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Economic optimization of the combined cycle integrated with multi-product gasification system

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ABSTRACT

The system taken into consideration consists of the Corex unit, combined cycle power plant and air separation unit (ASU). The Corex process (trademark of Siemens-VAI) is one of technologies for cokeless hot metal production. Coal is gasified by oxygen in the hot metal environment. The excess gas can be used out of installation. It has been assumed that the Corex export gas is fired in combined cycle. The gas turbine (GT) structure was assumed as a fixed simple cycle while the heat recovery steam generator (HRSG) and steam turbine arrangements are free for optimization. The examples of independent variables selected for optimization are number of HRSG pressure levels, GT pressure ratio, minimal temperature differences in HRSG, flow rate of compressed air form GT compressor to ASU. Finally, 16 independent variables have been qualified for optimization. The synthesis optimization is based on the superstructure method. The economic net present value (NPV) has been chosen as the objective function. All power plant facilities have been modeled on the GateCycle software. The off-design models include, among others, the GT blade cooling and HRSG heat transfer coefficient analyses. Two optimization methods – genetic algorithm and Powells conjugate directions have been coupled in one hybrid procedure. The whole optimization analysis has been repeated several times for different price scenarios on the coal, iron and electricity markets.

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1. Introduction

The worldwide consumption of coal for hot metal and steel production represents a significant part of the total coal demand. On the other hand, the well-known opportunities for integration between hot metal and power generation provide a big potential for increasing of the efficiency of fuel utilization and decreasing environment pollution.

The subject of this paper is therefore the thermo-economic analysis of integrated steel-and-power plant, fed with coal. The system taken into consideration consists of the Corex island, combined cycle CHP plant and air separation unit (ASU), as shown in Fig. 1.

The Corex process (trademark of Siemens-VAI) [8,18] is one of technologies for cokeless hot metal production belonging to the smelting reduction family. Coal is gasified by oxygen in the hot metal environment, while the produced gas is used as reducing agent (for iron ore reduction) in separate shaft reactor. From the power generation point of view the most interesting feature of this technology is simultaneous production of hot metal and medium-calorific export gas which can be fired in a gas turbine (GT) combustor. Both, process and system analyzes proved that the energy effectiveness of the Corex installation is higher than that of the blast-furnace plant [27].

The overall system (Corex, combined cycle CHP, ASU) can be thus perceived as some kind of multi-product IGCC. The case study presented here deals with location of such an integrated IGCC in southern Poland, nearby the existing steel mill and medium sized city. The demands for district heat and process steam (0.6 MPa, 270 °C) are given for this location as yearly duration curves.

As it was marked in Fig. 1, the combined cycle (CC) provides ASU with compressed air (air is extracted form GT compressor) and ASU provides combined cycle with nitrogen, which is injected into gas turbine combustor. Such an integration has been already analyzed and partially applied in practice [25,10], however the discussion on its optimum scope and benefits is still alive.

Main goal of the study presented here is to determine optimum structure and parameters of the combined cycle CHP working as a part of presented integrated system. Some preliminary studies related to this problem have been published in [20] and [21].

It was assumed that the Corex process operates with fixed capacity and parameters, however the ASU can by provided with compressed air by both the GT extraction and electric motor-driven compressors.

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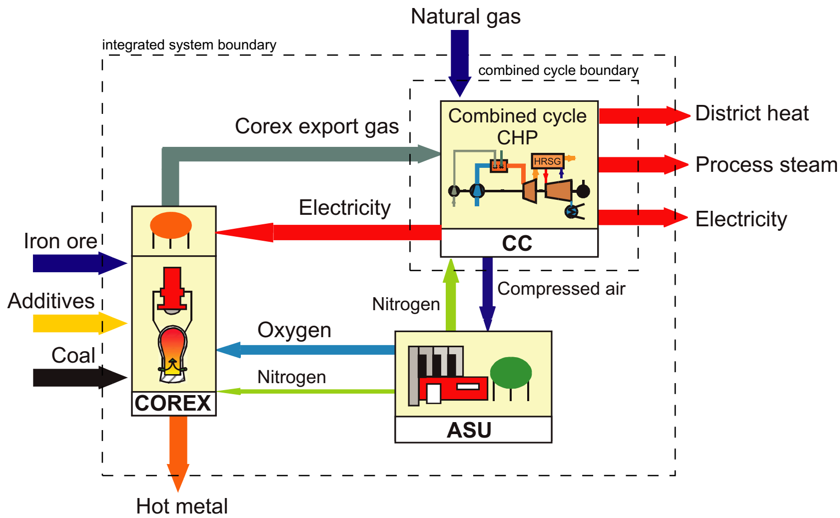

Fig. 1. Analyzed integrated system (IS).

Table 1
Parameters of Corex unit C-1000 [19,14]

Hot metal production, Mg/h	45
Raw material consumption	
Iron ore, Mg/h	66.6
Fixed carbon, Mg/h	25.6
Technological gas consumption	
Oxygen, Mg/h	35.4
Nitrogen, Mg/h	3.9
Electricity consumption, MW	2.9
Export gas production, kg/s	25

Table 2
Corex export gas data [15,13]

Parameter	Unit	Value
Composition (molar basis)		
CO	%	42.5
H_2	%	18
CO_2	%	35
CH_4	%	1
N_2	%	2
H_2O	%	1.5
H_2S	ppm	<70
Dust content (STP)	mg/m^3	<5
LHV (STP)	kJ/m^3	7500
	kJ/kg	6000
Pressure	kPa	200
Temperature	°C	50
Density (STP)	kg/m^3	1.28

The most relevant parameters of the Corex unit and the Corex export gas are given in Tables 1 and 2.

2. Formulation of the optimization problem

2.1. Combined cycle superstructure

The optimization of structure and parameters of combined cycle has been done simultaneously by defining the superstructure and eliminating of some of its elements. This elimination process is however not binary. It is based on conclusions derived from optimized values of some combined cycle parameters. For instance, if the optimal values of steam pressures in a double pressure heat recovery steam generator (HRSG) are equal to each other the conclusion is the optimal HRSG structure is a single pressure one.

The combined cycle superstructure, assumed for optimization is presented in Fig. 2.

Its main components are single shaft GT, two pressure level HRSG with reheater and deaerating vaporizer, dual pressure, tap-condensing steam turbine (ST) and wet, mechanical draft cooling tower.

The Corex gas is compressed in a fuel compressor, mixed with natural gas and nitrogen and then this mixture is fired in the GT combustor. The air extracted from GT air compressor is cooled down by nitrogen, which allows for waste heat regeneration (air must be delivered to ASU at lowest possible temperature). Some part of the Corex gas stream can be fired in a duct burner at the HRSG inlet. Steam produced in HRSG at two pressure levels is supplied to the ST, where some part of it is extracted for technological and heating purposes. The demand for process steam is basically covered by the first ST extraction. The admixture of live to process steam takes place to maintain its required temperature. District heat is generated in three heat exchangers: the low temperature economizer (LTE) in HRSG (the last one on the flue gas track) and two heat exchangers fed with extracted steam. The maximum district heat demand is equal to 50 MW (for the ambient temperature of −20 °C). The current heat demand is determined by the ambient temperature duration curve and heating network characteristic. This network is controlled by changing the water temperature – the water mass flow being constant. The maximum temperature of inlet/outlet district water is 70/130 °C.

2.2. Objective function

The economic net present value (NPV) [7] has been chosen as an objective function of optimization. It has been calculated on the boundary of a whole integrated system (IS, see Fig. 1):

$$\mathrm{NPV_{IS}} = \sum_{t=0}^{n} \frac{\mathrm{NCF}_{\mathrm{IS}t}}{(1+r)^t} \Rightarrow \max, \mathrm{USD} \tag{1}$$

while for $t \geqslant 1$:

$$\mathrm{NCF}_{\mathrm{IS}t} = G_{\mathrm{hm}}c_{\mathrm{hm}} + E_{\mathrm{el\,IS}}c_{\mathrm{el}} + Q_{\mathrm{dh}}c_{\mathrm{dh}} + Q_{\mathrm{ps}}c_{\mathrm{ps}} - G_{\mathrm{io}}c_{\mathrm{io}} - G_{\mathrm{c}}c_{\mathrm{c}} - G_{\mathrm{add}}c_{\mathrm{add}} - E_{\mathrm{ch\,ng}}c_{\mathrm{ng}} - G_{\mathrm{w}}c_{\mathrm{w}} - K_{\mathrm{nat}} - W_{\mathrm{IS}} - \beta_t I_{\mathrm{IS0}} - \mathrm{Tax_{IS}}, \mathrm{USD/year} \tag{2}$$

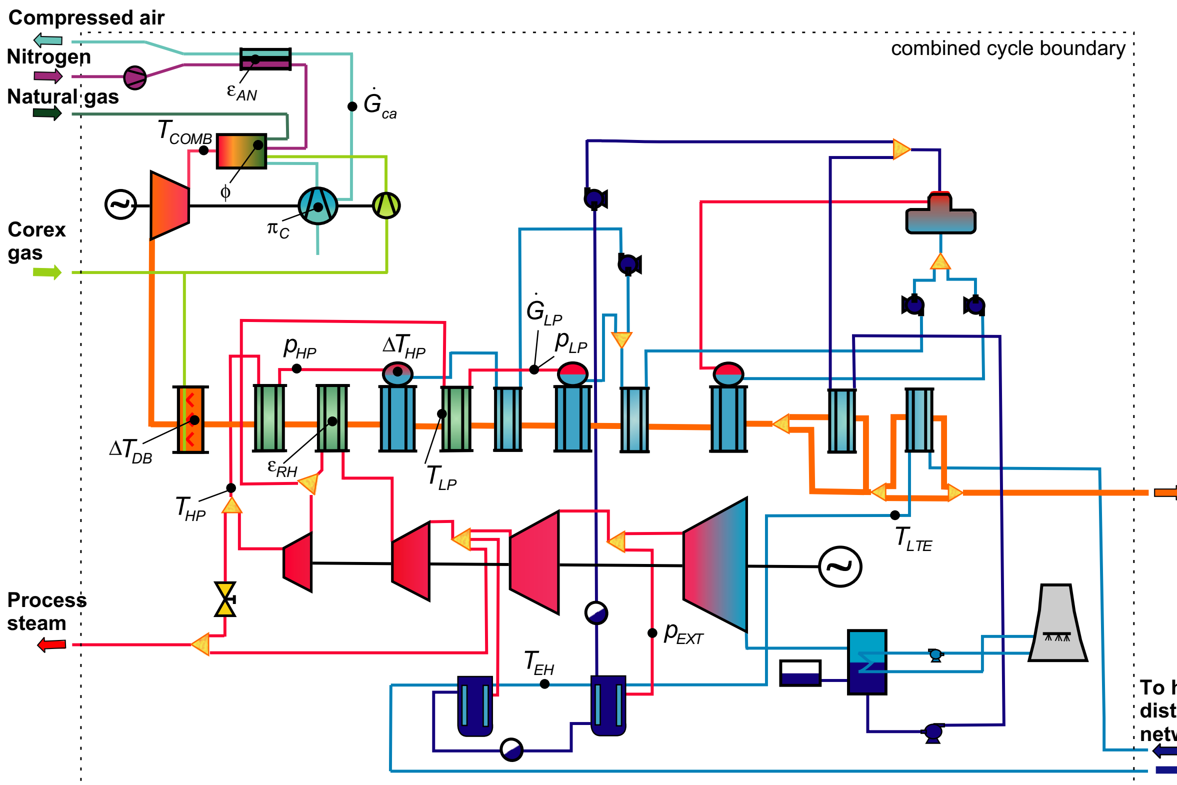

Fig. 2. Combined cycle superstructure.

where $E_{\mathrm{el\,IS}}$ is the yearly electricity production (net int the integrated system), MWh/year, Q_{dh}, Q_{ps} is the yearly district heat and process steam production, GJ/year, G_{hm}, G_{c}, G_{io}, G_{w}, G_{add} is the yearly hot metal production, yearly consumption of coal, iron ore, process water, and Corex process additives Mg/year, $E_{\mathrm{ch\,ng}}$ is the yearly consumption of chemical energy of natural gas, GJ/year, c_{hm}, c_{el}, c_{dh}, c_{ps}, c_{ng}, c_{c}, c_{io}, c_{w}, c_{add} is the prices of: hot metal USD/Mg, electricity USD/MWh, district heat USD/GJ, process steam USD/GJ, natural gas USD/GJ, coal USD/Mg, iron ore USD/Mg, process water USD/Mg, Corex process additives USD/Mg, K_{nat} is the yearly cost of pollutants emission, USD/year, W_{IS} is the yearly cost of human work, USD/year, β_t is the rate of operating and maintenance costs, I_{IS} is the investment cost, USD, $\mathrm{Tax}_{\mathrm{IS}}$ is the income tax, USD/year.

2.3. Independent variables

Selection of independent variables for optimization is determined by technical configuration of the analyzed system and accessibility of investment cost data as a functions of these variables. Investment cost functions have been found in literature and, where possible obtained directly from equipment producers. Finally, 16 variables have been selected as shown in Table 3 and Fig. 2. These values are supplied to the CC model as design point data.

The admixture ratio of natural to Corex gas (Table 3, no. 1), defined as the ratio of chemical energy fluxes at design conditions is responsible for scaling of the whole analyzed system:

$$\phi = \left(\frac{\dot{E}_{\mathrm{ch\,ng}}}{\dot{E}_{\mathrm{ch\,cx}}}\right)_{\mathrm{design}} \tag{3}$$

The flow rate of compressed air extracted from GT (Table 3, no. 2) determines the intensity of integration between CC and ASU.

Effectiveness of heat exchanger compressed air–nitrogen (Table 3, no. 5) and effectiveness of steam reheater (Table 3, no. 16) defined in accordance with Eq. (5) decide on introduction or elimination of these elements to/from analyzed system.

Maximum temperatures of district water in appropriate heat exchangers (Table 3, nos. 13 and 14) provide information on the division of district heat duty between HRSG and ST extractions. The maximum temperature at the extraction fed heater (EH) outlet (Table 3, no. 14) can be additionally limited by the saturation conditions, i.e. steam pressure in the second ST extraction (Table 3, no. 12). The temperature rise in the duct burner (Table 3, no. 15) indicates how much of the total Corex gas stream is fired in the duct burner.

The rest of variables presented in Table 3 represents typical GT and HRSG features. These variables impact among others on GT specific work and efficiency as well as number of pressure levels in HRSG.

2.4. Optimization constraints

Besides of the constraints of independent variables, visible in Table 3, which determine the hyper-area of potentially allowable solutions, some other CC parameters should be limited to their technically acceptable values, which is also related to the off-design operation. The limits for parameters which should be considered in both design and off-design modes of operation are collected in Table 4.

The constraint no. 1 determines the control procedures for GT working in varying ambient conditions – constant firing temperature, variable air flow rate, variable natural gas admixture. Other constraints are responsible for avoiding or reduction of air compressor surge, ST inlet section overheating, ST exit section erosion, HRSG exit section low temperature corrosion, ST exit section overheating.

Table 3
Independent variables for optimization

No.	Variable name and notation (see Fig. 2)	Unit	Lower value	Upper value
1	Natural gas admixture ratio, ϕ	–	0.3	2.5
2	Flow rate of compressed air extracted from GT, $\dot{G}_{ca}$	kg/s	0.1	41
3	GT air compressor pressure ratio, π_C	–	10	35
4	GT combustor exit temperature, T_{COMB}	°C	1000	1450
5	Effectiveness of heat exchange between compressed air and nitrogen, ε_{AN}	–	0.05	0.95
6	Live steam temperature, T_{HP}	°C	400	550
7	Temperature approach (pinch) at HP vaporizer, ΔT_{HP}	K	3	150
8	Hot end temperature approach at LP superheater, ΔT_{LP}	K	3	40
9	LP (HRSG) mass flow rate, $\dot{G}_{LP}$	kg/s	0.1	20
10	Steam pressure at LP HRSG part, p_{LP}	kPa	1000	5950
11	Steam pressure at HP HRSG part, p_{HP}	kPa	6000	15,000
12	Steam pressure in the second ST extraction, p_{EXT}	kPa	100	500
13	Maximal water temperature at LTE outlet, T_{LTE}	°C	71	130
14	Maximal water temperature at EH outlet, T_{EH}	°C	72	130
15	Duct burner temperature rise (flue gas), ΔT_{DB}	K	0	150
16	Effectiveness of steam reheater, ε_{RH}	–	0.05	0.95

Table 4
Constraints of optimization (design and off-design modes)

No.	Parameter	Unit	Constraint
1	Combustor exit temperature	°C	$=T_{COMB}$
2	GT air compressor map variable, CMV [2]	–	$\leqslant 0.95$
3	Live steam temperature	°C	$\leqslant T_{HP}$
4	ST exit steam quality	–	$\geqslant 0.86$
5	Flue gas temperature at LTE outlet	°C	$\geqslant T_{dew\ point}$
6	ST exit steam flow rate	kg/s	$\geqslant 0.1\dot{G}_{design}$

3. Strategy for problem solution

The choice of the optimization method for any particular problem depends on several conditions like the form and explicity of the objective function, existence of derivatives, computational effort, required accuracy, resistance to the local extremum. Most of the well-known methods start from one initial point and proceed in the iterative procedure to the final one by means of gradients or conjugate directions [24]. The problem is that there is some probability of finding local instead of the global extremum; however its indicated location is very accurate. On the other hand there are direct search or probabilistic methods (e.g. Monte Carlo) which find the area of global extremum inherently better, but the accuracy and computational effort in case of multidimensional problems might be a serious problem.

To the specific group of methods belong genetic algorithms, which apply the probabilistic rules in a way as they work in nature during the growth and decay of the population of living organisms [11]. A great advantage of genetic algorithms is that they provide not one but several points as a solution and the final choice can be made taking not quantified aspects (e.g. social ones) into consideration.

In the analysis presented here the hybrid method has been tried: the preliminary optimization is done by means of a genetic algorithm and then one or more of the resulting points serve as an initial point to the Powell method [24], which bases on the conjugate direction theory. This approach seems to ensure the maximum to be global and accurate.

The computer optimization codes have been taken from [9] (genetic algorithm) and [24] (Powell method). The general idea of computation is presented in Fig. 3.

In the current iteration the optimizing algorithm (genetic or Powell) generates a set of parameters (16 independent variables) which are input data to the CC design model. The design results are exported to the off-design models which are run many times

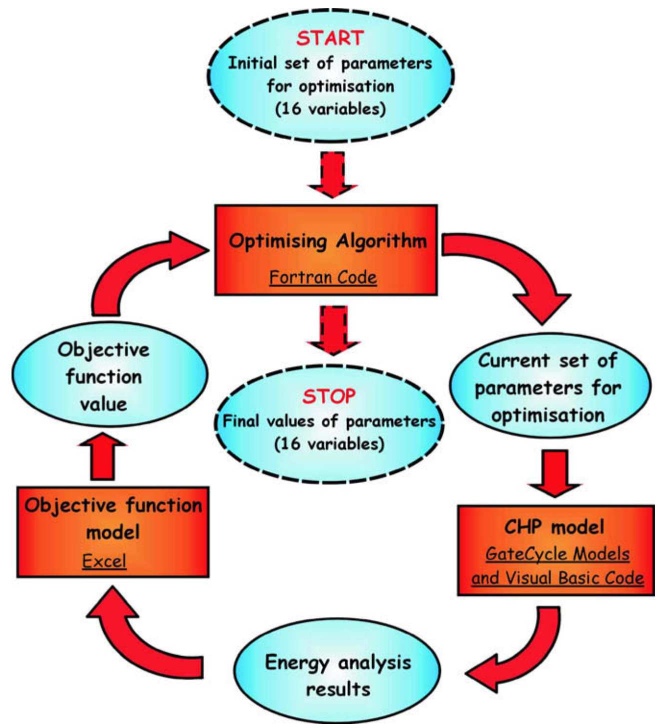

Fig. 3. General idea for optimization.

assuming different ambient temperature. Values of ambient temperature are taken from duration curve, proper for site conditions. Obtained in such a way energy and substance fluxes are then collected as functions of time and integrated to calculate the yearly values of fuel consumption (e.g. $E_{ch\,ng}$) and production of useful energy carriers (e.g. $E_{el\,IS}$, Q_{dh}, Q_{ps} – see Eq. (2)). The economic objective function (NPV) is finally calculated and supplied to the optimizing algorithm which starts the next iteration.

4. Economic background – computational scenarios

For economic optimization it is necessary to know values of several economic parameters, among others prices of purchased and sold goods as well as discount rate. These parameters (especially prices) depends usually on time and their changes could by very rapid. An example can be here the coal market. The coal price was changing rapidly several times in the past. As it was shown

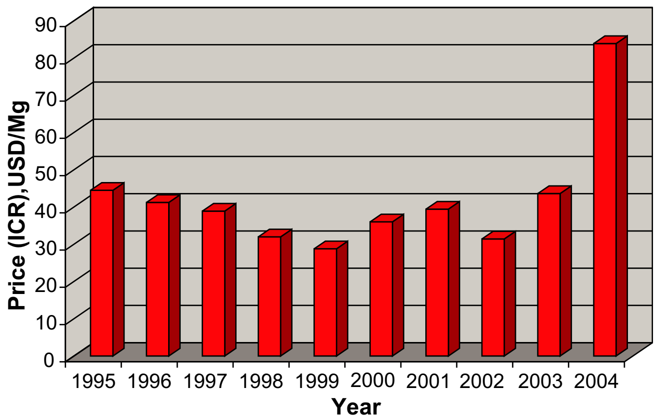

Fig. 4. Coal price for northern and western Europe (CIF), based on the International Coal Report data [22,23,1].

in Fig. 4 the price of coal increased in year 2004 by a factor of about 100% comparing to year 2003.

Because of unstable economic environment the analyzed optimization problem has been solved for more than one economic scenario. The analysis of historical data like this from Fig. 4 lead to definition of eight economic scenarios, as presented in Table 5. For each of them the independent optimization analysis has been done.

5. Combined cycle model

The CC model has been carried out basically on the GateCycle software [2]. Some advanced features like plant control strategies or modeling of some operational constraints have been included in dedicated Visual Basic scripts. The main assumptions and methods concerning modeling of crucial devices are briefly outlined below.

5.1. Gas turbine

Gas turbine design point calculation is based on the required pressure ratio, polytropic efficiencies of compressor and expander as well as combustor exit temperature. The blade film cooling model has been applied in accordance with theory presented in [12]. It was assumed that the maximum blade temperature is equal to 850 °C and the maximum number of cooled blade rows is 4 (2 expander stages). The cooling air is extracted from the compressor exhaust (for 1st stage cooling) and from lower pressure bleeding (2nd stage cooling).

For the off-design GT run the expander effective (throat) nozzle area has been fixed to the value calculated in design and the expander inlet pressure has been calculated from Eq. (4) [2,6]:

$$A_{\mathrm{nozz}} = \dot{G}\frac{\sqrt{RT_0}}{\psi p_0} \tag{4}$$

where A_{nozz} is the nozzle effective area, $\dot{G}$ is the mass flow rate at the expander inlet, $T_0,\ p_0$ is the stagnation temperature and stagnation pressure at expander inlet, R is the gas constant, ψ is the flow number (function of flue gas composition and pressure ratio).

The normalized compressor map [2] has been used to set the off-design points of air compressor operation.

5.2. Heat recovery steam generator

Heat transfer surface areas for every heat exchanger belonging to the HRSG have been calculated in design and fixed in off-design HRSG model. The ε – NTU method [17] has been used in both modeling cases, which can be in general expressed by the following formulas:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} = \frac{\dot{Q}}{\dot{W}_{\min}(\Delta T_{\max})} \tag{5}$$

$$\mathrm{NTU} = \frac{kA}{\dot{W}_{\min}} \tag{6}$$

$$\varepsilon = \varepsilon(\mathrm{NTU}, \dot{W}_{\min}/\dot{W}_{\max}, \text{flow geometry}) \tag{7}$$

where ε is the heat exchanger effectiveness, $\dot{Q}$, $\dot{Q}_{\max}$ is the actual and maximum obtainable heat transfer rate in the exchanger, $\dot{W}_{\min}$, $\dot{W}_{\max}$ is the lower and higher heat flux capacity in the exchanger, k is the overall heat transfer coefficient, A is the heat transfer surface area, $\Delta T_{\max}$ is the temperature difference between inlet streams.

The flue gas bypasses and water to steam injections have been modeled to control steam temperatures and avoid steaming in economizers. The overall heat transfer coefficient at each HRSG surface varies in off-design as a function of the flue gas mass flow rate in accordance with Eq. (8):

$$\frac{k}{k_{\mathrm{design}}} = \left(\frac{\dot{G}}{\dot{G}_{\mathrm{design}}}\right)^{0.8} \tag{8}$$

5.3. Steam turbine, condenser, cooling tower

The design ST model bases on adiabatic expansion theory. The steam mass flow rates are defined by external components. In off-design the Stodola equation for internal ST pressures and Spencer Cotton Cannon model [2] for efficiency simulation have been used.

Condenser has been modeled similarly like HRSG sections by the ε – NTU method. In off-design the overall heat transfer coefficient has been calculated in accordance with HEI method (Heat Exchange Institute) [16,2] – Eq. (9)

Table 5
Economic background scenarios – sets of input data for separate optimization runs

No.	Parameter, notation	Unit	Scenario no.							
			1	2	3	4	5	6	7	8
1	Price of iron ore, c_{io}	USD/Mg	40	40	40	40	60	60	60	60
2	Price of coal, c_c	USD/Mg	40	40	40	40	80	80	80	80
3	Price of hot metal, c_{hm}	USD/Mg	165	165	170	170	335	335	340	340
4	Price of electricity, c_{el}	USD/MWh	30	30	40	40	30	30	40	40
5	Price of natural gas, c_{ng}	USD/GJ	4	6	4	6	4	6	4	6
6	Price of district heat, c_{dh}	USD/GJ	6.3							
7	Price of process steam, c_{ps}	USD/GJ	12.2							
8	Discount rate, r	–	0.039							
9	Yearly time of operation, τ_Y	h/year	8000							

$$k = a_1 a_2 a_3 \sqrt{w} \tag{9}$$

where a_1 is the coefficient dependent on outer condenser tube diameter, a_2 is the coefficient dependent on cooling water temperature, a_3 is the coefficient dependent on condenser tube material, w is the cooling water velocity.

Model of wet, mechanical draft cooling tower has been based on widely known Merkel theory and semi-empirical formula describing film-type fill characteristic:

$$Me = 1.9\lambda^{0.6} \tag{10}$$

where Me is the Merkel number, λ is the ratio of air to water mass flow rates.

5.4. Selected results of thermodynamic simulation

The exemplary results obtained from thermodynamic CC model are presented in Figs. 5–8. All of them deals with the optimization results for scenario no. 4 (see Table 6).

5.5. Estimation of investment costs

Investment costs of analyzed equipment have been evaluated on literature [4,5,3] basis. Some of the cost functions have been tuned according to market prices published in [3]. All investment cost functions have been updated to the same moment (2004) by the CEPCI indexes (Chemical Engineering Plant Cost Index [26]).

Exemplary investment cost functions for GT components, HRSG and ST are presented below. They represent purchase cost of appropriate equipment:

$$I_C = c_1 39.5 \dot{G}_a \pi_C \ln(\pi_C), \text{USD} \tag{11}$$

$$I_{COMB} = c_1 25.6 \dot{G}_{fg} [1 + \exp(0.018 T_{COMB} - 26.4 c_2)], \text{USD} \tag{12}$$

$$I_E = c_1 266.3 \dot{G}_{fg} \ln(\pi_E) [1 + \exp(0.036 T_{COMB} - 54.4 c_2)], \text{USD} \tag{13}$$

while

$$c_1 = 21; \quad c_2 = 1.207 \tag{14}$$

$$I_{HRSG} = 21200 \left[\sum_n \left(\frac{\dot{Q}}{\Delta T_{\log}} \right)_n^{0.6} + \sum_m \left(\frac{\dot{Q}}{\Delta T_{\log}} \right)_m^{0.79} \right], \text{USD} \tag{15}$$

$$I_{ST} = 1.1 \left(3197280 A_{ST}^{0.261} + 823.7 N_{ST}^{1.543} \right), \text{USD} \tag{16}$$

$$I_{COND} = 2870 A_{COND}^{0.79}, \text{USD} \tag{17}$$

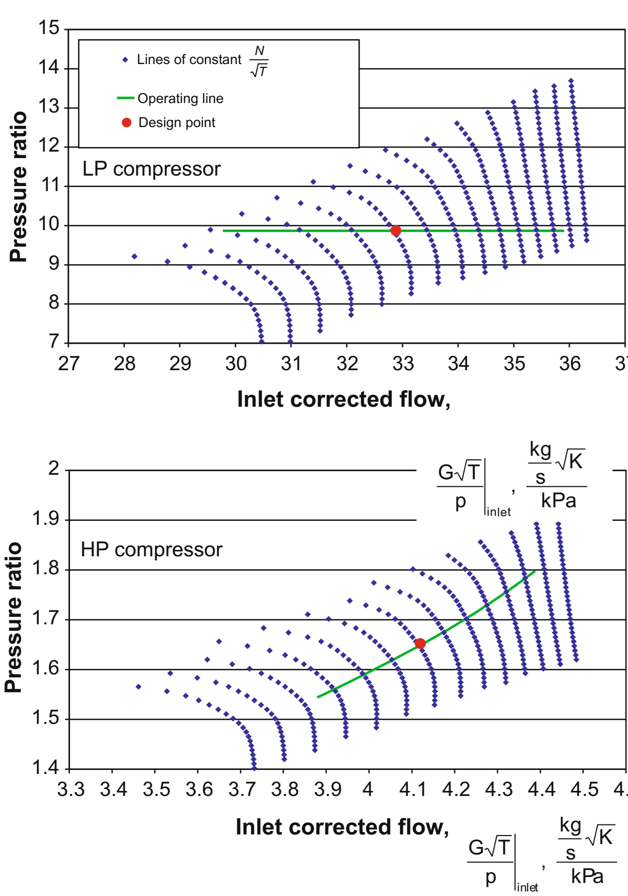

Fig. 5. GT air compressor map; N – rotational speed; T, p – temperature and pressure at inlet; the air extraction to ASU occurs between LP and HP compressors.

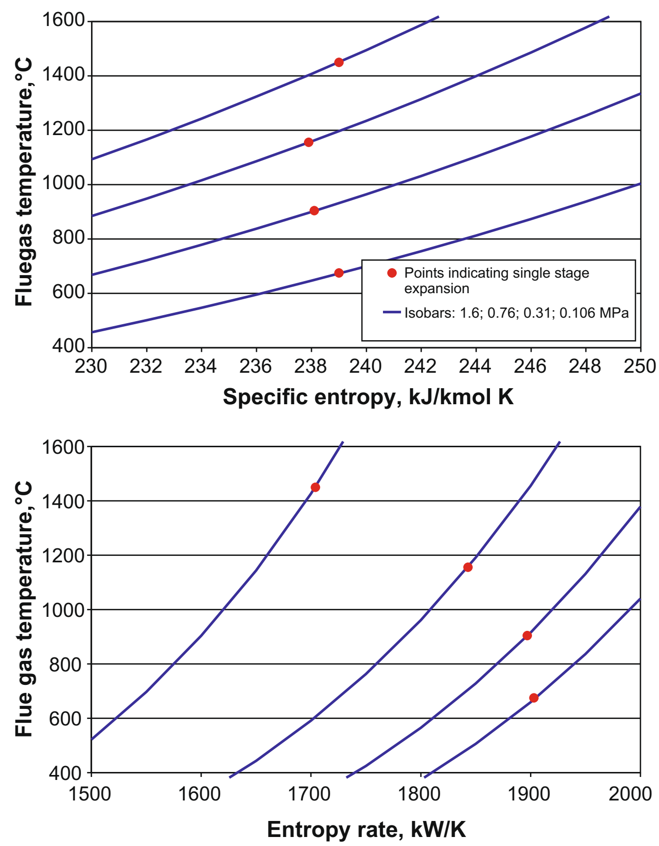

Fig. 6. Impact of blade cooling on expansion line in expander.

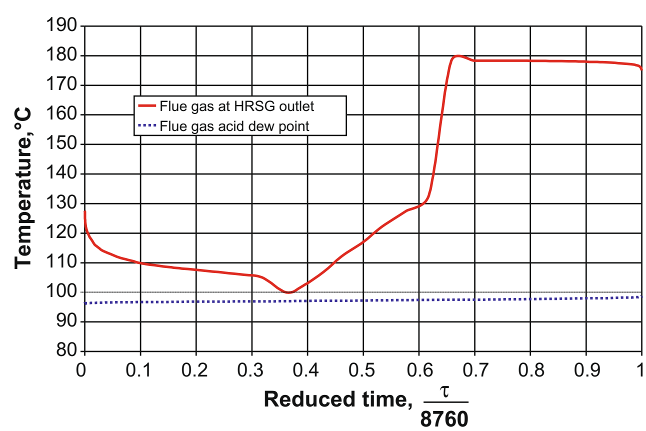

Fig. 7. Flue gas parameters at HRSG outlet.

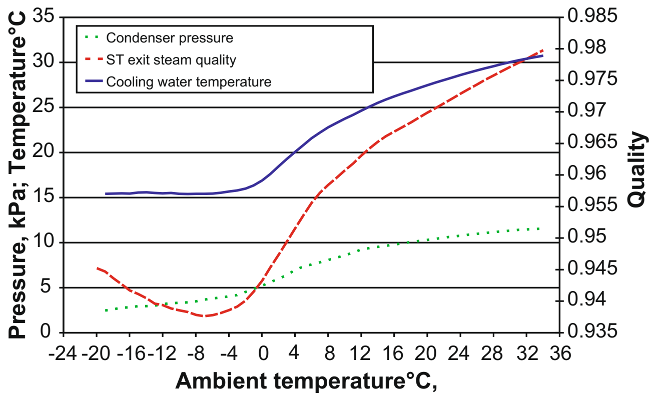

Fig. 8. Selected parameters of condenser and ST exit section.

where I_C, I_{COMB}, I_E, I_{HRSG}, I_{ST}, I_{COND} is the investment cost for air compressor, combustor, expander, HRSG, ST and condenser, USD, $\dot{G}_a$ is the air mass flow rate at compressor inlet, kg/s, $\dot{G}_{fg}$ is the flue gas mass flow rate at expander inlet, kg/s, T_{COMB} is the combustor exit temperature, K, π_C is the air compressor pressure ratio, π_E is the expander pressure ratio, $\dot{Q}$ is the heat transfer rate in analyzed boiler section, kW, ΔT_{log} is the mean logarithmic temperature difference between flue gas and steam/water in analyzed boiler section, K, n applies to superheaters, vaporizers, and economizers excluding those where condensation on flue gas site takes place, m applies to boiler sections where condensation on flue gas site takes place, A_{ST} is the ST exit section area, m^2, N_{ST} is the ST shaft power, MW, A_{COND} is the condenser heat transfer surface area, m^2.

Investment cost for the Corex process and ASU has been assumed as a fixed value.

Additional investment costs related to assembly, insurance, control systems, etc. have been evaluated as 15% of purchase cost of equipment.

6. Optimization results and sensitivity analysis

Optimized values of independent variables and other results are presented in Table 6. They are discussed in detail in Section 7.

Before drawing final conclusions it is important to know how much is the objective function sensitive to changes of independent variables and parameters within the neighborhood of optimal point. This knowledge can be useful when it is not possible to design the system precisely at calculated optimum. The proper tool to solve these problems is sensitivity analysis.

The sensitivity analysis, carried out within the confines of presented study is based on the following sensitivity factors:

- with respect to the independent variables:

$$\lambda_{ISi} = \left|\frac{\Delta NPV_{IS}}{NPV_{IS\,opt}}\right|_i; \quad i = 1 \ldots 16 \tag{18}$$

The increase ΔNPV_{IS} is calculated within given i for deviation of independent variable x_i from its value in optimal point $x_{i\,opt}$ according to equation:

$$\frac{x_i - x_{i\,opt}}{\bar{x}_i} = 0.05 \tag{19}$$

and under condition: $x_j = x_{j\,opt}$ for $j \neq i$

- with respect to the parameters:

$$\mu_{IS\,i} = \left|\frac{\Delta NPV_{IS}}{NPV_{IS\,opt}}\right|_k; \quad k = 1 \ldots 8 \tag{20}$$

The increase ΔNPV_{IS} is calculated within given k for deviation of parameter a_k from its basic value $a_{k\,bas}$ according to equation:

$$\frac{a_k - a_{k\,bas}}{\bar{a}_k} = 0.1 \tag{21}$$

and under condition: $a_l = a_{l\,bas}$ for $l \neq k$

Moreover

$$\bar{x}_i = \frac{1}{8}\sum_{u=1}^{8} x_{iu} \tag{22}$$

$$\bar{a}_k = \frac{1}{8}\sum_{u=1}^{8} a_{ku} \tag{23}$$

Subscripts in Eq. (18)–(23) have following meaning:

i index of independent variable,
u index of economic environment scenario,
k index of objective function parameter,
opt value at optimal point,

Table 6
Optimization results

No.	Variable (see Table 3)	Unit	Scenario no. 1	2	3	4	5	6	7	8
1	ϕ	–	2.44	0.94	2.41	0.90	2.42	0.90	2.50	0.85
2	$\dot{G}_{ca}$	kg/s	21.43	20.42	22.67	19.12	19.07	0.37	22.93	0.52
3	π_C	–	14.4	14.5	16.2	16.3	15.6	14.9	14.5	16.6
4	T_{COMB}	°C	1449	1450	1450	1448	1447	1450	1448	1449
5	ε_{AN}	–	0.95	0.93	0.95	0.94	0.94	0.93	0.95	0.95
6	T_{HP}	°C	550	550	550	550	550	550	550	550
7	ΔT_{HP}	K	29	95	5	88	36	73	17	140
8	ΔT_{LP}	K	26	6	26	10	27	8	8	4
9	$\dot{G}_{LP}$	kg/s	1.67	13.71	4.48	9.49	11.98	7.27	8.69	11.02
10	p_{LP}	kPa	1746	3329	2457	2554	2232	2350	2830	3014
11	p_{HP}	kPa	14,944	14,633	14,996	14,852	14,954	14,925	14,988	14,901
12	p_{EXT}	kPa	114	100	100	100	101	105	100	100
13	T_{LTE}	°C	95	73	77	89	77	83	72	90
14	T_{EH}	°C	126	111	115	112	111	109	109	126
15	ΔT_{DB}	K	0	0	0	1	0	0	0	48
16	ε_{RH}	–	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.92
Combined cycle size										
17	GT shaft power	MW	195.8	109.4	199.2	110.9	198.6	112.9	198.7	107.1
18	ST shaft power; (extractions closed)	MW	93.9	56.2	97.7	48.6	96.1	50.7	106.1	48.4
Objective function										
19	NPV_{IS}	10^6 USD	232.4	159.0	462.1	279.8	585.3	510.9	816.3	617.1

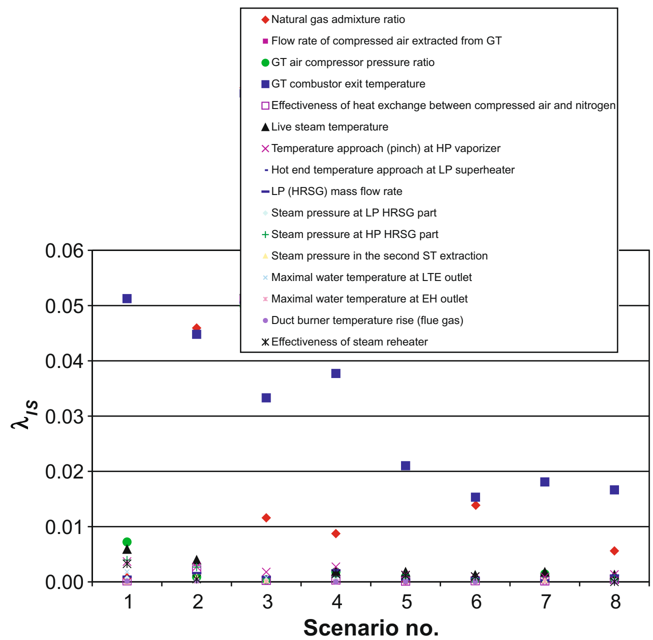

Fig. 9. Sensitivity factor of the objective function NPV_{IS} on values of independent variables.

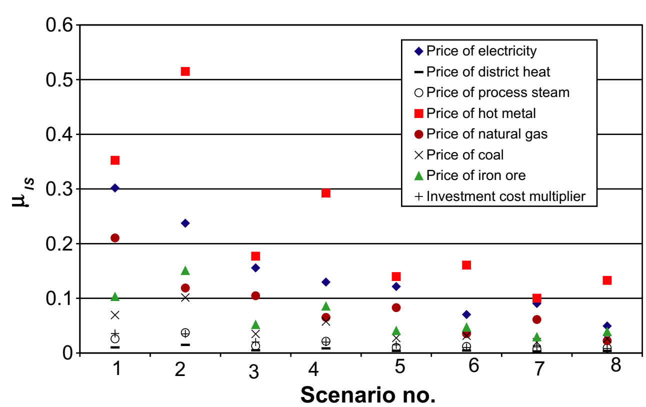

Fig. 10. Sensitivity factor of the objective function NPV_{IS} on values of parameters.

bas basic value of parameter assigned to economic environment scenario in Table 5.

Calculated sensitivity factors are presented in Figs. 9 and 10. The investment cost multiplier – one of parameters included in sensitivity analysis (Fig. 10) is defined as ratio of additional CC investment costs to purchase cost of CC equipment. Basic value of this parameter has been assumed to 0.15 as described in Section 5.5.

7. Conclusions

(1) Optimized values of some independent variables do not depend on economic environment scenario. Moreover, they are close to lower or upper limits defined in Table 3. This conclusion concerns following variables (see Table 6): T_{COMB}, ε_{AN}, T_{HP}, p_{HP}, p_{EXT}, ΔT_{DB}, ε_{RH}.

(2) GT combustor exit temperature (T_{COMB}), live steam temperature (T_{HP}), and steam pressure at HP HRSG part (p_{HP}) should be as high as possible (within their analyzed range).

(3) Steam pressure in the second ST extraction (p_{EXT}) should be as low as possible.

(4) The combined cycle structure should include steam reheater ($\varepsilon_{RH} \to \max$) and heat exchanger air–nitrogen ($\varepsilon_{AN} \to \max$). This conclusion is valid for each economic scenario.

(5) Supplementary firing of the Corex gas in HRSG is not preferred form economic point of view ($\Delta T_{DB} \to \min$), expecting scenario no. 8, where some increase of flue gas temperature in duct burner is desired.

(6) Values of remaining independent variables are diverse depending on the economic environment scenario. For scenarios characterized by high price of natural gas the natural gas admixture ratio (ϕ) aims at its minimal value, determined by demands for district heat and process steam. For low natural gas prices contrary conclusion can be drawn – natural gas admixture is close to assumed higher constraint.

(7) In case of low prices of coal, iron ore and hot metal (scenario nos. 1–4) the extraction of compressed air from GT to ASU is preferred ($\dot{G}_{ca} \gg 0$). For scenarios 5–8 this conclusion is equivocal. If price of natural gas is high such an GT-ASU integration should not occur. The reason is that the extracted air flow rate impacts yearly natural gas consumption. On the other hand sensitivity factor related to this variable is close to zero (Fig. 9) which makes this whole conclusion low relevant.

(8) Optimized values of variables: ΔT_{HP}, ΔT_{LP} and $\dot{G}_{LP}$ provide an information on preferred HRSG structure. The HRSG should by of single pressure design for scenario nos. 1 and 3 and of double pressure design for other analyzed economic cases. The exemplary HRSG temperature profiles justifying such a conclusion are presented in Fig. 11.

(9) The objective function (NPV_{IS}) is clearly sensitive to GT combustor exit temperature (T_{COMB}) and natural gas admixture ratio (ϕ) – Fig. 9.

(10) Sensitivity factors related to some independent variables are very low or close to zero. Besides already mentioned ($\dot{G}_{ca}$), this conclusion concerns following variables: ΔT_{LP}, p_{LP}, p_{EXT}, T_{LTE}, T_{EH}, ΔT_{DB}. Summing up, there is some freedom in final selection of these parameters (in analyzed neighborhood of the optimal point).

(11) Parameters of the objective function which have major impact on its value are price of hot metal, price of electricity and price of natural gas. The relevance of investment cost multiplier is by order of magnitude lower – Fig. 10.

(12) The analyzed integrated system is characterized by promising economic features. The discounted pay back (DPB_{IS}; $\sum_{t=0}^{DPB} \frac{NCF_t}{(1+r)^t} = 0$) depending on the economic environment scenario varies from 3 to 7 years.

Final remarks

(1) The optimization study like this one presented here supports the designer at the stage of preliminary studies and during the negotiations with equipment providers.

(2) The final selection of combined cycle equipment should be done with respect to results of sensitivity analysis; the independent variables with higher sensitivity factors should be kept constant primarily.

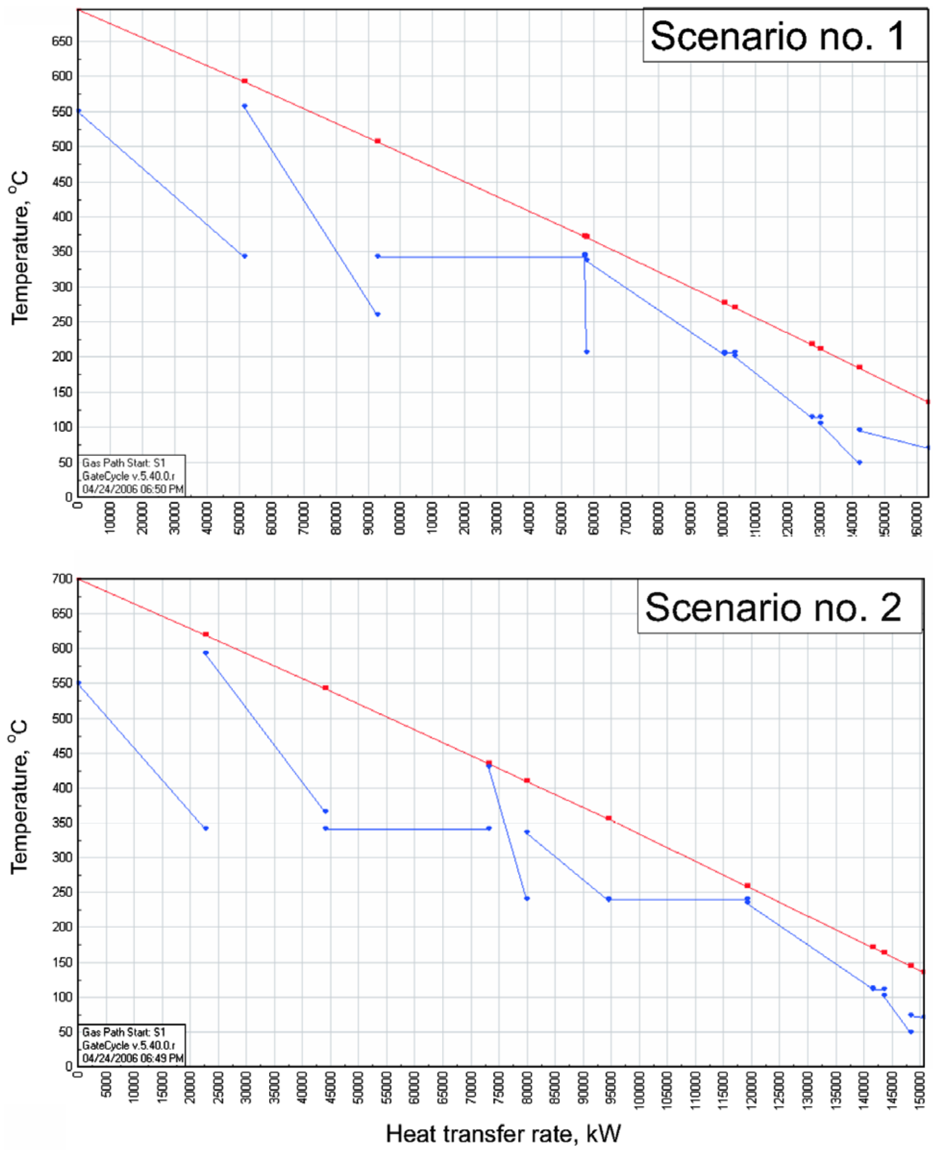

Fig. 11. Exemplary HRSG temperature profiles (design mode of operation).

(3) The sensitivity of economic objective function to its parameters can be significantly higher than sensitivity to independent variables. Therefore, accurate estimation of prices of sold energy carriers and bought fuels is of major importance.

References

[1] Steam and coking coal prices. Energy prices and taxes, 3rd quarter. International Energy Agency; 2004.
[2] GateCycle version 5.40, Copyright 1989–2001. GE Enter Software, LLC; 2001. <www.gepower.com>.
[3] 2004–2005 GTW handbook. Gas Turbine World, Pequot Publishing Inc.; 2004.
[4] Agazzani A, Massardo AF. A tool for thermoeconomic analysis and optimization of gas, steam and combined plants. Trans ASME. J Eng Gas Turbines Power 1997;119:885–92.
[5] Attala L, Facchini B, Ferrara G. Thermoeconomic optimization method as design tool in gas – steam combined plant realization. Energy Convers Manage 2001;42:2163–72.
[6] Bathie WW. Fundamentals of gas turbines. New York, Singapore: John Wiley and Sons Inc.; 1996.
[7] Behrens W, Hawranek PM. Manual for the preparation of industrial feasibility studies. Warszawa: United Nations Industrial Development Organization; 2003.
[8] Bohm C, Eberle A, Gould L, Kriechmair J, Wdlinger R. The Corex revolution. Steel Times 1995;5:176–9.
[9] Carroll DL. FORTRAN genetic algorithm driver version 1.7a; 2001. <http://cuaerospace.com/carroll/ga.html>.
[10] Farina G, Bressan L. Optimizing IGCC design: improve performance, reduce capital cost. Foster Wheeler Rev 1999;1:16–21.
[11] Goldberg DE. Genetic algorithms in search, optimization, and machine learning. Addison-Wesley Pub. Co.; 1989.
[12] Horlock JH. Advanced gas turbine cycles. Amsterdam, Tokyo: Elsevier Science; 2003.
[13] Voest Alpine Industrieanlagenbau. The Corex C-3000 generation; 2000.
[14] Voest Alpine Industrieanlagenbau. The victory march of Corex; 2001.
[15] Voest Alpine Industrieanlagenbau. Corex status report, September 2000.
[16] Standards for steam surface condensers. 8th ed. Cleveland: Heat Exchange Institute; 1984.
[17] Kays WM, London AL. Compact heat exchangers. 3rd ed. New York: McGraw-Hill; 1984.
[18] Lee HK, Joo S, Kang ChO. The corex process for hot metal production without coke. In: Proceedings of international conference on new developments in metallurgical process, Dusseldorf; 1999. p. 36–41.
[19] Lemperle M, Maschlanka W. Corex today and tomorrow. Metall Plant Technol (MPT) Int 1993;4:70–6.
[20] Liszka M, Manfrida G, Ziebik A. Parametric study of HRSG in case of repowered industrial CHP plant. Energy Convers Manage 2003;44:995–1012.
[21] Liszka M, Ziebik A. An economic optimisation of the structure and parameters of a combined cycle CHP fired with COREX export gas. In: Proceedings of ECOS '04, Guanajuato, Mexico; 2004.

[22] Maiello D. International coal trade and price developments in 2002. In: United Nations Economic and Social Council. Economic Commission for Europe. Committee on sustainable energy – 12th session, Geneva; 2002.

[23] Maiello D. International coal trade and price developments in 2003. In: United Nations Economic and Social Council. Economic Commission for Europe. Committee on sustainable energy – sixth session, Geneva; 2003.

[24] Press WH, Teukolsky SA, Vetterling WT, Flannery BP. Numerical recipes in Fortran77. The art of scientific computing. 2nd ed. Cambridge: Cambridge University Press; 1994.

[25] Smith AR, Klosek J. A review of air separation technologies and their integration with energy conversion processes. Fuel Process Technol 2001;70:115–34.

[26] Vatavuk WM. Updating the plant cost index. Chem Eng 2002; January.

[27] Ziebik A, Lot G, Fechner R. Process and system analysis of COREX technology. In: Proceedings of ECOS '99, Tokyo; 1999.