy advantages are evaluated and efficient real operation modes of HPI with electric and cogeneration drives are determined, with the account of the impact of drive energy sources of steam compressor heat pumps and energy losses in the process of generation, supply and conversion of electric energy to HPI. In research [4 – 5] methodical fundamentals of comprehensive assessment of energy efficiency of steam compressor heat pump plants (HPP) with electric and cogeneration drives, with the account of complex impact of HPP variable operation modes, peak sources of heat of HPP, sources of HPP drive energy and with the account of energy losses in the process of generation, supply and conversion of electric energy are suggested. In [5 – 6] scientific fundamentals are suggested and comprehensive assessment of energy efficiency of steam compressor HPP with cogeneration drive with the account of complex impact of HPP variable operation modes, HPP peak sources of heat, sources of drive energy of steam compressor HPP of various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy is performed.

In research [7] the assessment of ESS energy efficiency on the base of combined CHPI are realized, efficient operation modes of ESS 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 processes of generation, supply and conversion of electric energy are determined. In research [8] energy efficiency of ESS, based on combined CHPI and peak sources of heat (PSH) is evaluated, 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 various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy are determined. In research [9] methodical fundamentals are developed, 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 various power levels, with the account of energy losses in the process of generation, supply and conversion of electric energy, is performed.

In accordance with [8 – 9], 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 $\beta = Q_{CHPI}/Q_{ESS}$. In the paper [8] it is suggested to realize 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.) from the researches [8 – 9, 11 – 12],

K_{CHPI} – dimensionless criterion of CHPI within ESS energy efficiency from the researches [2, 7 – 8].

In research [8] spheres of energy efficiency operation of CHPI of various power levels, obtained on the base of the research [7] and determined by CHPI energy efficiency dimensionless criterion K_{CHPI}, depending on real values of HPI coefficient of performance φ_r and efficient factor of gas-piston engine-generator (GPE) η_{EGPE}. Energy efficient operation modes of CHPI correspond to the condition $K_{CHPI} > 1$.

Dimensionless criterion of peak source of heat energy efficiency– hot-water fuel-fired boiler –within ESS K_{PSH}, according to [8], 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.

High values of energy efficiency dimensionless criterion for ESS with CHPI, obtained in [8], confirm high energy efficiency of such combined energy supply systems. In [9] 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 research [11] 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 research [11] under conditions of $K_{CHPI} > 1$ and $K_{ESS} > \eta_{FB}$ and modes of energy efficient operation of CHPI, areas of energy efficient operation and energy efficient operation modes of ESS with CHPI and peak fuel-fired boilers for various power levels and ESS elements energy efficiency are determined. It is determined, that ESS with CHPI and peak fuel-fired boilers, suggested in the research [11], 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 will be inferior by their energy efficiency to the above-mentioned ESS. Under these conditions the above-mentioned ESS can be recommended as energy efficient energy supply systems.

In research [12] methodical fundamentals are developed, spheres of energy efficient operation of ESS with CHPI and PSH in heat supply systems, on conditions of CHPI optimal operation modes are determined, energy efficient operation modes of ESS with CHPI and PSH in heat supply systems 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 research [12] on conditions of minimal 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 $\beta = (0{,}32\ldots0{,}37)\ldots0{,}63$ and $K_{CHPI} = 1{,}1\ldots1{,}6$ are determined. Under these conditions energy efficiency of these ESS exceeds energy efficiency of high efficient electric and fuel-fired boilers.

In research [12] 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 $\beta = (0{,}16\ldots0{,}26)\ldots0{,}63$ and $K_{CHPI} = 1{,}1\ldots2{,}1$ are determined. The investigated ESS can be competitive with modern high efficient electric and fuel-fired boilers in heat supply and energy supply systems.

In research [13] the areas of high energy efficiency of ESS with large power CHPI and FB, on conditions of optimal operation modes of CHPI are determined; energy efficient operation modes of ESS with large power CHPI and FB with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI of large power, with the account of energy losses in the process of generation, supply and conversion of electric energy are determined.

In [1 – 13] the authors did not determine the areas of high energy efficiency of energy supply systems with combined CHPI of large power and FB for HSS, on conditions of optimal operation modes of CHPI.

Objective. Aim of the research is the determination of the areas of high energy efficiency of ESS with CHPI of large power and peak FB for HSS on conditions of optimal operation modes of CHPI, determination of energy efficient operation modes of ESS with large power CHPI and peak FB in HSS with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI of large power, with the account of energy losses in the process of generation, supply and conversion of electric energy.

Materials and methods. The research contains the evaluation of high energy efficient operation modes of ESS with CHPI of large power and peak FB for heat supply systems. Energy efficiency of ESS with steam compressor HPI of large power (higher than 1 MW) with cogeneration drive from GPE was studied. Fuel-fired boiler houses were provided to be used as peak sources of heat in ESS. The investigated ESS with CHPI of large power and FB can completely or partially provide auxiliary needs in electric energy and provide the consumers needs in heating and hot water supply. Schemes of the ESS with CHPI and peak FB for HSS are presented in works [1, 10]. Methodical fundamentals of energy efficiency evaluation of ESS with large power CHPI and peak FB for HSS are given in research [8].

Areas of high energy efficiency of ESS with CHPI of large power and peak FB for HSS can be determined from the dependences, suggested in the research [11 – 12], on conditions of $K_{CHPI} > 1$ and $K_{ESS} > 1$ [11]. If the above-mentioned conditions are realized, the investigated ESS with CHPI of large power and FB 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.

In our study the areas of high energy efficiency of ESS with CHPI of large power and peak FB for heat supply systems are defined on conditions of optimal operation modes of large power CHPI on the base of the research, carried out [7 – 8].

Results and discussion. Application of the suggested approaches, aimed at determination of the areas of ESS with CHPI of large power and FB high energy efficiency for heat supply systems will be demonstrated on the specific examples.

Figs. 1 – 2 shows the results of research, aimed at determination of the areas of high energy efficiency of ESS with CHPI of large power and FB in HSS for energy efficient operation modes of CHPI, based on the results of the studies [7 – 8]. The values of the dimensionless criterion of energy efficiency of ESS with large power CHPI and FB in HSS 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. As above mentioned, the areas of high energy efficiency of ESS with CHPI of large power and FB can be determined on conditions of K_{CHPI} > 1 and K_{ESS} > 1 [11]. The research is carried out for energy efficient operation modes of large power 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), based on the results of the studies [7 – 8]. The above-mentioned values of CHPI K_{CHPI} energy efficiency criterion correspond to the values of real coefficient of performance of CHPI within the limits of φ_r = 2,7…5,4 for CHPI of large power, according to [8].

Fig. 1 shows the area of high energy efficiency of ESS with CHPI of large power and peak fuel-fired boiler for HSS, on conditions of minimal efficiency of GPE and FB.

In the given research, in accordance with [2, 7], 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} = 0,9. 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 $K^{FB}_{PSH} = 0{,}8$.

As it is seen from Fig. 1, the values of complex dimensionless criterion of ESS energy efficiency are $K_{ESS} = 1{,}01…1{,}12$ on condition on 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 within the limits of $K_{ESS} = 1{,}05…1{,}304$. High efficient operation modes of these ESS are provided on conditions of energy efficient modes of CHPI operation with the values of energy efficiency index $K_{CHPI} = 1{,}3…1{,}6$.

As it is seen from Fig. 1, on conditions of K_{CHPI} > 1,3 and K_{ESS} > 1 [11], dependence, shown in Fig. 1, determine area of high energy efficiency of ESS with CHPI of large power and peak fuel-fired boiler (boiler house) for HSS, on conditions of minimal efficiency of GPE and fuel-fired boiler (boiler house). On such conditions, the above-mentioned ESS can be recommended as high efficient energy supply systems, as their efficiency exceeds energy efficiency of high efficient electric and fuel-fired boilers. The studied ESS can be competitive with modern high efficient electric and fuel-fired boilers in heat and energy supply systems.

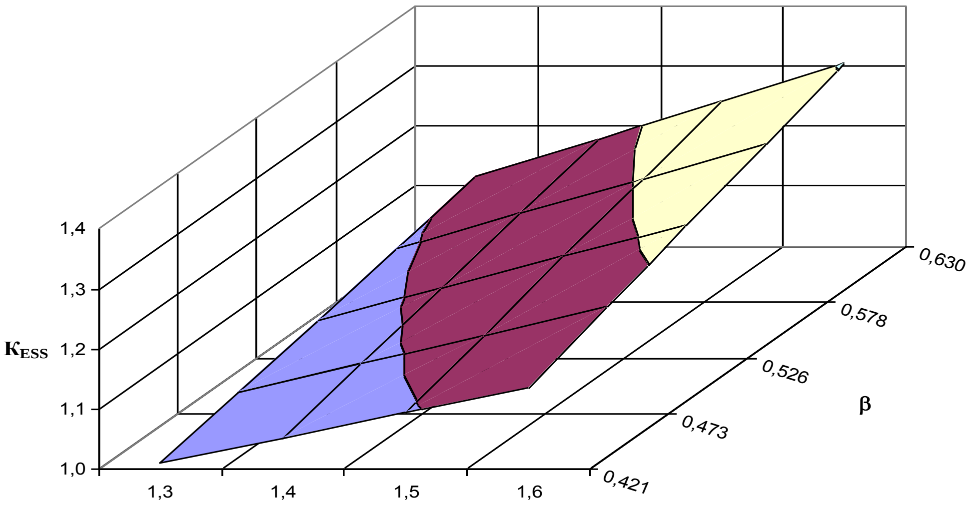

Fig. 1 – Area of high energy efficiency of ESS with CHPI of large power and peak fuel-fired boiler, on conditions of minimal efficiency of GPE and FB for heat supply systems

Fig. 2 shows the area of high energy efficiency of ESS with CHPI of large power and peak fuel-fired boiler for HSS, on conditions of maximal efficiency of GPE and FB. In the given research, according to [2, 7], 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} = 0,9. 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 $K^{FB}_{PSH} = 0{,}9$.

As it is seen from Fig. 2, the values of complex dimensionless criterion of ESS energy efficiency are K_{ESS} = 1,01…1,15 on condition on 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 within the limits of $K_{ESS} = 1{,}03…1{,}656$. High efficient operation modes of these ESS are provided on conditions of energy efficient modes of CHPI operation with the values of energy efficiency index $K_{CHPI} = 1{,}3…2{,}1$.

As it is seen from Fig. 2, on conditions of K_{CHPI} > 1,3 and K_{ESS} > 1 [11], dependence, shown in Fig. 2, determine area of high energy efficiency of ESS with CHPI of large power and peak fuel-fired boiler (boiler house) for HSS, on conditions of maximal efficiency of GPE and fuel-fired boiler (boiler house). On such conditions, the above-mentioned 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. The studied ESS can be competitive with modern high efficient electric and fuel-fired boilers in heat and energy supply systems.

It is determined, that ESS with CHPI of large power and peak fuel-fired boilers for HSS, suggested in the research, will be high energy efficient, if the share of CHPI loading in ESS will be $\beta > 0{,}264\ldots0{,}421$ (depending on various ESS elements energy efficiency) and the value of energy efficient criterion of CHPI will be $K_{CHPI} > 1{,}3$; that corresponds to the results of research, shown in Figs. 1-2.

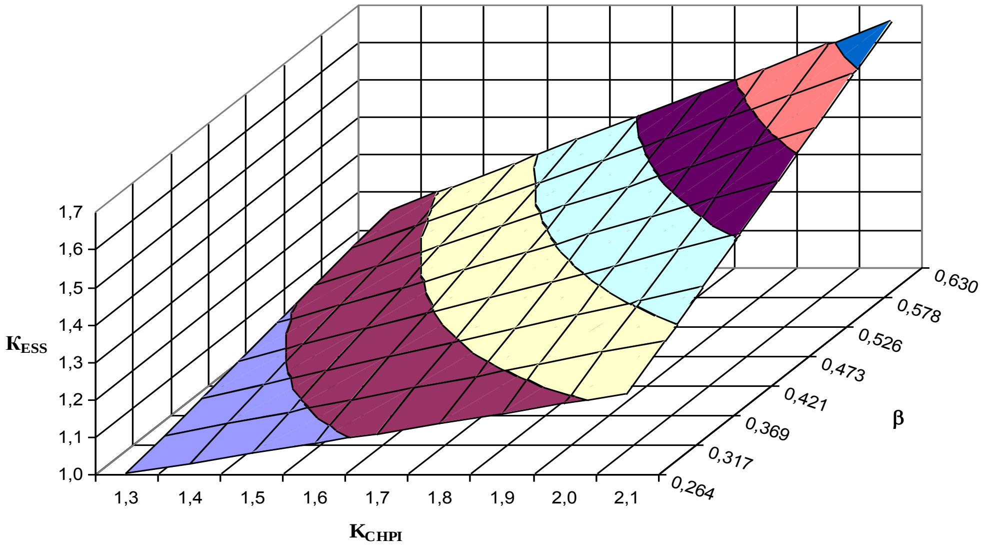

Fig. 2 – Area of high energy efficiency of ESS with CHPI of large power and peak fuel-fired boiler, on conditions of maximal efficiency of GPE and FB for heat supply systems

Dependence, shown in Fig. 1, determine the area of high efficient operation of ESS with CHPI of large power 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 $\beta = 0{,}421\ldots0{,}63$ and $K_{CHPI} = 1{,}3\ldots1{,}6$ these ESS can be recommended as high efficient energy supply systems for heat supply, as their efficiency exceeds energy efficiency of high efficient electric and fuel-fired boilers. Dependence, shown in Fig. 2 determine the area of high efficient operation of ESS with CHPI of large power 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 $\beta = 0{,}264\ldots0{,}63$ and $K_{CHPI} = 1{,}3\ldots2{,}1$ these ESS can be recommended as high efficient energy supply systems for heat supply, as their efficiency almost 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. At these conditions the areas of high energy efficiency of the above-mentioned ESS for HSS are determined. Under realization of these conditions, modern high efficient electric and fuel-fired boilers will be inferior by energy efficiency to the above-mentioned ESS.

Under such conditions, the above-mentioned ESS can be recommended as high efficient energy supply systems for heat supply, as even in case of minimal efficiency of GPE and peak fuel-fired boiler, energy efficiency of ESS exceeds energy efficiency of high efficient electric and fuel-fired boilers. This ESS can be competitive with modern high efficient electric and fuel-fired boilers in the systems of heat and energy supply.

Conclusions. Areas of high energy efficiency of ESS with large power CHPI and FB for HSS, on conditions of optimal operation modes of CHPI are determined; energy efficient operation modes of ESS with large power CHPI and FB for HSS with the account of complex impact of variable operation modes, sources of drive energy for steam compressor HPI of large power, 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 high energy efficiency of ESS with CHPI of large power and FB for HSS 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 FB in ESS;

→ it enables to determine areas and modes of high energy efficient operation of ESS with large power CHPI and FB for HSS, at which energy efficiency of the studied ESS almost two times exceeds energy efficiency of modern high energy efficient electric and fuel-fired boilers;

→ methodical fundamentals, suggested in [8], and the results of research, presented in the given paper, could be used for the determination of the areas of high efficient operation of ESS with FB and steam compressor CHPI of large power for heat supply, with various refrigerants, sources of low temperature heat and scheme solutions;

→ it allows to develop recommendations, aimed at high energy efficient operation of ESS with large power CHPI and FB for HSS with different scheme solutions.

Under conditions of $K_{CHPI} > 1{,}3$ and $K_{ESS} > 1$ and modes of energy efficient operation of CHPI, areas of high energy efficiency and high energy efficient operation modes of ESS with CHPI of large power and peak fuel-fired boilers for heat supply, for various ESS elements energy efficiency are determined.

It is determined, that ESS with CHPI of large power and peak fuel-fired boilers for HSS, suggested in the research, will be high energy efficient, if the share of CHPI loading in ESS will be $\beta > 0{,}264\ldots0{,}421$ (depending on various ESS elements energy efficiency) and the value of energy efficient criterion of CHPI will be $K_{CHPI} > 1{,}3$. On conditions of $\beta = 0{,}421\ldots0{,}63$ and $K_{CHPI} = 1{,}3\ldots1{,}6$ ESS with CHPI of large power and peak FB, on conditions of minimal efficiency of GPE and FB, can be recommended as high efficient energy supply systems for heat supply, as their efficiency exceeds energy efficiency of high efficient electric and fuel-fired boilers. On conditions of $\beta = 0{,}264\ldots0{,}63$ and $K_{CHPI} = 1{,}3\ldots2{,}1$ ESS with CHPI of large power and peak FB, on conditions of maximal efficiency of GPE and FB, can be recommended as high efficient energy supply systems for heat supply, as their efficiency almost 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.

If this condition is realized, modern high efficient electric and fuel-fired boilers will be inferior by their energy efficiency to the above-mentioned ESS for heat supply. Under these conditions the above-mentioned ESS can be recommended as high efficient energy supply systems for HSS, as their efficiency almost two times exceeds energy efficiency of high efficient electric and fuel-fired boilers.

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Области высокой энергоэффективности систем энергоснабжения с когенерационно-теплонасосными установками большой мощности и пиковыми топливными котлами в системах теплоснабжения

О. П. Остапенко

Аннотация. Предложен подход по определению областей высокой энергоэффективности систем энергоснабжения (СЭ) с когенерационно-теплонасосными установками (КТНУ) большой мощности и пиковыми топливными котлами (ТК) для систем теплоснабжения (СТ), при условиях оптимальных режимов работы КТНУ, с учетом комплексного влияния переменных режимов работы, источников приводной энергии для парокомпрессионных теплонасосных установок (ТНУ) большой мощности, с учетом потерь энергии при генерировании, снабжении и преобразовании электрической энергии.

Ключевые слова: *область высокой энергоэффективности, система энергоснабжения, когенерационно-теплонасосная установка, пиковый топливный котел, система теплоснабжения.*