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The influence of a CO_2 separation and compression unit on the optimal parameters of combined cycle power plants

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Abstract

This paper presents the results of optimization of the design parameters of the combined cycle power plant, which was conducted using a genetic algorithm. Thermodynamic calculations were made for the objective function, which was the power of the steam turbine. The process of optimization was divided into three structures of combined cycle power plants: single-pressure (1P), double-pressure with steam reheater (2 PR) and triple-pressure with steam reheater (3PR). Each system was optimized in two versions: with and without steam extraction in the turbine in the steam cycle, for the integration of the systems with a CO_2 separation and compression unit (CCS). The resulting values of power and efficiency of the optimized systems are summarized and compared with each other. a sensitivity analysis was performed for the 2PR and 3PR systems in the versions with steam extraction. The impact of energy consumption in the process of desorption in the CO_2 separation unit on the decrease in efficiency of combined cycle power plants was also examined.

Keywords: combined cycle power plant, CO_2 separation and compression, genetic algorithm

1. Introduction

The combined cycle power plant (CCPP) is based on a combination of a gas turbine and a steam cycle. This electricity generation technology enjoys the highest efficiencies of the technologies currently available. The choice of a heat recovery steam generator (HRSG) structure significantly influences the efficiency of combined cycle power plants. At present a triple-pressure CCPP with steam reheater achieves the highest efficiency: up to 60...61% [1, 2].

Combined cycle power plants are characterized by high reliability, high heat flexibility, high automation and favorable environmental statistics. They emit only 330 $kgCO_2$/MWh with net efficiency of about 60% (a conventional coal-fired power plant emits 860 $kgCO_2$/MWh at 45% net efficiency) [1, 3]. Despite the relatively low investment costs a serious obstacle to using this technology in Poland is the high price of natural gas. Nevertheless, new CO_2 emission restrictions may act as a drive for change—the European Union sets permitted levels of CO_2 emissions. One way to help achieve reductions in CO_2 emissions is through CO_2 separation and compression (CCS—Carbon Capture and Storage). However, CO_2 capture and compression units require capital investment and entail a significant reduction in efficiency [4–7]. This paper looks at the influence of introducing a CCS unit on the efficiency and optimal parameters of a combined cycle power plant.

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Table 1: The characteristic of the gas turbine model

Parameter	Value
1. Net efficiency, %	39.1
2. Flue gas temperature at combustion chamber outlet, °C	1,500
3. Compressor pressure ratio,	23.0
4. Flue gas temperature at gas turbine outlet, °C	595
5. Isentropic efficiency of the air compressor,	0.880
6. Mechanical efficiency of the compressor and expander,	0.985
7. Efficiency of the combustion chamber,	0.990
8. Isentropic efficiency of the expander,	0.900
9. Efficiency of the electricity generator,	0.980

2. Characteristics of combined cycle power plants

In order to perform optimization and comparison of the analyzed combined cycle power plants the authors performed a literature review [8–10] and proposed a G class gas turbine with net electrical power ($N_{\mathrm{n.TG}}$) of 260 MW. Open-air film cooling in the gas turbine is used. The ratio of cooling air to compressed air is 1 to 5. The natural gas stream to the combustion chamber is 13.3 kg/s, consisting of 98% methane (CH_4) and 2% nitrogen (N_2). The characteristics of the gas turbine model are presented in Table 1 (for ambient parameters according to ISO). The stream of the exhaust gases ($\dot{m}_{4a}$) from the gas turbine is 617 kg/s, temperature 595°C and enthalpy (h_{4a}) 641 kJ/kg. The stream of carbon dioxide ($\dot{m}_{\mathrm{CO2}}$) in the flue gas is 35.5 kg/s. The chemical energy stream $\left(\dot{m}_{1\mathrm{p}} \cdot W_{\mathrm{d}}\right)$ of the fuel is 664 kJ/s.

Each structure was optimized in two versions: with and without steam extraction in the turbine in the steam part for the integration of the systems with the CO_2 separation and compression unit. The assumptions for the optimized CCPP are presented in Table 2.

In the double-pressure and triple-pressure combined cycle power plant (Fig. 2 and Fig. 3) a steam reheater is used. This is done by feeding the steam—after expansion in the high-pressure part of the steam turbine—back to the heat recovery steam generator. This solution causes the steam directed to the low pressure steam turbine to have high enthalpy. Consequently, it increases the efficiency and vapor quality of the steam in the last stage of the steam turbine, so that the problems associated with erosion conditions are minimized.

Table 2: Parameters of the combined cycle power plants

	Parameter	Value
1.	Pressure in the condenser, MPa	0.005
2.	Internal efficiency of the steam turbine,	0.900
3.	Internal efficiency of the pump,	0.850
4.	Mechanical efficiency of the steam turbine and generator,	0.990
5.	Efficiency of the water heater, evaporator, superheater,	0.990

All the structures were modeled using a GateCycle™ program. The single-pressure CCPP is shown in Fig. 1.

3. The CO_2 separation and compression unit

Absorption based on chemical sorbents is currently the best way of separating CO_2 from flue gas according to comparative research on the subject of CO_2 capture [4, 5, 11–14]. The absorption process is based on the absorption of gas molecules by a liquid(s). The high efficiency of the whole process and the high purity of the captured carbon dioxide are the main advantages of this method [12]. Chemical absorption is carried out in an absorber/stripper (Fig. 4). This unit is integrated with the combined cycle power plants at points a and B (Fig. 1, Fig. 2 and Fig. 3).

The flue gas stream from HRSG (point A) directed to the absorber column is cooled to 40°C. The recovery rate of carbon dioxide is 90%, which means that only 10% of the CO_2 contained in the flue gas is emitted into the atmosphere. A solution of MEA (monoethanolamine) with CO_2 is directed to the stripper column. a heat flow is required to regenerate the MEA. Steam extraction is used for this

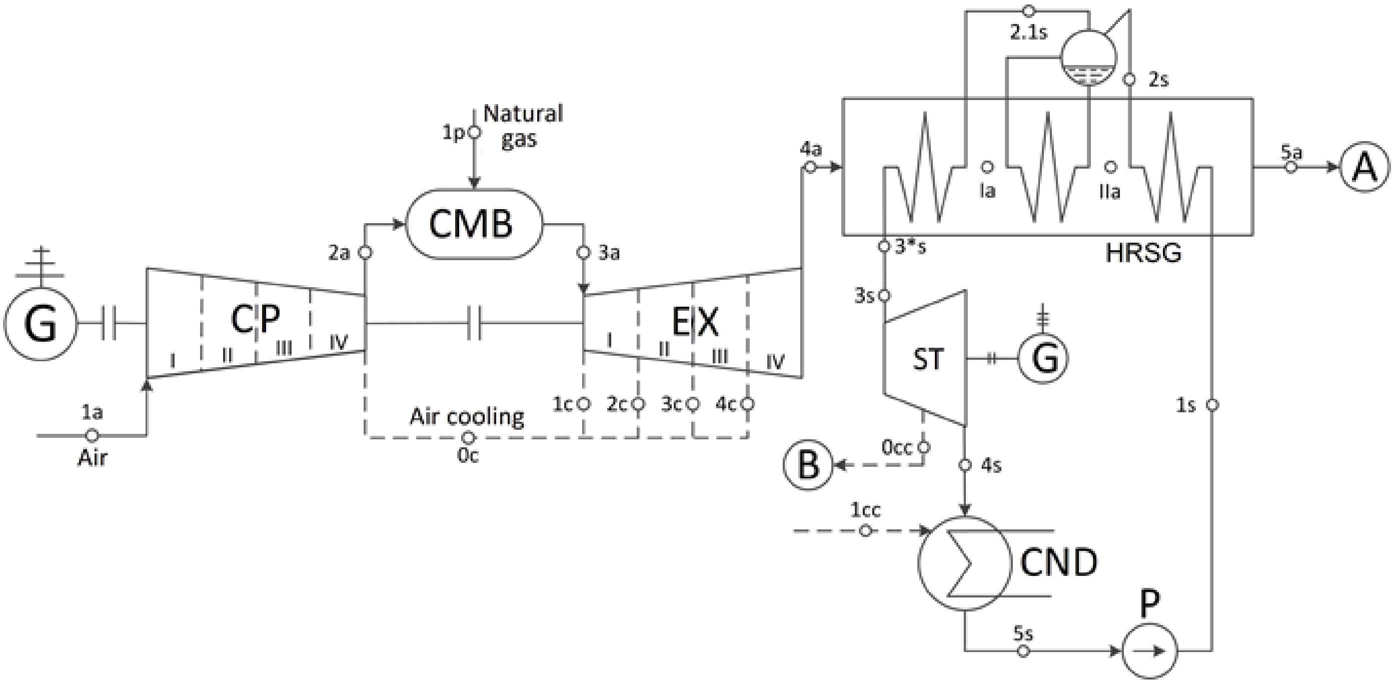

Figure 1: Schematic diagram of a single-pressure combined cycle power plant (1P)(G—generator, CND—condenser, P—condensate pump, SP—steam turbine, HRSG—heat recovery steam generator, A—flue gas stream, B—steam stream)

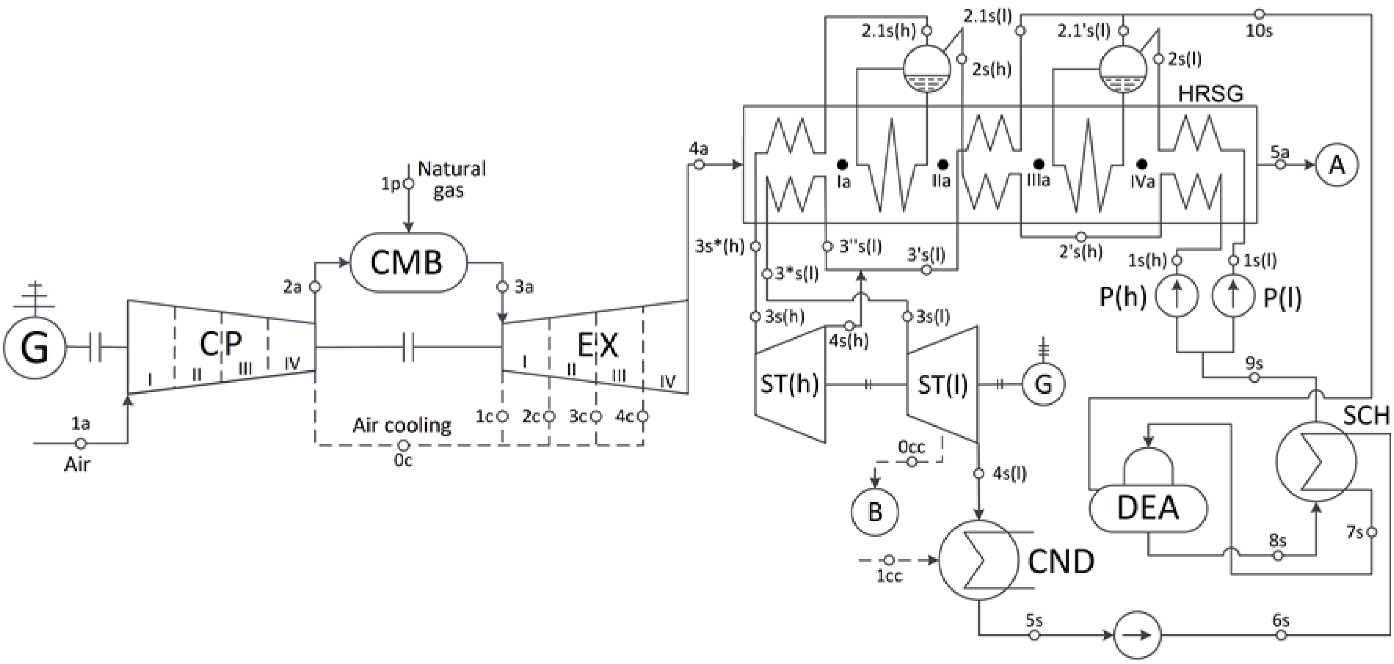

Figure 2: Schematic diagram of a double-pressure combined cycle power plant with a steam reheater (2PR)

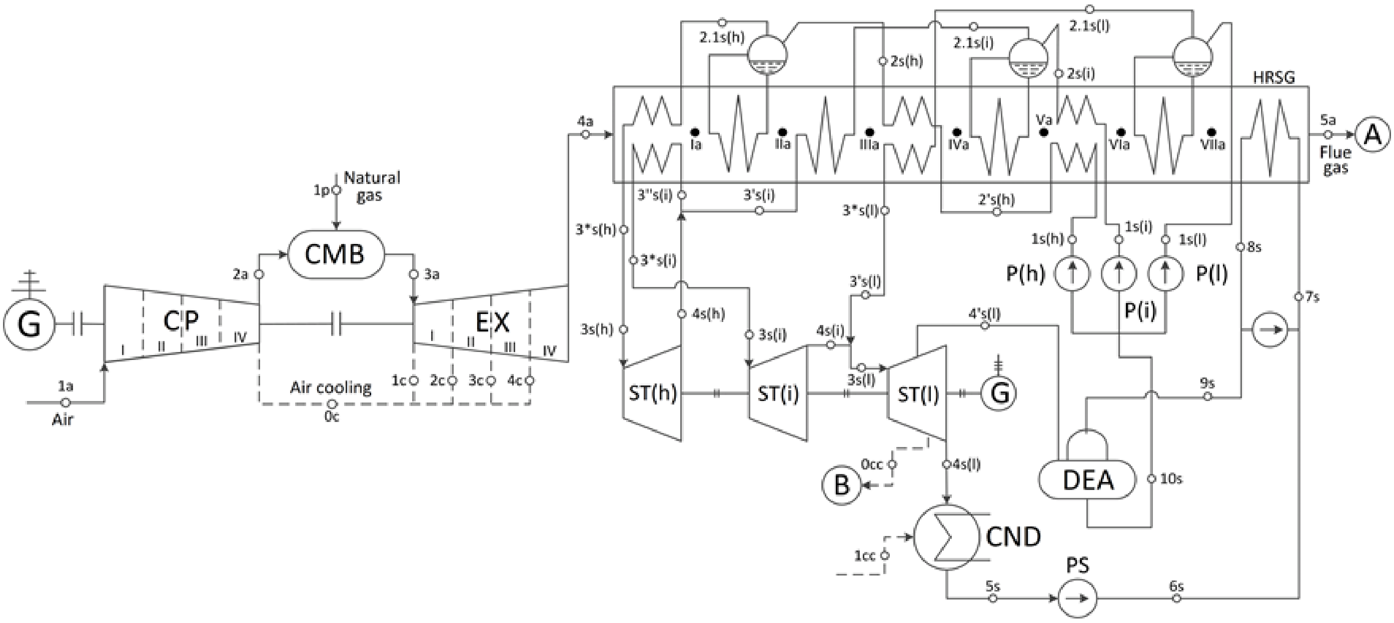

Figure 3: Schematic diagram of a triple-pressure combined cycle power plant with a steam reheater (3PR)

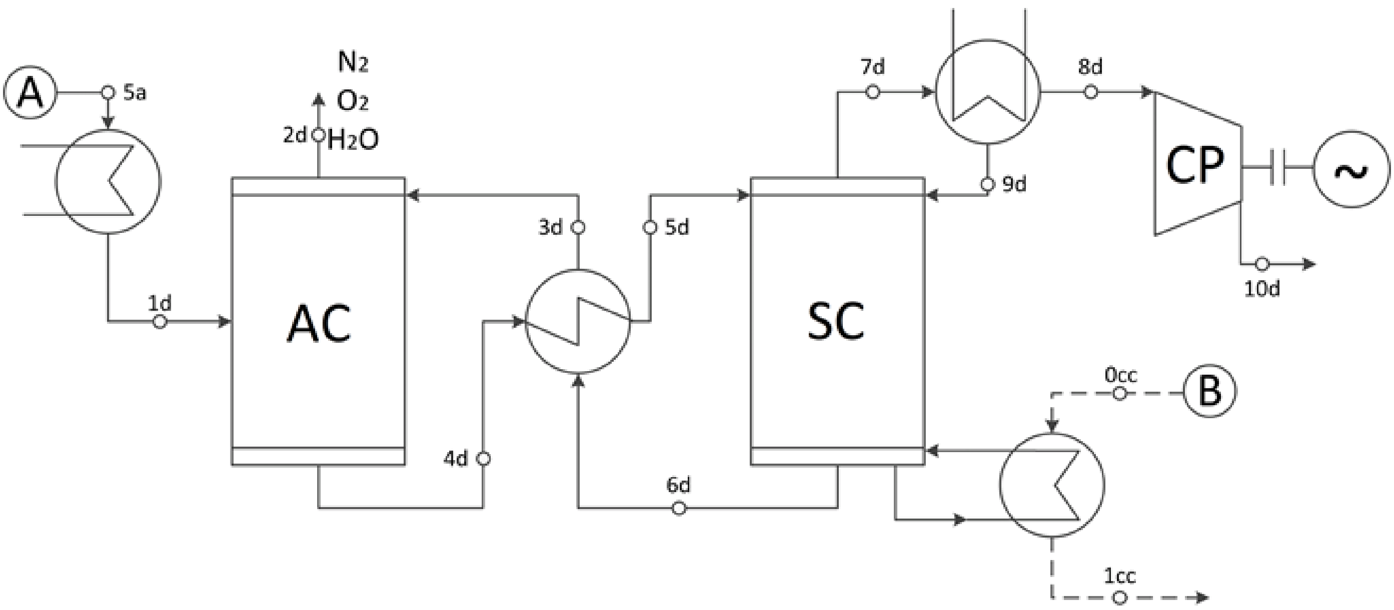

Figure 4: The system of CO_2 separation and preparation for transport (AC—absorber column, SC—stripper column, CP—CO_2 compressor, A—flue gas from the HRSG, B—steam flow from steam turbine bleed)

purpose: the steam flow from steam turbine bleed (point B) heats the medium in the stripper heat exchanger to the temperature (T) of 125°C with a pinch temperature (ΔT_S) of 5 K. The pressure loss between the steam turbine and heat exchanger (ς) was established at 0.02. The pressure of the steam used to regenerate the MEA is 287 kPa. This pressure depends on the saturation pressure ($p_S(T + \Delta T_S)$) for temperature ($T + \Delta T_S$) and the pressure loss coefficient between the steam turbine and stripper heat exchanger (ς), according to the formula:

$$p_{0cc} = p_S(T + \triangle T_S)/(1 - \varsigma) \quad (1)$$

It was assumed that the energy consumption (q_S) of the sorbent is 4 MJ/kgCO_2. The efficiency of the stripper heat exchanger (η_{WC}) was set at 0.99. The steam flow from the steam turbine bleed ($\dot{m}_{0cc}$) directed to the stripper depends (2) on the efficiency of the stripper heat exchanger (η_{WC}), enthalpy of water returning to the steam cycle (h_{1cc}), steam enthalpy directed to the stripper heat exchanger (h_{0cc}), the CO_2 recovery rate (R), mass flow of CO_2 contained in the flue gas ($\dot{m}_{CO2}$) and energy consumption (q_S) of the sorbent.

$$\dot{m}_{0cc} = (q_S \cdot \dot{m}_{CO2} \cdot R)/\left[(h_{0cc} - h_{1cc}) \cdot \eta_{WC}\right] \quad (2)$$

The use of steam extraction to regenerate MEA in the CO_2 separation and compression unit causes a significant reduction in the power of a steam turbine. The lower steam turbine power negatively impacts both the efficiency of the steam cycle $\left(\eta_{CP} = N_{b.TP} \big/ \dot{Q}_{4a}\right)$ and the efficiency of the combined cycle power plant. The compression of the separated carbon dioxide causes a further reduction in the power and efficiency of the combined cycle power plant.

The energy consumption of the CO_2 compression (υ) of the carbon dioxide is 0.1 kWh/kgCO_2 which corresponds to 360 kJ/kgCO_2 [11]. The power (N_{SP}) required for the CO_2 compression to a pressure of 15 MPa required for the transport is 11.47 MW. This value is determined from the CO_2 recovery rate (R), the energy intensity of the CO_2 compression (υ) and the CO_2 mass flow ($\dot{m}_{CO2}$) contained in the flue gas.

$$N_{SP} = \dot{m}_{CO2} \cdot R \cdot \upsilon \quad (3)$$

4. The objective function of the optimization algorithm

The net electrical efficiency ($\eta_{n.GP}$) of the combined cycle power plant depends on the net electrical power of the CCPP ($N_{n.GP}$) referenced to the chemical energy of the fuel, expressed as the ratio of the fuel stream $\left(m_{1p}\right)$ directed to the combustion chamber and fuel calorific value (W_d):

$$\eta_{n.GP} = N_{n.GP}/(m_{1p} \cdot W_d) \quad (4)$$

The net power of the CCPP ($N_{n.GP}$) is expressed as the sum of the net power of the gas turbine ($N_{n.TG}$) and the steam turbine gross power ($N_{b.TP}$) reduced by the auxiliary power (N_{PW}) of the whole unit:

$$N_{n.GP} = N_{n.TG} + N_{b.TP} - N_{PW} \quad (5)$$

The auxiliary power of the CCPP in equation (5) depends on the gross electrical power of the steam turbine ($N_{b.TP}$), the net power of the gas turbine ($N_{n.TG}$), the electrical power needed for CO_2 compression (N_{SP}) and the rate of auxiliary power of the unit ($\delta_{PW} = 0.03$):

$$N_{PW} = \delta_{PW} \cdot (N_{n.TG} + N_{b.TP}) + N_{PW} \quad (6)$$

In the CCPP the steam part and the gas part are not autonomous. If we assume that the net electrical power of the gas turbine is constant and does not change the parameters of the gas turbine, then complete optimization of the CCPP comes down to optimizing the efficiency of the steam part. Therefore, the net efficiency of the CCPP reaches its maximum value when the gross electrical power of the steam turbine reaches its maximum value. The objective function for the optimization algorithm takes the form:

$$N_{b.TP} \to \max \quad (7)$$

Represented by equation (7) the objective function for the genetic algorithm is the function of the following decision variables:

- The temperatures of the steam for each pressure level $(\Delta t_{3s})_Y$ (for Y = h, i, l where h—high pressure, i—medium pressure, l—low pressure)

- The pressures of the steam for each pressure level $(\Delta p_{3s})_Y$ (for Y = h, i, l)

- Water subcooling at the outlet of the water heaters $(\Delta T_{ap})_Y$ (for Y = h, i, l i D where D—concerns deaeration heat exchanger)

- Differences in temperature between the steam and flue gas in HRSG for each pressure level $(\Delta T_{pp})_Y$ (for Y = h, i, l)

- The temperature difference at the hot end of the superheater $(\Delta T_{he})_Y$ (for Y = i, l) and the first part of the high-pressure water heaters. \end{enumerate}

In Table 3 the ranges of decision variables for CCPP without and with a CO_2 separation and compression unit are shown.

Optimization using the genetic algorithm was conducted with the following constraints:

- The temperature of the flue gas from HRSG (t_{5a}) higher than the limit temperature for which there is a possibility of low-temperature corrosion (t_{gr} = 80°C)

- The steam quality at the outlet of the steam turbine (X_{4s}) above the limit value for which there is a risk of turbine blade erosion (X_{gr} = 0.88)

5. The genetic algorithm

The solution of equation (7) is one of the issues in the area of the functions optimization of the several decision variables (for 1P—4 variables, for 2PR—10 variables, for 3PR—14 variables). The calculations of the genetic algorithm built in VBA environment (Visual Basic) in Microsoft Office Excel were carried out. A genetic algorithm with the commercial program GateCycle^{TM} ver. 5.40.0.r was integrated.

Genetic algorithms are random optimization methods. They are based on rules of heredity and evolution. In multidimensional tasks, genetic algorithms are characterized by high efficiency. The main operators in algorithm optimization are: selection, crossing and mutation. The detailed operating rules of genetic algorithms are presented in the literature [15–17]. In Fig. 5 a block diagram of the genetic algorithm is shown.

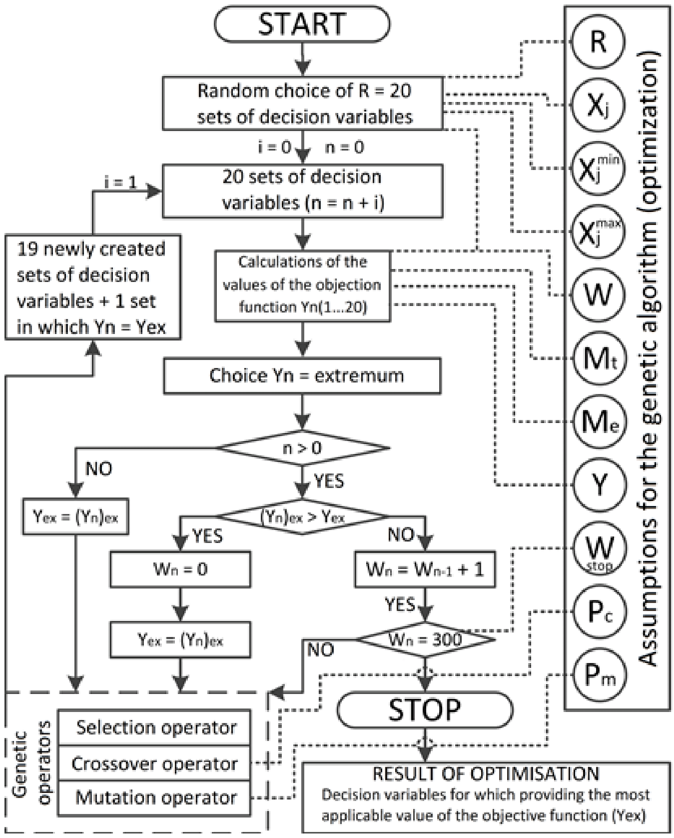

Figure 5: Block diagram of the genetic algorithm

In the genetic algorithm optimization the following operators were used:

- Elitism for the best individual in the population;

- Probability of mutation of 0.02;

- Probability of uniform crossover of two progeny of 0.25;

- The first population is selected by drawing lots.

The work process of the genetic algorithm starts by sampling a population selection of 20 individuals. Any given member (individual) is a set of 13 decision variables, of which the values lie within the ranges specified in Table 3. Individuals whose decision variables did not fall within the ranges were automatically eliminated from the optimization process. The objective function to each individual in the population is assigned. An individual featuring the extreme of the objective function is selected and moved to the next population on the road of elitism.

Table 3: The ranges of values of decision variables

Decision variables			1P / 1P z CCS min	1P / 1P z CCS max	2PR / 2PR z CCS min	2PR / 2PR z CCS max	3PR / 3PR z CCS min	3PR / 3PR z CCS max
1		ΔT_{he}, K	-	-	5	20	5	20
2		ΔT_{ap}, K	5	20	5	20	5	20
3	h	ΔT_{pp}, K	5	20	5	20	5	20
4		t_{3s}, °C	500	560	500	560	500	560
5		p_{3s}, MPa	2	17.5	10	17.5	15	17.5
1		ΔT_{ap}, K	-	-	5	20	5	20
2		ΔT_{pp}, K	-	-	5	20	5	20
3	i	ΔT_{he}, K	-	-	5	20	5	20
4		t_{3s}, MPa	-	-	0.287	5	1	5
5		p_{3s}, °C	-	-	300	560	500	560
1		ΔT_{pp}, K	-	-	-	-	5	20
2	1	ΔT_{he}, K	-	-	-	-	50	100
3		p_{3s}, MPa	-	-	-	-	0.1	1
1	D	ΔT_{ap}, K	-	-	-	-	10	50

Genetic operators create 19 new sets of variables (individuals). On each occasion, after creating a new population, the value of the objective function for all elements of the population was determined. An individual with a less preferred extreme is replaced by an individual with the best extreme of the population.

6. The results of the optimization

The optimal values of decision variables for which the objective function reached the most favorable extremes for all 6 systems were generated by the genetic algorithm. Table 4 presents the optimal values of the decision variables for all the studied systems. Fig. 6 shows the result of the optimization algorithm in the search of the objective function.

Table 5 compares power and efficiency of the optimized units. The net efficiency of the combined cycle power plants (in Table 5) from equation (4) is determined. Additionally, Table 5 shows the decrease in power and efficiency caused by the use of steam bleed in a steam turbine for the integration of the unit with the CCS unit.

A sensitivity analysis was performed to illustrate the impact of each decision variable on the gross power of the steam turbine. Fig. 7 shows the results for a triple-pressure combined cycle power plant with the steam reheater integrated with CCS. Fig. 8 shows the results for a double-pressure combined cycle power plant with the steam reheater integrated with CCS.

In the course of investigations each decision variable was subsequently varied within the range of relative values ($\frac{\Delta x_i}{x_{iopt}} = \frac{x_i - x_{iopt}}{x_{iopt}}$, where x_i—deviation from optimal value, x_{iopt}—optimal value of decision variable) from -0.2 to 0.2, the other quantities remaining unchanged at the optimal level.

The impact of the energy consumption of the sorbent in the CO_2 separation unit on the decrease in efficiency of the optimized units is determined as part of the analysis. Fig. 9 shows the results of the calculation.

7. Conclusion

Integration of the combined cycle power plants with a CO_2 separation and compression unit by using steam bleeding in a steam turbine causes a decrease in the gross power of the steam turbine and a decrease in the efficiency of the whole unit. The power

Table 4: Optimal values of the decision variables

Decision variables			1P	1P z CCS	2PR	2PR z CCS	3PR	3PR z CCS
1		ΔT_{he}, K	-	-	5	5	5	5
2		ΔT_{ap}, K	5	5	5	5	5	5
3	h	ΔT_{pp}, K	5	5	5	5	5	5
4		t_{3s}, °C	560	560	560	560	560	560
5		p_{3s}, MPa	6.212	6.212	17.500	17.500	17.500	17.500
1		ΔT_{ap}, K	-	-	5	5	5	5
2		ΔT_{pp}, K	-	-	5	5	5	5
3	i	ΔT_{he}, K	-	-	5	5	5	5
4		t_{3s}, °C	-	-	560	311.2	560	560
5		p_{3s}, MPa	-	-	1.792	1.000	3.740	4.250
1		ΔT_{pp}, K	-	-	-	-	5	5
2	1	ΔT_{he}, K	-	-	-	-	100	100
3		p_{3s}, MPa	-	-	-	-	0.345	0.345
1	D	ΔT_{ap}, K	-	-	-	-	25	25

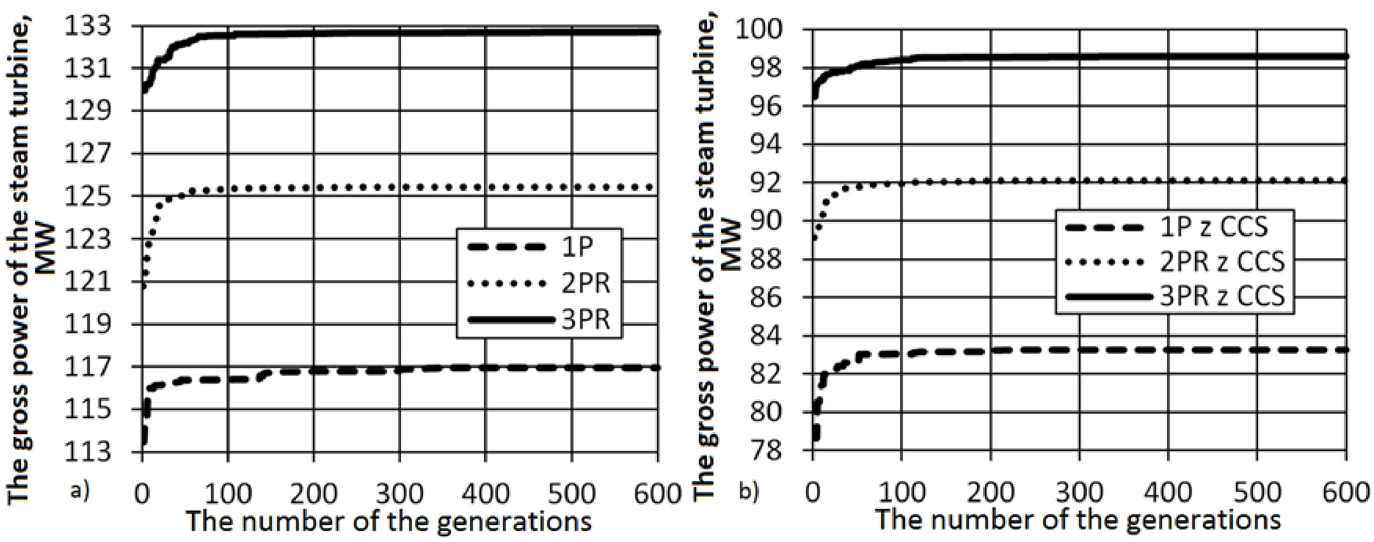

Figure 6: Extreme objective function values generated by the genetic algorithm for: a) CCPP without CCS, b) CCPP with CCP

Table 5: Power and efficiency of the optimized combined cycle power plants

Structure of the CCPP	Gross power of the steam turbine $N_{b.TP}$ MW	Net efficiency of the unit $\eta_{n.G-P}$ %
Single—pressure CCPP without CCS	116.92	55.02
Single—pressure CCPP with CCS	83.26	48.40
△(Difference)	33.66	6.62
Double—pressure CCPP without CCS	125.43	56.26
Double—pressure CCPP with CCS	92.11	49.67
△(Difference)	33.32	6.59
Triple—pressure CCPP without CCS	132.72	57.32
Triple—pressure CCPP with CCS	98.62	50.62
△(Difference)	34.10	6.70

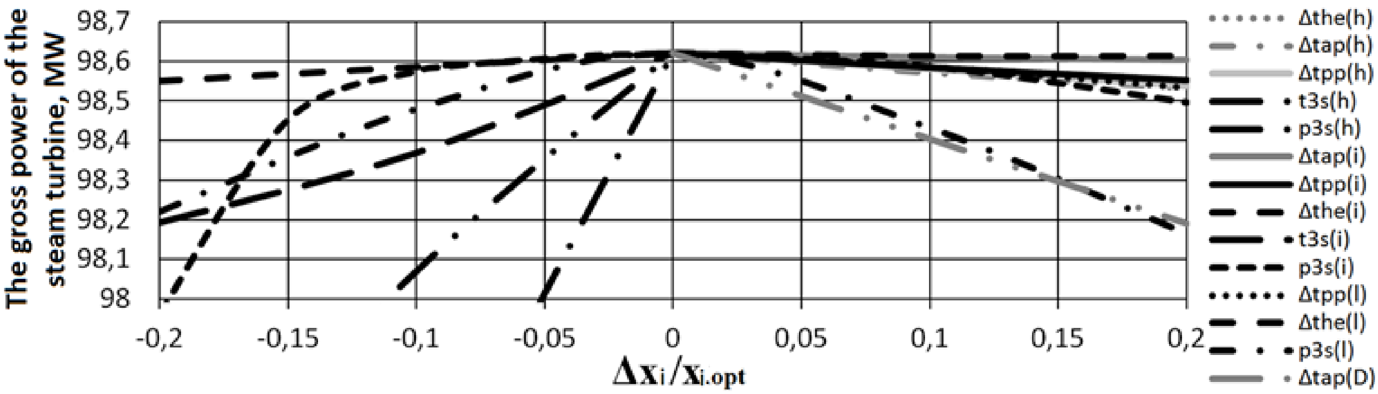

Figure 7: Sensitivity analysis for a triple-pressure combined cycle power plant with the steam reheater integrated with CCS

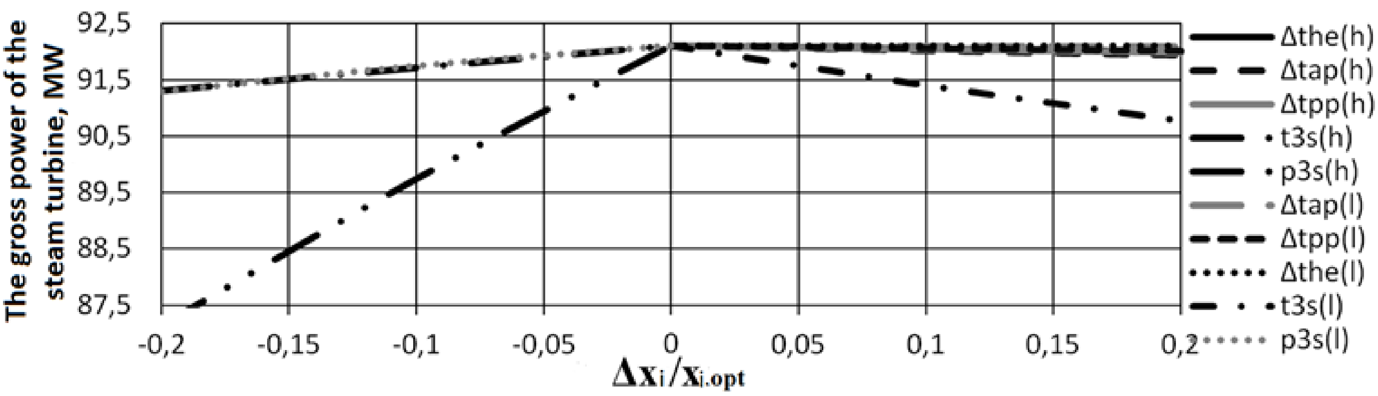

Figure 8: Sensitivity analysis for a double-pressure combined cycle power plant with the steam reheater integrated with CCS

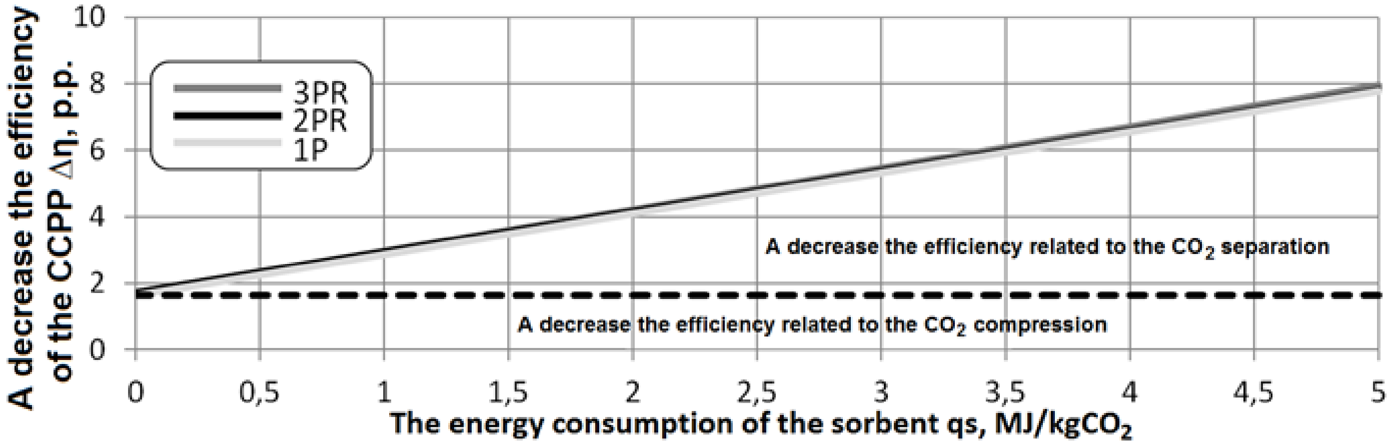

Figure 9: The decrease in efficiency of the units as a function of sorbent energy consumption

degradation resulting from the integration of a CO_2 separation and compression unit is 33.3 ÷ 34.1 MW, which corresponds to a decrease in the net efficiency of the units of 6.6 ÷ 6.7 percentage points.

The temperature differences and water subcooling have little effect on the gross power of the steam turbine in a sensitivity analysis for units 2PR and 3PR in the variant with steam bleeding in the steam turbine. The steam pressures and temperatures at the inlet to the steam turbine show the greatest impact in a sensitivity analysis.

The decrease in efficiency of the units as a function of sorbent energy consumption is shown in Fig. 9 . The use of less energy consuming chemical sorbents in the future will reduce the loss in efficiency of the CCPP integrated with the CCS unit.

Genetic algorithms can be used to optimize multi-variable design parameters of the CCS unit and the power units. The genetic algorithm handled 14 decision variables for the analyzed plant. As one of the random optimization methods, this method is characterized by high effectiveness. However, there is no 100% certainty that the achieved objective function extreme is the extreme global.

References

[1] J. Kotowicz, Elektrownie gazowo – parowe, KAPRINT, Lublin, 2008.

[2] J. Kotowicz, S. Lepszy, Wpływ temperatury otoczenia i strumieni ciepła grzewczego na charakterystyki termodynamiczne elektrociepłowni gazowo-parowej, Inżynieria Chemiczna i Procesowa 26 (2005) 907–922.

[3] L. Remiorz, M. Brzeczek, Wpływ instalacji ccs na sprawnosc układow gazowo-parowych, Rynek Energii 106 (3) (2013) 81–86.

[4] J. Kotowicz, A. Skorek Osikowska, K. Janusz Szymańska, Membrane separation of carbon dioxide in the integrated gasificaion combined cycle systems, Archives of Thermodynamics 31 (2010) 145–164.

[5] J. Kotowicz, L. Bartela, Optimisation of the connection of membrane ccs installation with a supercritical coal-fired power plant, Energy 38 (2012) 118–127.

[6] J. Kotowicz, A. Skorek Osikowska, . Bartela, Economic and environmental evaluation of selected advanced power generation technologies, Proceedings of the Institute of Mechanical Engineers, Part A: Journal of Power and Energy 225 (3) (2011) 221–232.

[7] J. Chmielniak, T., J. Kotowicz, J. Łyczko, Parametric analysis of a dual fuel parallel coupled combined cycle, Energy 26 (12) (2001) 1063–10–74.

[8] J. Milewski, M. Wołowicz, K. Badyda, Z. Iwanski, Analiza zastosowania zrzutu spalin z turbiny gazowej do układu regeneracji siłowni parowej, Rynek Energii 94 (3) (2011) 26–32.

[9] K. Badyda, Charakterystyki złożonych układów z turbinami gazowymi, Rynek Energii 88 (3) (2010) 80–86.

[10] J. Kotowicz, M. Job, Optymalizacja parametrów części parowej układu gazowo-parowego ze spalaniem tlenowym i instalacją wychwytu co2, Rynek Energii 91 (6) (2013) 51–55.

[11] T. Chmielniak, K. Wójcik, Wychwyt i transport co2 ze spalin – efekty energetyczne i analiza ekonomiczna, Rynek Energii 91 (6) (2010) 51–55.

[12] J. Kotowicz, K. Janusz, Sposoby redukcji emisji co2 z procesów energetycznych, Rynek Energii (1) (2007) 10–18.

[13] J. Kotowicz, K. Janusz Szymańska, Influence of membrane co2 separation on the operating characteristics of a coal-fired power plant., Chemical and Process Engineering - Inżynieria Chemiczna i Procesowa 31 (4) (2010) 681–698.

[14] J. Kotowicz, K. Janusz-Szymańska, Wpływ systemu separacji co2 na efektywność elektrowni węglowej na parametry nadkrytyczne, Rynek Energii 93 (2) (2011) 8–12.

[15] J. Kotowicz, L. Bartela, The influence of the legal and economical environment and the profile of activities on the optimal design features of a natural-gas-fired combined heat and power plant, Energy 36 (1) (2011) 328–338.

[16] J. Kotowicz, . Bartela, Optymalizacja termodynamiczna i ekonomiczna elektrowni gazowo - parowej z wykorzystaniem algorytmów genetycznych, Rynek Energii 69 (2) (2007) 1–8.

[17] M. Z., Algorytmy genetyczne + struktury danych = programy ewolucyjne, Wydawnictwa Naukowo - Techniczne, Warszawa, 1996.