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Energy and economic effectiveness of gas-steam combined heat and power plants fired with natural gas

The paper presents the energy and economic effectiveness analysis of technological systems of natural gas fired gas-steam combined heat and power (CHP) plants, operating in district heating systems. The analysis was performed for the following technological systems of gas-steam CHP plants: (1) gas-steam CHP plant with two-pressure heat recovery steam generator (HRSG) and extraction-condensing steam turbine, and (2) gas-steam CHP plant with three-pressure HRSG and extraction-condensing steam turbine. For particular kinds of technological systems of gas-steam CHP plants there were determined the following quantities characterizing their energy effectiveness: annual efficiency of electricity produced in cogeneration, annual efficiency of heat produced in cogeneration, annual overall efficiency, power to heat ratio and primary energy savings (PES). In the second part of the paper there is presented the analysis of the following quantities characterizing the economic effectiveness of natural gas fired gas-steam CHP plants: net present value (NPV), internal rate of return (IRR) and unitary electricity generation costs (EGC). The results of performed calculations of these quantities are presented in figures and in table.

Nomenclature

a, b – numerical coefficients determining mass fractions of natural gas and oxidizer related to 1 kg of combustion gases
D_{gt} – flow rate of combustion gases of gas turbine, kg/s
D_{s1}, D_{s2}, D_{s3} – flow rates of high, medium and low pressure steam, kg/s
D_{se1}, D_{se2} – flow rates of extraction steam of steam turbine, kg/s
D_c – flow rates of steam at the outlet of steam turbine, kg/s
h – physical enthalpy of combustion gases, gaseous fuel or air, kJ/kg

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h_{cg1}, h_{cg2} – physical enthalpy of combustion gases at the inlet and at the outlet of gas turbine, kJ/kg

$h_{cg2}, ., h_{cg10}$ – physical enthalpy of combustion gases in particular points of two-pressure HRSG, kJ/kg

$h_{cg2}, ., h_{cg13}$ – physical enthalpy of combustion gases in particular points of three-pressure HRSG, kJ/kg

$h_{fw11}, h_{fw12}, h_{fw13}$ – enthalpy of high pressure feeding water, kJ/kg

$h_{fw21}, h_{fw22}, h_{fw23}$ – enthalpy of medium pressure feeding water, kJ/kg

h_{fw31}, h_{fw32} – enthalpy of low pressure feeding water, kJ/kg

h_{se1}, h_{se2}, h_c – enthalpy of extraction and outlet steam of steam turbine, kJ/kg

h_{s1}, h_{s2}, h_{s3} – HRSG outlet enthalpy of high, medium and low pressure steam, kJ/kg

$h_{s11}, h_{s21}, h_{s31}$ – steam turbine inlet enthalpy of high, medium and low pressure steam, kJ/kg

h_{ss2} – enthalpy of medium pressure saturated steam, kJ/kg

h_{we2} – enthalpy of condensate in heat exchanger, kJ/kg

$\Delta_{tpp1}, \Delta_{tpp2}, \Delta_{tpp3}$ – pinch points of high, medium and low pressure parts of HRSG, K

H_e – utilization time of nominal electric power of CHP plant, hours/a

H_h – utilization time of thermal power produced in cogeneration of CHP plant, hours/a

$\Delta H_{i(T_0,T_{cg})}$
$\Delta H_{i(T_0,T_g)}$
$\Delta H_{i(T_0,T_{0X})}$ – increments of molar physical enthalpy of particular components of combustion gases, gaseous fuel and oxidizer (air) related to the temperature T_0, kJ/kmol

$\Delta H_{i(T_0,T)}$ – increments of molar physical enthalpy of particular components of combustion gases, gaseous fuel or air related to the temperature T_0, kJ/kmol

$\Delta h_{\left(T_0,T_{H_2O}\right)}$ – increment of physical enthalpy of water or steam related to the temperature T_0, kJ/kg

M_i – molar mass of particular components of combustion gases, gaseous fuel and oxidizer, kg/kmol

n – number of components of combustion gases ($n = 5$, CO_2, H_2O, O_2, N_2, Ar), gaseous fuel ($n = 11$), and of air ($n = 3$, O_2, N_2, Ar)

p_{cgi}, p_{gi}, p_{oxi}	– partial pressure of particular component of the combustion gases, gaseous fuel and oxidizer (air)
p_i	– partial pressure of particular component of the combustion gases or air
P_{igt}, P_{ic}	– internal power of the gas turbine and the compressor, respectively, kW
P_{elgt}, P_{elst}	– electric power of the gas and steam turbine generator, respectively, kW
Q_c	– thermal power in cogeneration of gas-steam CHP block, kW
Q_h^g	– lower heating value of natural gas kJ/Nm^3
Q_{he}	– heat transferred to water of district heating system in heat exchanger, kW
Q_{HRSG}	– heat transferred to water of district heating system in HRSG, kW
Q_{wgi}	– combustion heat of particular components of natural gas, kJ/Nm^3
ΔQ	– heat losses to the environment, kW
T_{cg}, T_g, T_{ox}	– temperature of combustion gases, gaseous fuel and oxidizer (air), K
T_o	– reference temperature (288.15 K)
η_{gg}	– efficiency of gas turbine generator
η_{mg}	– mechanical efficiency of gas turbine
η_{gs}	– efficiency of steam turbine generator
η_{ms}	– mechanical efficiency of steam turbine

1 Introduction

One of the important goals of the development of the technology of electricity generation in power plants fired with fossil fuels in 21st century will be decreasing of CO$_2$ emission to the atmosphere. It is justified by the necessity of decreasing of greenhouse gases emission according to the United Nations Framework Convention on Climate Change and from policy of sustainable development of energy systems. This goal may be achieved by increasing the efficiency of power plants fired with coal and by increasing the share of combined heat and power (CHP) plants in electricity generation, and also by partial replacing of coal by other fuels, for example by natural gas or biomass. Use of natural gas in cogeneration of electricity and heat allows one to obtain significant energy and ecological effects. Replacement of coal by natural gas in CHP plants allows one to:

- increase the efficiency of generation of electricity and useful heat, and due to this to increase the effectiveness of utilization of chemical energy of fuel;
- decrease significantly harmful influence of CHP plants on natural environment, that is to eliminate totally the emission of SO_2 and of dust, and decrease significantly the emission of CO_2 and of NOx to the atmosphere;
- decrease the investment costs, and decrease the period of construction of CHP plants.

2 Technological systems of analysed gas-steam CHP plants

In this paper for comparative analysis of energy and economic effectiveness the following natural gas fired gas-steam CHP plants were chosen:

- gas-steam CHP plant of electric power of about 100 MW with two-pressure heat recovery steam generator (HRSG) and extraction-condensing steam turbine (Fig. 1),
- gas-steam CHP plant of electric power of about 400 MW with three-pressure HRSG and extraction- condensing steam turbine (Fig. 2).

3 Analysis of energy effectiveness

The performance of energy balances of particular variants of technological systems of gas-steam CHP plants was the basis of analysis of these systems from the point of view of energy effectiveness of electricity and of heat produced in cogeneration. The following quantities characterizing the energy effectiveness of particular technological systems of analyzed CHP plants were determined [1]: annual efficiency of electricity produced in cogeneration, annual efficiency of heat produced in cogeneratio, annual overall efficiency, power to heat ratio and primary energy savings (PES).

The base for calculation of annual production of electricity and heat was determined by electric power of generators of gas turbines and of steam turbines and thermal power produced in cogeneration and the assumed utilization of nominal electric power (H_e) and thermal power produced in cogeneration (H_h) of CHP plants.

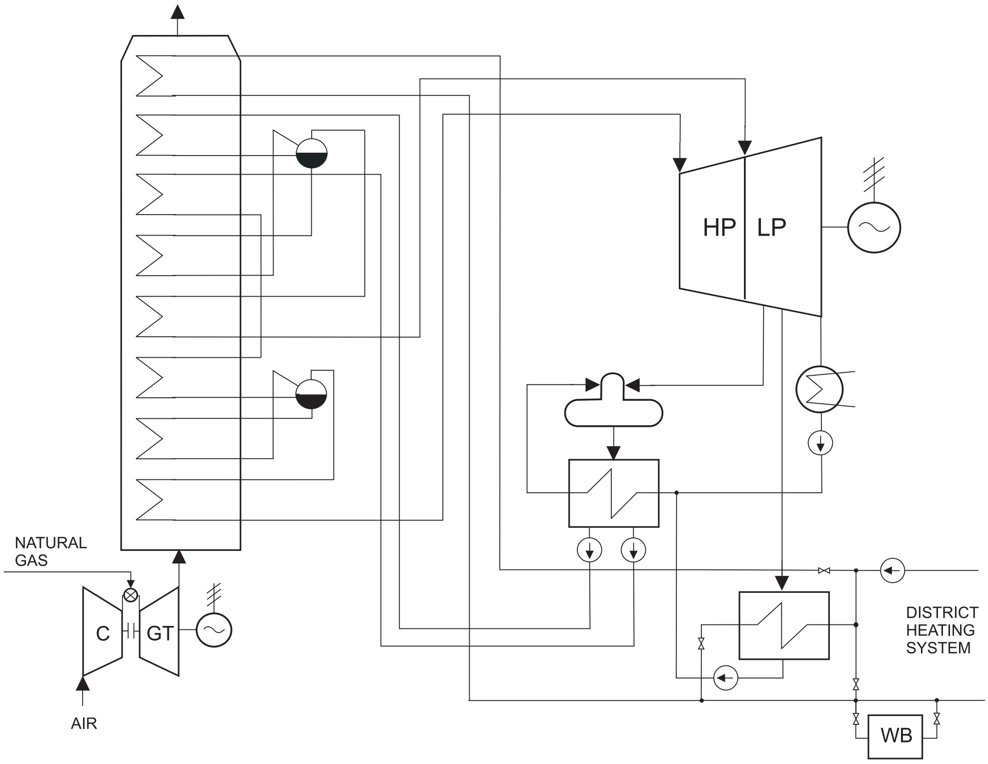


Figure 1. Technological system of gas-steam CHP plant with two-pressure HRSG and extraction-condensing steam turbine: C – compressor, GT – gas turbine, HP – high pressure, LP – low pressure, WB – water boiler.

Electric power of the generator of gas turbine was determined with the help of the following formula:

$$P_{e\,\mathrm{lg}\,t} = \left(P_{igt} - P_{ic}\right)\eta_{mg}\eta_{gg}\ . \tag{1}$$

Internal power of gas-turbine was determined with the help of the following formula:

$$P_{igt} = D_{gt}\left(h_{cg1} - h_{cg2}\right)\ . \tag{2}$$

The solution of equation of energy balance of combustion chamber of gas turbine allow to determine the air consumption of gas turbine and composition of combustion gases necessary for calculation of P_{ic}, h_{cg1} and h_{cg2}. This equation was

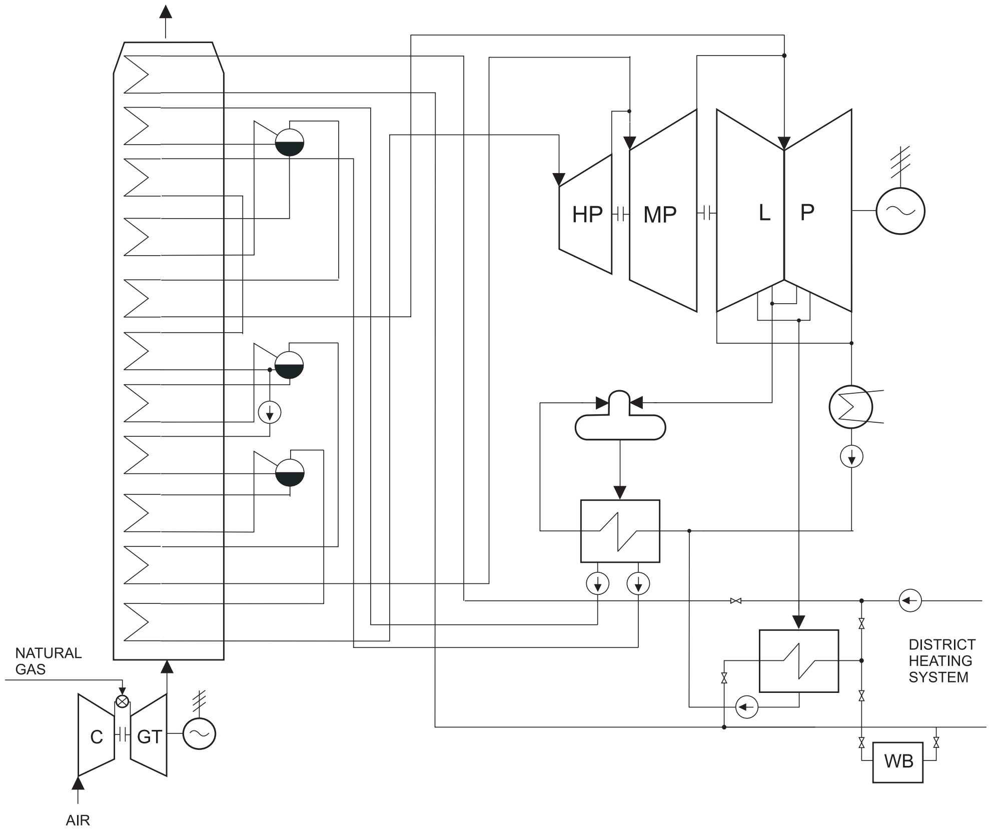


Figure 2. Technological system of gas-steam CHP plant with three-pressure HRSG and extraction-condensing steam turbine.

formulated in the following form:

$$\begin{aligned}&\frac{1}{\sum\limits_{i=1}^{5} M_i p_{cgi}} \sum_{i=1}^{5} p_{cgi}\Delta H_{i(T_o,T_{cg})} - a\frac{1}{\sum\limits_{i=1}^{11} M_i p_{gi}}\sum_{i=1}^{11} p_{gi}\left(Q_{wgi}+\Delta H_{i(T_o,T_g)}\right)\\&-b\frac{1}{\sum\limits_{i=1}^{3} M_i p_{oxi}} \sum_{i=1}^{3} p_{oxi}\Delta H_{i(T_o,T_{ox})} + \Delta Q = 0\ .\end{aligned} \tag{3}$$

High and low pressure steam flow rates, for the technological system of a gas-steam power plant with two-pressure HRSG, were determined as the solution of the following system equations (Fig. 3):

$$D_{gt}\left(h_{cg2}-h_{cg4}\right)-D_{s1}\left(h_{s1}-h_{fw13}\right)=0\ , \tag{4}$$

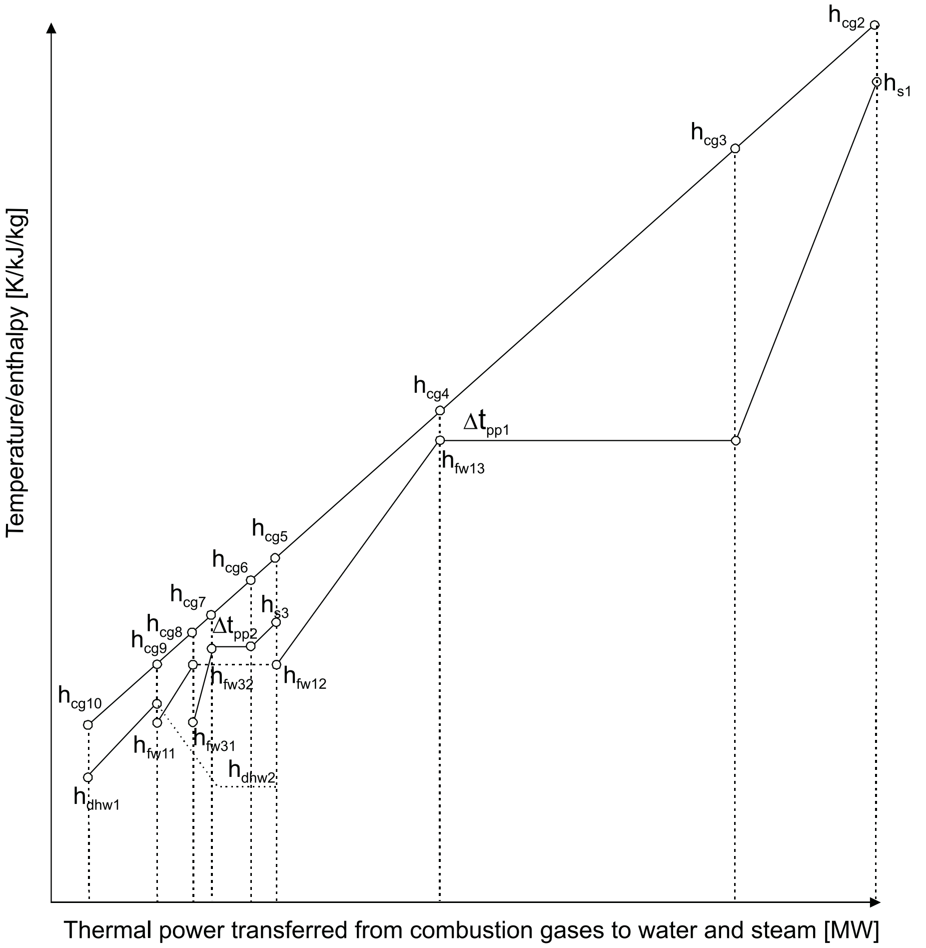


Figure 3. Combustion gases and water (steam) temperature profile of HRSG of gas-steam CHP plant with two-pressure HRSG.

$$D_{gt}\left(h_{cg4}-h_{cg7}\right)-D_{s1}\left(h_{fw13}-h_{fw12}\right)-D_{s2}\left(h_{s2}-h_{fw22}\right)=0\ . \tag{5}$$

Electric power of the generator of steam turbine of gas-steam power plant with two-pressure HRSG was calculated with the help of the following formula:

$$P_{elst}=\big(D_{s1}h_{s11}+D_{s2}h_{s21}-D_{se1}h_{se1}-D_{se2}h_{se2}-D_{c}h_{c}\big)\eta_{ms}\eta_{gs}\ . \tag{6}$$

High, medium and low pressure steam flow rates, for the technological system of a gas-steam power plant with three-pressure HRSG, were determined as the solution of the following system equations (Fig. 4):

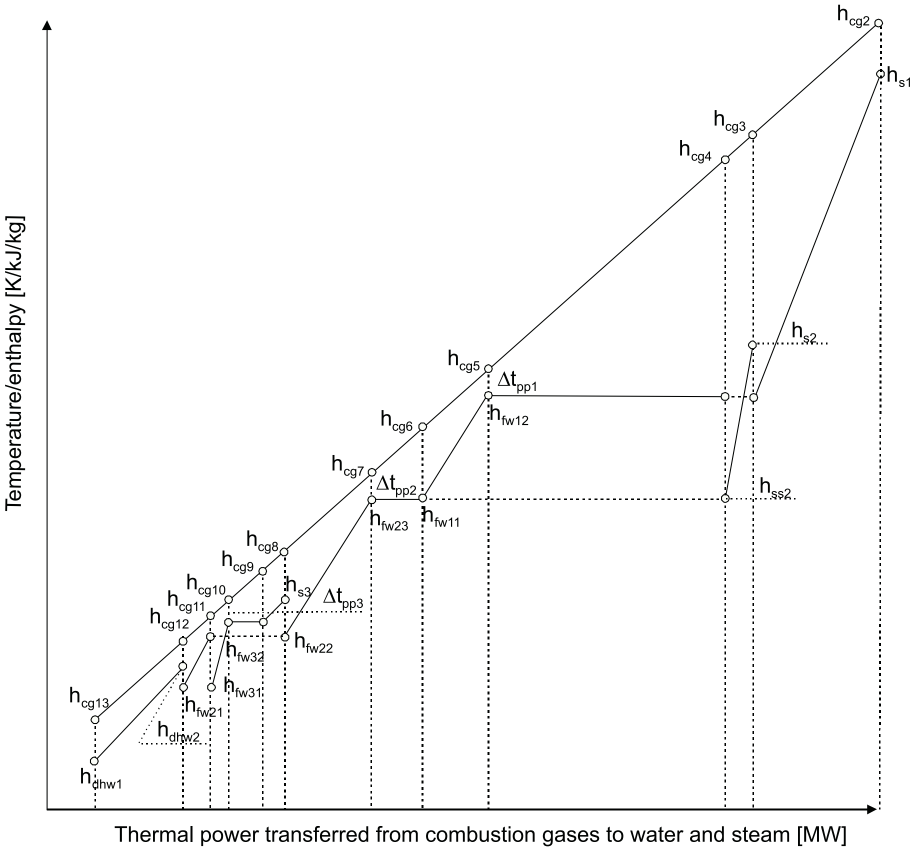


Figure 4. Combustion gases and water (steam) temperature profile of HRSG of gas-steam CHP plant with three-pressure HSRG and extraction-condensing steam turbine.

$$D_{gt}\left(h_{cg2}-h_{cg5}\right)-D_{s1}\left(h_{s1}-h_{fw12}\right)-D_{s2}\left(h_{s2}-h_{ss2}\right)=0\ , \tag{7}$$

$$D_{gt}\left(h_{cg5}-h_{cg7}\right)-D_{s1}\left(h_{fw12}-h_{fw11}\right)-D_{s2}\left(h_{ss2}-h_{fw23}\right)=0\ , \tag{8}$$

$$D_{gt}\left(h_{cg7}-h_{cg10}\right)-\left(D_{s1}+D_{s2}\right)\left(h_{fw23}-h_{fw22}\right)-D_{s3}\left(h_{s3}-h_{fw32}\right)=0\ . \tag{9}$$

Electric power of the generator of steam turbine of gas-steam power plant with three-pressure HRSG was calculated with the help of the following formula:

$$P_{elst}=\big(D_{s1}h_{s11}+D_{s2}h_{s21}+D_{s3}h_{s31}-D_{se1}h_{se1}-D_{se2}h_{se2}-D_{c}h_{c}\big)\eta_{ms}\eta_{gs}\ . \tag{10}$$

Thermal power produced in cogeneration of gas-steam CHP plants was determined with the help of the formula

$$Q_c = Q_{he} + Q_{HRSG} \ , \tag{11}$$

where:

$$Q_{he} = D_{he} \left(h_{se2} - h_{we2} \right) \ , \tag{12}$$

$$Q_{HRSG} = D_{gt} \left(h_{cg9} - h_{cg10} \right) \text{ for CHP block with two-pressure HRSG} \tag{13}$$

$$Q_{HRSG} = D_{gt} \left(h_{cg12} - h_{cg13} \right) \text{ for CHP block with three-pressure HRSG.} \tag{14}$$

Physical enthalpy of combustion gases, gaseous fuel and air were determined with the help of partial pressure and molar physical enthalpy of their components

$$h = \frac{1}{\sum\limits_{i=1}^{n} M_i p_i} \sum_{i=1}^{n} p_i \Delta H_{i(T_0,T)} \ . \tag{15}$$

The relations describing temperature functions of the increments of molar physical enthalpy of particular components of combustion gases $[\Delta H_{i(T_0,T_{cg})}]$, gaseous fuel $[\Delta H_{i(T_0,T_g)}]$ and air $[\Delta H_{i(T_0,T_{0X})}]$ have been determined with the help of statistical physics [5].

For calculations of quantities characterizing the energy effectiveness of analysed gas-steam CHP plants the following types of gas turbines were chosen [2]: SGT-1000F for gas-steam CHP block with two-pressure HRSG and SGT5-4000F for gas-steam CHP block with three-pressure HRSG. The following composition of natural gas in calculations was assumed: $CH_4 = 97.4387\%$, $C_2H_6 = 1.045\%$, $C_3H_8 = 0.376\%$, $C_4H_{10} = 0.139\%$, $C_5H_{12} = 0.0203\%$, $C_6H_{14} = 0.021\%$, N_2=0.877%, $CO_2 = 0.066\%$, He = 0.017%. The lower heating value of this gas is $Q_c^g = 36133.69$ kJ/Nm^3.

The results of calculations of quantities characterizing the energy effectiveness of gas-steam CHP plants are presented in Tab. 1.

4 Analysis of economic effectiveness

For gas-steam CHP plants, which technological systems are presented in Figs. 1–2 there was performed comparative analysis of their economic effectiveness. The following quantities characterizing the economic effectiveness of particular technological system were assumed:

- net present value (NPV),

Table 1. The results of calculations of quantities characterizing the energy effectiveness of gas-steam CHP plants.

Quantity	Quantities for the block with:	
	two-pressure HRSG	three-pressure HRSG
Electric power of CHP block during heating season, MW	90.483	384.892
Electric power of CHP block during summer, MW	99.863	418.104
Thermal power in cogeneration of CHP block during heating season, MW	76.929	263.035
Annual production of electricity, GWh	597.849	2516.829
Annual production of heat, GWh	338.489	1157.353
Annual consumption of fuel chemical energy, GWh	1214.325	4709.391
Annual efficiency of electricity generation, %	49.23	53.44
Annual efficiency of heat generation, %	27.87	24.58
Annual overall efficiency of CHP block, % [9]	77.10	78.02
Power to heat ratio [8]	1.551	1.964
Annual production of electricity in cogeneration, GWh [6]	524.996	2273.041
Share of annual production of electricity in cogeneration in total annual electricity production, %	87.81	90.31
Electrical efficiency of cogeneration production, % [6]	48.64	53.01
Heat efficiency of cogeneration production, % [6]	31.36	26.99
Primary energy savings, PES, % [8]	22.44	24.54

- internal rate of return (IRR),
- unitary electricity generation costs (EGC), discounted on 2012 [7].

For performed calculations of these quantities there were assumed data from Tab. 1 and the following entry data:

- the period of plant construction, $T_{e1} = 2$ years,
- the period of plant exploitation, $T_{e2} = 25$ years,
- the time utilization of nominal electric power: $H_e = 6400$ hours/year and thermal power in cogeneration $H_h = 4400$ hours/year,
- sale producer's price of heat $c_c = 31.56$ PLN/GJ,
- the price of natural gas for gas-steam CHP plant, as a large consumer, $c_g = 38.1$ PLN/GJ,
- discount rate 7.5%.

The results of calculations of quantities characterizing the economic effectiveness of analysed technological systems of gas-steam CHP plants, presented on Figs. 1 and 2, are shown in Figs. 5–8 and in Tab. 2.

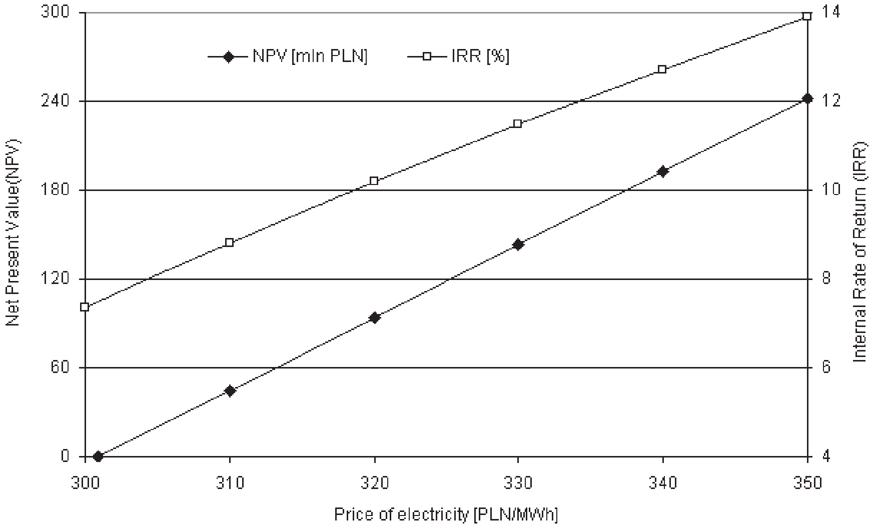
Table 2. Electricity generation costs and selling price of electricity.

Kind of generation unit	Unitary electricity generation costs, discounted on 2012 [PLN/MWh]	Selling price of electricity with certificate revenue of high efficiency cogeneration (2011) [PLN/MWh]
Gas-steam CHP block with two-pressure HRSG and extraction-condensing steam turbine without CO_2 emission payment	301	312
Gas-steam CHP block with two-pressure HRSG and extraction-condensing steam turbine with CO_2 emission payment (160 PLN/tCO_2)	351	312
Gas-steam CHP block with three-pressure HRSG and extraction-condensing steam turbine without CO_2 emission payment	283	315
Gas-steam CHP block with three-pressure HRSG and extraction-condensing steam turbine with CO_2 emission payment (160 PLN/tCO_2)	330	315

5 Conclusions

The results of performed calculations of energy and economic effectiveness of chosen technological systems of gas-steam CHP plants allow one to formulate the following conclusions:

1. Both the gas-steam CHP block with three-pressure HRSG and extraction-condensing turbine and the gas-steam CHP block with two-pressure HRSG are characterized by high energy effectiveness, that is, they show high electrical efficiency, overall efficiency and primary energy savings. The former gas-steam CHP block has higher energy effectiveness then the latter gas-steam CHP block (Tab. 1).
2. The gas-steam CHP blocks‘ energy effectiveness essentially impacts their economic effectiveness [1,3,4]. Therefore, the unitary electricity generation costs of gas-steam CHP blocks with three-pressure HRSG are lower



Figurě 5. Dependence of NPV and IRR on electric energy selling price for gas-steam power plant with two-pressure HRSG, for natural gas price of 38.1 PLN/GJ, without CO_2 emission payment.

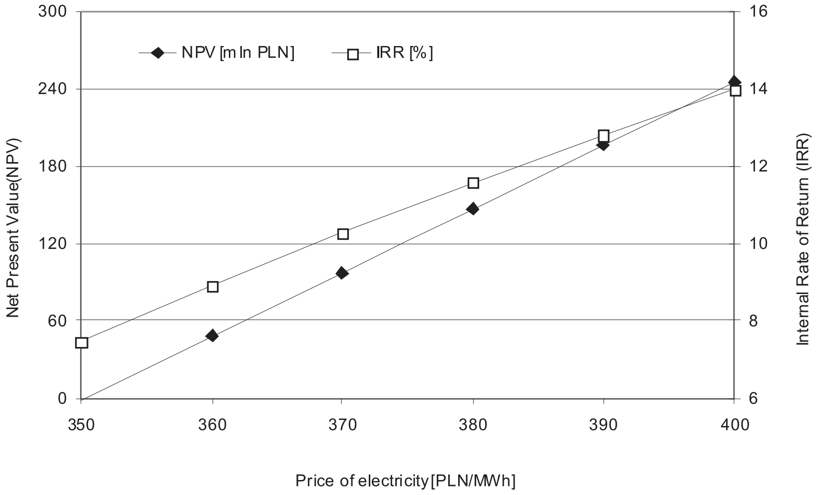


Figure 6. Dependence of NPV and IRR on electric energy selling price for gas-steam CHP plant with two-pressure HRSG for natural gas price of 38.1 PLN/GJ, with CO_2 emission payment (160 PLN/tCO_2).

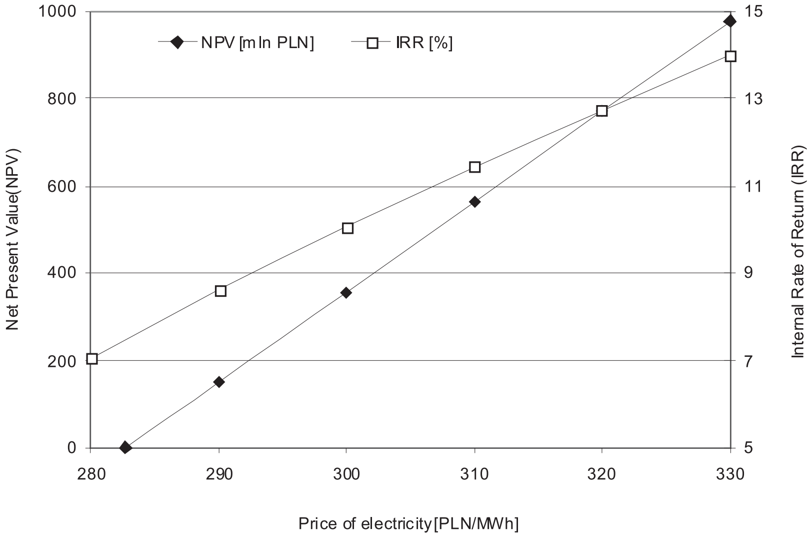


Figure 7. Dependence of NPV and IRR on electric energy selling price for gas-steam power plant with three-pressure HRSG for natural gas price of 38.1 PLN/GJ, without CO_2 emission payment.

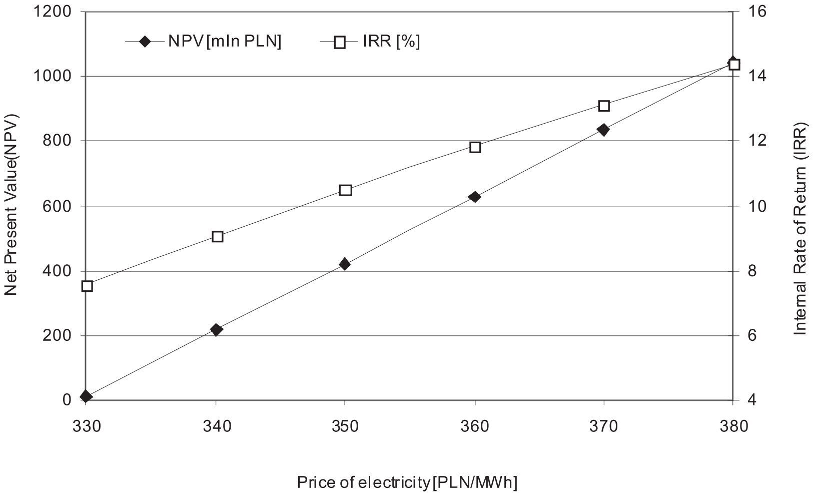


Figure 8. Dependence of NPV and IRR on electric energy selling price for gas-steam power plant with three-pressure HRSG, for natural gas price of 38.1 PLN/GJ, with CO_2 emission payment (160 PLN/tCO_2).

than the ones of gas-steam CHP block with two-pressure HRSG. The unitary electricity generation costs, discounted for 2012, without CO_2 emission payment, are lower than the selling price of electricity on competitive market with certificate revenue of high efficiency cogeneration (Tab. 2) [9]. Therefore, the construction of gas-steam CHP block fired with natural gas is economically justified, under such conditions.

3. The unitary electricity generation costs, discounted for 2012, after implementation of CO_2 emission payment from 2013, will be higher than the selling price of electricity on competitive market. Therefore to make the construction of gas-steam CHP block fired with natural gas economically justified, after implementation of CO_2 emission payment from 2013, the selling price of electricity on competitive market has to increase.

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Efektywność energetyczna i ekonomiczna elektrociepłowni gazowo-parowych opalanych gazem ziemnym

Streszczenie

W pracy przedstawiono analizę efektywności energetycznej i ekonomicznej układów technologicznych elektrociepłowni gazowo-parowych opalanych gazem ziemnym, pracujących w miejskich systemach ciepłowniczych. Analiza była wykonana dla następujących układów technologicznych elektrociepłowni gazowo-parowych: 1) elektrociepłowni gazowo-parowej z dwuciśnieniowym kotłem odzysknicowym i upustowo-kondensacyjną turbiną parową i 2) elektrociepłowni gazowo-parowej z trójciśnieniowym kotłem odzysknicowym i upustowo-kondensacyjną turbiną parową. Dla każdego z tych układów były wyznaczane następujące wielkości, charakteryzujące ich efektywność energetyczną: średnioroczna sprawność wytwarzania energii elektrycznej w skojarzeniu, średnioroczna sprawność wytwarzania ciepła w skojarzeniu, średnioroczna sprawność ogólna elektrociepłowni, wskaźnik skojarzenia oraz oszczędność energii pierwotnej. W drugiej części pracy jest przedstawiona analiza następujących wielkości charakteryzujących efektywność ekonomiczną elektrociepłowni gazowo-parowych opalanych gazem ziemnym: wartości bieżąca netto (ang. *net present value* – NPV), wewnętrznej stopa zwrotu (ang. internal rate of return – IRR) oraz jednostkowych kosztów wytwarzania energii elektrycznej. Wyniki wykonanych obliczeń tych wielkości są przedstawione na wykresach i w tablicy.