Thermodynamic and economic analysis of a gas turbine combined cycle plant with oxy-combustion

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Abstract   This paper presents a gas turbine combined cycle plant with oxy-combustion and carbon dioxide capture. A gas turbine part of the unit with the operating parameters is presented. The methodology and results of optimization by the means of a genetic algorithm for the steam parts in three variants of the plant are shown. The variants of the plant differ by the heat recovery steam generator (HRSG) construction: the single-pressure HRSG (1P), the double-pressure HRSG with reheating (2PR), and the triple-pressure HRSG with reheating (3PR). For obtained results in all variants an economic evaluation was performed. The break-even prices of electricity were determined and the sensitivity analysis to the most significant economic factors were performed.

Keywords: Gas turbine combined cycle; Oxy-combustion

1   Introduction

Gas turbine combined cycle (CCGT) is a combination of a gas turbine with heat recovery steam generator (HRSG) feeding a steam turbine making it, by mutual cooperation of the cycles, one of the most efficient technologies of electricity generation from fossil fuels. There are various structures of the CCGT units differing in the construction of the HRSG. The most commonly used are the single-, double- or triple-pressure HRSG, in the latter two steam

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reheater can be used. These units belong to fastest developing designs, currently achieving efficiency exceeding 60%. Moreover CCGT units are characterized by fast construction time, relatively low investment costs, high reliability and favorable ecological characteristics. Emission level of nitrogen oxides is $NO_X < 10$ ppm, and with the CCGT plant 60% efficiency emits around 330 $kgCO_2$/MWh, which is about 2.5 times less carbon dioxide (CO_2) emission level in comparison to a coal-fired plants which emit over 800 $kgCO_2$/MWh [1–3].

The energy sector is facing new challenges of reducing the CO_2 emission level. Currently, the carbon capture and storage (CCS) technologies are being developed, allowing for near zero-emission production of electricity from fossil fuels, however, of an expense of the decrease in the efficiency and a significant increase in the construction cost of such plants. One of the CCS technologies is oxy-combustion, based on the combustion of fuel in an oxidant atmosphere with increased proportion of oxygen. By elimination of nitrogen from the combustion process the flue gas consist primarily of carbon dioxide and water vapor, allowing the separation of CO_2 with a relatively low energy cost. The separated carbon dioxide is then prepared for a transport and storage in a supercritical state. Although the separation of carbon dioxide in oxy-combustion systems is accompanied by low energy consumption in relation to other CCS technologies, the process of oxygen separation is associated with a significant electricity demand. At the moment, in oxy-combustion units the use of cryogenic air separation unit (ASU) is considered due to the requirement of a sufficient purity of oxygen and a high performance. In the worldwide available literature there are few publications concerning oxy-combustion technology in CCGT plants, and those are often about the customized units, e.g., [4,5].

2 Structure of the CCGT unit with oxy-combustion

2.1 Gas turbine cycle

The general structure of the analyzed plant is shown in Fig. 1. The unit consists of two separate heat cycles, the gas turbine cycle and the steam cycle, connected by the HRSG. The unit also includes a cryogenic ASU and the installation of conditioning and compression of carbon dioxide.

The gas turbine part consists of a turbine, a combustion chamber and a compressor. The combustion chamber outlet temperature is assumed at $t_{3a} = 1500$ °C and a pressure ratio in the compressor equal $\beta_C = 50$. The
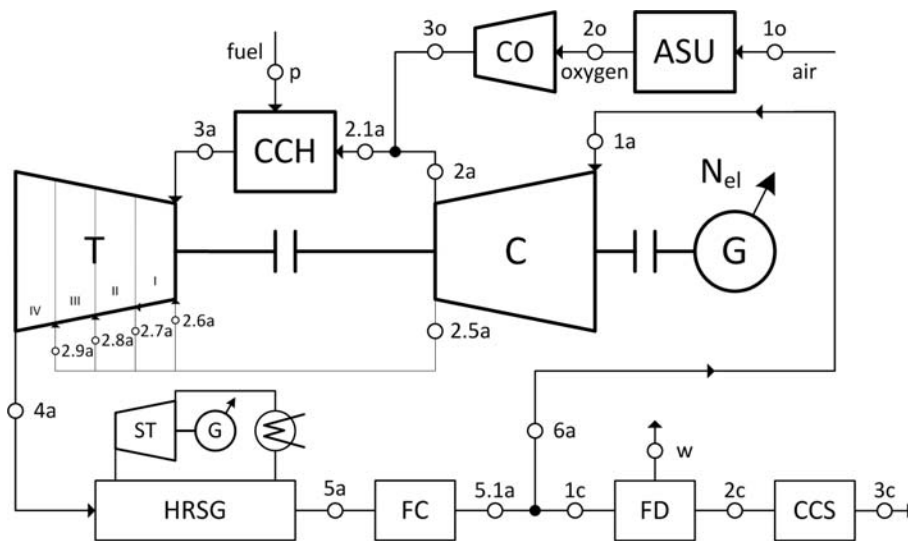
Figure 1. A scheme of the gas turbine combined cycle unit with oxy-combustion: T – gas turbine, C – compressor, CCH – combustion chamber, G – generator, ASU – cryogenic air separation unit, CO – oxidant compressor, HRSG – heat recovery steam generator, ST – steam turbine, FC – flue gas cooler, FD – flue gas dryer, CCS – installation of CO_2 separation.

selection of these parameters was preceded by the analysis in [6]. The recirculated flue gas from behind the cooler (FC) is compressed, mixed with separately compressed oxidant and directed to the combustion chamber. To eliminate the influence of the steam part on the gas turbine working parameters, the recirculated flue gas temperature is maintained at a constant level by FC, chosen so as to avoid condensation of water vapor in the flue gas ($t_{5.1a} = 90$ ºC). The oxidant provided by the ASU consists of 99.5% O_2 and 0.5% N_2. Streams of oxidant and recirculated flue gas are determined by the assumption of constant oxide content in the combustion chamber outlet flue gas at a rate of 2%. Not recirculated flue gas stream is firstly cooled in the FD to the temperature of $t_{2c} = 20$ ºC for drying and subsequently compressed in the CCS to the pressure of 15 MPa and transported to the place of storage.

The combustion chamber is fed with natural gas with the volumetric composition: 98.21% CH_4, 1.27% N_2, 0.52% CO_2 and lower heating value of LHV = 50.18 MJ/kg. The flue gas behind the CCH is expanded in the gas turbine. The gas turbine blades are cooled by the flue gas stream ob-

tained from the compressor outlet. The amount of the flue gas used for the turbine cooling is specified by the rate

$$\gamma_c = \dot{m}_{2.5a}/(\dot{m}_{2.1a} + \dot{m}_{2.5a}) \ , \tag{1}$$

where $\dot{m}_{2.5a}$ and $\dot{m}_{2.1a}$ are the mass flows of the flue gas for the turbine cooling and the flue gas at the combustion chamber inlet, respectively.

The steam cycle is fed by the flue gas in HRSG, in which the live steam is produced and then expanded in condensing steam turbine. The analysis was performed for three units differed by the steam part construction, the unit with: I – single-pressure HRSG (1P), II – double-pressure HRSG with reheater (2PR) and III – triple-pressure HRSG with reheater (3PR). Diagrams of the analyzed units are presented in Section 2.2. For the analysis the models of the gas turbine part and the steam part were made in the Gate-Cycle software [13]. In the analysis the detailed operating parameters of the cryogenic ASU and CCS installation were not considered. Only the unit energy consumption of oxygen production equal to $E_{N(ASU)} = 0.2$ kWh/kgO$_2$, and carbon dioxide compression at the level of $E_{N(CCS)} = 0.1$ kWh/kgCO$_2$ were assigned appropriate values.

Effectiveness of the CCGT unit is evaluated by the electricity production efficiency. Gross electric efficiency is defined by the relationship

$$\eta_{el.gross} = \frac{N_{elGT} + N_{elST}}{\dot{m}_f \, LHV} \ , \tag{2}$$

where N_{elGT}, N_{elST} are the gas turbine and steam turbine electric power, respectively $\dot{m}_f$ is the fuel mass flow, and LHV is the lower heating value of fuel.

Electric efficiency of the gas turbine part (η_{elGT}) and steam part (η_{elST}) are described by equations

$$\eta_{elGT} = \frac{N_{elGT}}{\dot{m}_f \, LHV} \ , \tag{3}$$

$$\eta_{elST} = \frac{N_{elST}}{\dot{Q}_{4a}} \ , \tag{4}$$

where $\dot{Q}_{4a}$ is the heat flow at the HRSG inlet.

With the use of the ratio

$$\alpha = \frac{\dot{Q}_{4a}}{N_{elGT}} \tag{5}$$

Eq. (2) can be transformed into

$$\eta_{el.gross} = \eta_{elGT} \left(1 + \alpha\, \eta_{elST}\right) . \qquad (6)$$

Two additional installations operate within the oxy-combustion plant, i.e., ASU and CCS with own needs equal to:

$$N_{ASU} = \dot{m}_{2o}\, E_{N(ASU)} , \qquad (7)$$

$$N_{CCS} = \dot{m}_{2c}\, E_{N(CCS)} , \qquad (8)$$

where N_{ASU} and N_{CCS} are, respectively, own needs power of ASU and CCS installation, $\dot{m}_{2o}$, $\dot{m}_{2c}$ are the mass flows of oxidant from ASU and compressed CO_2.

The net electric efficiency of the CCGT unit is defined by analogy to (2), including the plant own needs:

$$\eta_{el} = \frac{N_{elGT} + N_{elST} - \Delta N_{el} - N_{ASU} - N_{CCS}}{\dot{m}_f\, LHV} , \qquad (9)$$

wherein the own needs of power plant not including additional installations are assumed equal to $\Delta N_{el} = 2\%$ of the unit's gross power.

Other assumptions for the gas turbine part are as follows:

- gas turbine electric power $N_{elGT} = 200$ MW,

- isentropic efficiency of the gas turbine equals 90%, and of the compressors is 88%, respectively

- mechanical efficiency of the gas turbine, compressors and the generator is equal to 99%,

- combustion chamber heat loss is 1%, compressor inlet pressure loss 0,7% and combustion chamber pressure loss 4.5%,

- carbon capture effectiveness is 98%, i.e., 2% of the CO_2 produced in the combustion process is emitted to the atmosphere.

Characteristic parameters of the gas turbine part obtained from the model are shown in Tab. 1. The HRSG is fed by the flue gas stream equal to $\dot{m}_{4a} = 416.8$ kg/s with a temperature $t_{4a} = 642.2$ °C and volumetric composition: 64.72% H_2O, 32.53% CO_2, 2.00% O_2, 0.75% N_2.

Table 1. Characteristic parameters of the gas turbine part.

Parameter	Value
Gas turbine internal power, N_{iT}	520.6 MW
Compressor internal power, N_{iC}	283.3 MW
Oxidant compressor internal power, N_{iCO}	27.0 MW
Gas turbine electric power, N_{elTG}	200.0 MW
HRSG inlet heat flow, $\dot{Q}_{4a}$	386.0 MW
Ratio of $\dot{Q}_{4a} / N_{elTG}$, α	1.9298
Fuel chemical energy flow, $m_f\,LHV$	568.5 MW
Gas turbine part electric efficiency, $\eta_{el.GT}$	0.3518
Own needs of the ASU, N_{ASU}	32.5 MW
Own needs of the CCS installation, N_{CCS}	11.6 MW

2.2   The steam part optimization

For given operating parameters of the gas turbine part, in accordance with Eq. (9) the efficiency of the CCGT unit depends only on the steam part electric power (N_{elST}) as well as own needs of the plant ΔN_{el}, which are also dependent on N_{elST}. Thus, the optimization of the CCGT unit is reduced to optimization of the steam part only, i.e., finding the $N_{el.ST} = max$. Common assumptions for all analyzed units are as follows:

- condensator operating pressure 5 kPa,
- isentropic efficiency of the steam turbine equals 90%,
- mechanical efficiency of the steam turbine and the generator is 99%,
- efficiency of heat exchangers in HRSG equal to 99%,
- pressure loss: in economizers 1%, in evaporators 4%, in superheaters 3%, high-pressure steam at the inlet of steam turbine 3%, intermediate and low-pressure steam at the inlet of steam turbine 2%.

With the assumptions made, the steam part efficiency (according to the number of pressure levels) is a function of HRSG parameters, i.e., following decision variables [7]:

- pressures of live steam for each pressure level $p_{3s(Y)}$ (Y=h, i, l, R, where: h – high, i – intermediate, l – low pressure level, R – reheated steam),
- temperatures of live steam $t_{3s(Y)}$, or alternatively temperature differences at the hot ends of superheaters $\Delta t_{HE(Y)}$ (Y=h, i, l, R),

- minimum pinch point temperature differences $\Delta t_{PP(Y)}$ (Y=h, i, l),
- subcooling of water at the outlets of economizers $\Delta t_{AP(Y)}$ (Y=h, i, l, D, where D is the deaeration economizer).

According to the above, in the optimization process there are respectively: four decision variables for the single-pressure HRSG, ten decision variables for the double-pressure HRSG with reheating, and fourteen decision variables for the triple-pressure HRSG with reheating. In addition, the searched solution should meet the limiting conditions based on working conditions of machines and devices in the system:

- HRSG outlet flue gas temperature t_{5a} should be not less than the limit $t_{5a} \geq t_{5a\,lim}$, where $t_{5a\,lim} = t_{5.1a} = 90$ °C.
- The steam turbine outlet steam quality, x_{4s}, should be higher than the limit value $x_{4s\,lim} = 0.88$, due to the erosion risk in the steam turbines blading system.

The optimization of the steam parts was performed using a genetic algorithm. It is a probabilistic algorithm based on the fundamental principles of evolution, allowing to achieve high effectiveness for solving multidimensional tasks. The description of the applied optimization algorithm is presented in [6], whereas genetic algorithms are used to solve similar optimization cases, among the others in [8–10]. In order to verify the results obtained by the optimization algorithm the sensitivity analysis was performed for all variables, which where the basis for the final results of optimization.

Structure of the 1P unit with a single-pressure HRSG is presented in Fig. 2. In this unit the live steam is generated in HRSG consisting of an economizer, an evaporator and a superheater. The decision variables and results of optimization for the 1P unit are shown in Tab. 2. In this case the maximum pressure limit is the minimum steam turbine outlet steam quality ($x_{4s} = 0.88$, $t_{5a} = 117.0$ °C). Other parameters have reached the limit values of the investigated ranges.

Figure 3 presents the structure of the 2PR unit, with double-pressure HRSG with reheating. In this unit there can be distinguished a two-section steam turbine with steam reheating and deaerator fed by a low-pressure steam taken from the evaporator. The high-pressure economizer is divided into two sections, hence the temperature difference at the hot end of first section of the economizer, $\Delta t_{HE(h)}$, is the additional decision variable. The decision variables and results of optimization for the 2PR unit are shown in
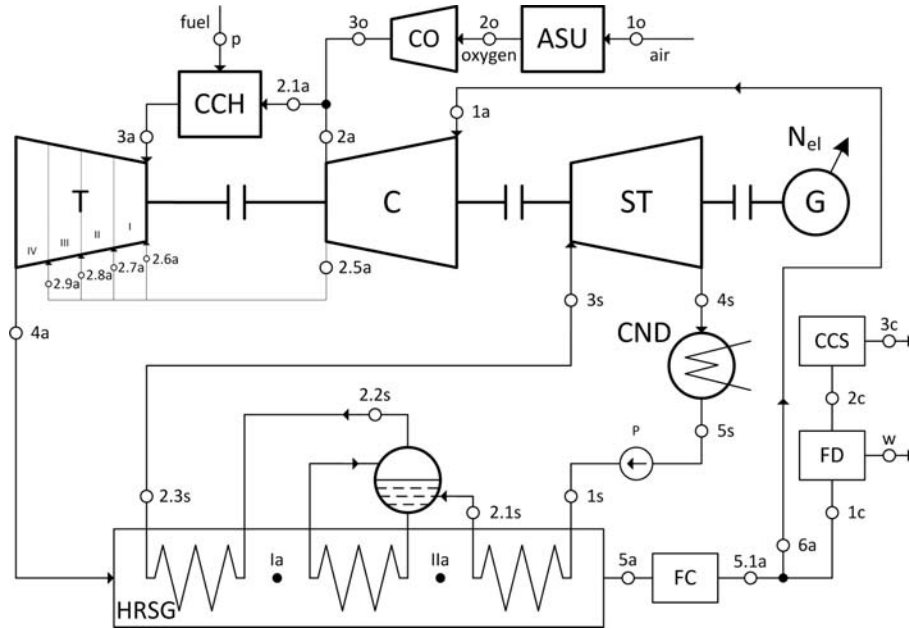
Figure 2. A structure of the CCGT 1P unit with oxy-combustion and single-pressure HRSG (CND - condenser, P – pump).

Table 2. Ranges of decision variables and results of optimization in the 1P unit

Variable	Min	Max	Result
p_{3s}, MPa	2.0	10.0	9.29
t_{3s}, °C	500	600	600.00
Δt_{PP}, °C	5	20	5.00
Δt_{AP}, °C	5	20	5.00

Tab. 3. In this unit all decision variables except live steam low pressure have reached the limit values of the investigated ranges and limiting conditions were not exceeded in the optimization process ($x_{4s} = 0.97$, $t_{5a} = 123.3\,°C$).

Structure of the 3PR unit, with a triple-pressure HRSG with reheating, is presented in Fig. 4. In this unit the three-section steam turbine is working with steam reheating before the intermediate-pressure steam turbine section. The deaerator is fed by an extraction steam from the low-pressure steam turbine section. The deaeration economizer is applied in the HRSG,
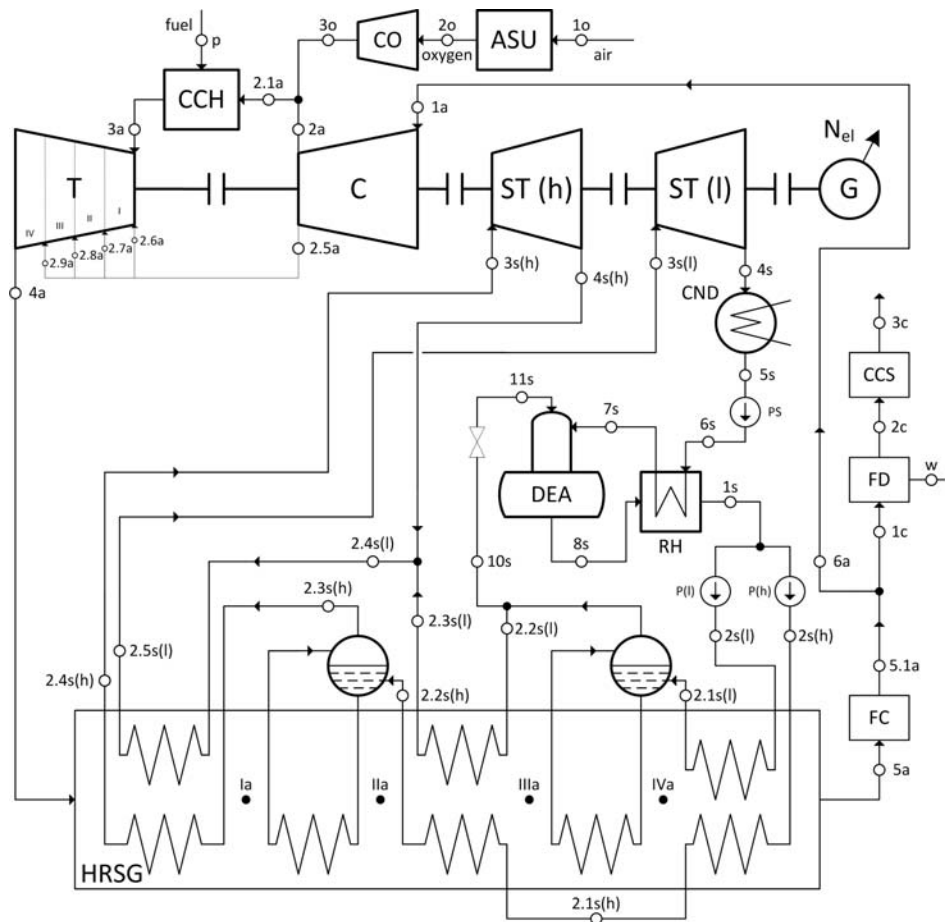
Figure 3. A structure of the CCGT unit with oxy-combustion and double-pressure HRSG with reheating (DEA - deaerator, RH – regenerative heat exchanger, (h) – high-pressure, (l) – low-pressure level).

replacing the low-pressure economizer. The high-pressure economizer is divided into two sections. The decision variables and results of optimization for the 3PR unit are shown in Tab. 4. In analogy to the 2PR unit, during optimization almost all variables have reached the border values, except for $p_{3s(i)}$ and $\Delta t_{PP(l)}$. In this case the HRSG outlet flue gas temperature is the constraint ($x_{4s} = 0.93$, $t_{5a} = 90.1\,^{\circ}\mathrm{C}$). Characteristic parameters of steam part and CCGT unit achieved after optimization process for all analyzed units are presented in Tab. 5.

Table 3. Ranges of decision variables and results of optimization in the 2PR unit.

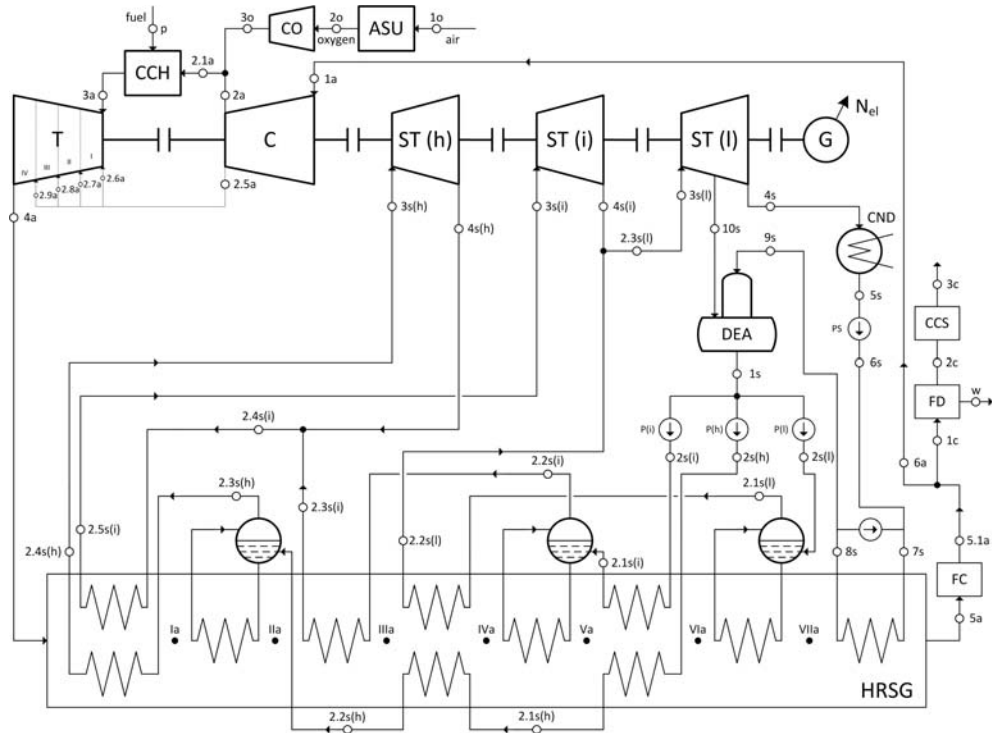| Variable	Min	Max	Result
$p_{3s(h)}$, MPa	10.0	17.5	17.50
$t_{3s(h)}$, °C	500	600	600.00
$\Delta t_{PP(h)}$, °C	5	20	5.00
$\Delta t_{AP(h)}$, °C	5	20	5.00
$\Delta t_{HE(h)}$, °C	5	20	5.00
$p_{3s(l)}$, MPa	1.0	5.0	1.80
$\Delta t_{HE(l)}$, °C	5	20	5.00
$\Delta t_{PP(l)}$, °C	5	20	5.00
$\Delta t_{AP(l)}$, oC	5	20	5.00
$t_{3s(R)}$, oC	500	600	600.00

Figure 4. A structure of the CCGT unit with oxy-combustion and triple-pressure HRSG with reheating: (h) – high-pressure, (i) – intermediate-pressure, (l) – low-pressure level.

Table 4. Ranges of decision variables and results of optimization in the 3PR unit.

Variable	Min	Max	Result	Variable	Min	Max	Result
$p_{3s(h)}$, MPa	10.0	17.5	17.50	$\Delta t_{PP(i)}$, °C	5	20	5.00
$t_{3s(h)}$, °C	500	600	600.00	$\Delta t_{AP(i)}$, °C	5	20	5.00
$\Delta t_{PP(h)}$, °C	5	20	5.00	$t_{3s(R)}$, °C	500	600	600.00
$\Delta t_{AP(h)}$, °C	5	20	5.00	$p_{3s(l)}$, MPa	0.3	1.0	0.30
$\Delta t_{HE(h)}$, °C	5	20	5.00	$\Delta t_{HE(l)}$, °C	50	100	100.00
$p_{3s(i)}$, MPa	1.0	5.0	3.36	$\Delta t_{PP(l)}$, °C	5	20	6.50
$\Delta t_{HE(i)}$, °C	5	20	5.00	$\Delta t_{AP(D)}$, °C	10	50	10.00

Table 5. Characteristic parameters of the 1P, 2PR and 3PR unit.

Parameter	1P	2PR	3PR
$N_{el.TP}$, MW	126.2	133.3	141.0
$\eta_{el.TP}$, −	0.3273	0.3453	0.3654
$N_{el.gross}$, MW	326.2	333.3	341.0
$\eta_{el.gross}$, −	0.5738	0.5862	0.5998
ΔN_{el}, MW	6.5	6.6	6.8
N_{el}, MW	275.6	282.5	290.1
η_{el}, −	0.4848	0.4969	0.5103
e_{CO2}, kg/MWh	7.9	7.7	7.5

3   Economic model

For the economic evaluation of the units the break-even price of electricity was used (C_{el}^{b-e}, PLN/MWh). It is the price of electricity that makes the net present value (NPV) equal to zero, which means the investment at the end of operation brings in no profit or losses

$$NPV = \sum_{t=0}^{t=n} \frac{CF_t}{(1+r)^t} = 0 \; , \tag{10}$$

$$CF_t = \left[S - J - (K + T + K_{wc}) + A + F + L \right]_t \; , \tag{11}$$

where: CF_t – cash flow, r – discount rate, t – consecutive year of investment, n – total number of periods, S – profit from sales, J – total investment costs, K – costs of production including amortization charges and interest, T – income tax, K_{wc} – changes of the working capital (neglected in the

calculations, $K_{wc} = 0$), A – amortization charges, F – interest, L – salvage value.

Break-even price of electricity equation is obtained after transformation of (10) to the form

$$C_{el}^{b-e} = \frac{\sum\limits_{t=0}^{t=n} \frac{[J+(K+T+K_{wc})-A-F-L]_t}{(1+r)^t}}{\sum\limits_{t=0}^{t=n} \frac{\int\limits_{o}^{\tau} N_{el} d\tau}{(1+r)^t}} \; , \tag{12}$$

where N_{el} is the net electric power of the plant. The following C_{el}^{b-e} can be also described as a sum of the components: the investment part C_J^{b-e}, the fuel part C_F^{b-e}, and nonfuel part including all remaining production costs C_{NF}^{b-e}:

$$C_{el}^{b-e} = C_J^{b-e} + C_F^{b-e} + C_{NF}^{b-e} \; , \tag{13}$$

where

$$C_J^{b-e} = \frac{\sum\limits_{t=0}^{t=n} \frac{[J]_t}{(1+r)^t}}{\sum\limits_{t=0}^{t=n} \frac{\int\limits_{o}^{\tau} N_{el} d\tau}{(1+r)^t}} \; , \tag{14}$$

$$C_F^{b-e} = \frac{\sum\limits_{t=0}^{t=n} \frac{[K_F]_t}{(1+r)^t}}{\sum\limits_{t=0}^{t=n} \frac{\int\limits_{o}^{\tau} N_{el} d\tau}{(1+r)^t}} \; , \tag{15}$$

$$C_{NF}^{b-e} = \frac{\sum\limits_{t=0}^{t=n} \frac{[(K+T+K_{wc})-A-F-L-K_F]_t}{(1+r)^t}}{\sum\limits_{t=0}^{t=n} \frac{\int\limits_{o}^{\tau} N_{el} d\tau}{(1+r)^t}} \; , \tag{16}$$

where K_F is the cost of fuel.

Significant for economic evaluation is to determine the investment costs as closely as possible. In preliminary estimates statistical data from the implementation of similar projects are most commonly used. It is more difficult in the evaluation of new technologies as discussed oxy-combustion,

resulting in risk of a significant error in the investment costs estimations. Investment cost was assessed from the relation:

$$J = J_{CCGT} + K_{ASU} + K_{CCS} \ , \tag{17}$$

where the CCGT unit investment cost (J_{CCGT}) was determined using relations described in [7], costs of cryogenic ASU (K_{ASU}) and of CCS installation (K_{CCS}) were estimated based on the data given in [11]. Total investment costs of the plants are presented in Tab. 6.

Table 6. Investment costs of analyzed units.

Parameter	1P	2PR	3PR
J_{g-p}, PLN $\times 10^6$	747.3	820.9	908.9
K_{ASU}, PLN[1] $\times 10^6$	446.2	446.2	446.2
K_{CCS}, PLN[1] $\times 10^6$	101.5	101.5	101.5
J, PLN $\times 10^6$	1295.0	1368.6	1456.6
j_{gross}, PLN/kW$_{gross}$	3970.0	4077.0	4271.0
j_{net}, PLN/kW$_{net}$	4699.0	4810.0	5021.0

[1] Currency USD adjusted to 2012 with CPI index and converged to PLN with average exchange rate for 2012.

The following key assumptions necessary to carry out the economic analysis of the plants, have been made:

- Annual time of operation – 8000 h.

- Time of operation – 20 years.

- Time of constructing the power plant is 3 years, with division of the investment costs for subsequent years – 30%/50%/20%.

- Investment is self-financed in 20% and 80% is obtained from commercial loans.

- Repayment time of the loan is 10 years, with the actual interest of the loan equal to 6%.

- Discount rate amounts to 6.2%.

- Assumed depreciation is 6.67%.

- Rate of income tax is 19%.

- Salvage value of the plant assumed equal to 0.2 × total investment costs.

- Price of fuel calculated according to the price list of PGNiG S.A. for 2013, with the consumed fuel amounts to $C_F = 37.94$ PLN/GJ.

- Maintenance and repair costs assumed with respect to the investment costs at the level: 0.5% for the first 5 years, 1% for the following 5 years, 1.5% for the next 5 years, and 2% for the last 5 years of operation.

- Price of CO_2 emission allowances assumed equal to $C_{EA} = 167.4$ PLN/MgCO$_2$.

4   Results of economic evaluation

To determine the economic viability of investment in oxy-combustion units in relation to other technologies, the economic assessment was performed for two additional, comparative units, analyzed in [13]:

- The CCGT plant with triple-pressure HRSG with reheating, without carbon capture technology (case CCGT).

- The same plant as CCGT, with added the post-combustion carbon capture installation by chemical absorption method using monoethanolamine (MEA) (case ABS).

Parameters of the comparative plants required for the economic evaluation are presented in Tab. 7. In the ABS unit 90% CO_2 capture effectiveness was assumed, and 10% of carbon dioxide produced in fuel combustion process is emitted to the atmosphere. The unit operation cost of the considered installation at the level of 20 PLN/MgCO$_2$, due primarily to the need to supplement the absorbent were also included in the analysis. Break-even prices of electricity with the shares of their components for all compared units are presented in Tab. 8.

Sensitivity analyzes of break-even price of electricity were performed on the variation of the economic factors such as:

- investment costs J in the range of 0.8–1.2 J; results presented in Fig. 5,
- price of fuel C_F in the range 0.8–1.2 C_p; results presented in Fig. 6,
- price of carbon dioxide emission allowances C_{EA} in the range 0–250 PLN/MgCO$_2$; results presented in Fig. 7.

Table 7. Characteristic parameters of the comparative units.

Parameter	CCGT	ABS
$N_{el.gross}$, MW	392.7	358.6
m_f LHV, MW	664.5	664.5
$\eta_{el.gross}$, $-$	0.5910	0.5397
N_{el}, MW	380.9	336.4
η_{el}, $-$	0.5733	0.5062
e_{CO2}, kg/MWh	332.8	37.7
j_{gross}, PLN/kW$_{gross}$	2139	3793

Table 8. Break-even price of electricity — results.

Parameter	1P	2PR	3PR	CCGT	ABS
C_{el}^{b-e}, PLN/MWh	351.2	345.8	341.5	326.7	341.6
C_{J}^{b-e}, PLN/MWh	59.6 (17.0%)	61.0 (17.6%)	63.6 (18.6%)	28.0 (8.6%)	51.3 (15.0%)
C_{F}^{b-e}, PLN/MWh	281.8 (80.2%)	274.9 (79.5%)	267.7 (78.4%)	238.2 (72.9%)	269.8 (79.0%)
C_{NF}^{b-e}, PLN/MWh	9.8 (2.8%)	9.9 (2.9%)	10.2 (3.0%)	60.5 (18.5%)	20.5 (6.0%)

The price of CO_2 emission allowances is particularly important in the assessment of the analyzed units, as EU emissions trading system will be the driving force for the implementation of CCS technology. Therefore, C_{EA} value was determined, for which the plant with oxy-combustion technology becomes economically justified, i.e., the C_{el}^{b-e} value for the oxy-combustion plant is equal to the value for the plant without CCS technology. For the 3PR unit this value is $C_{EA} = 213$ PLN/MgCO$_2$. However, this value does not take into account the costs associated with the infrastructure necessary for the transport and storage of captured carbon dioxide.

5   Conclusion

- The structure and working parameters of the oxy-combustion gas turbine were presented, which despite the high compression ratio equal $\beta_C = 50$ reaches the electric efficiency equal to $\eta_{el.GT} = 35.18\%$, while
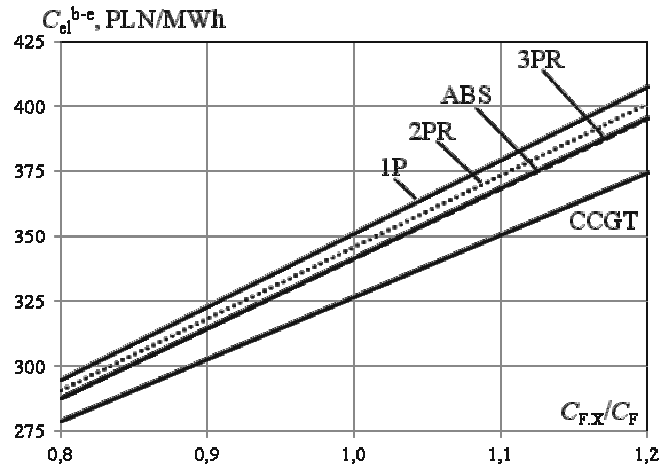
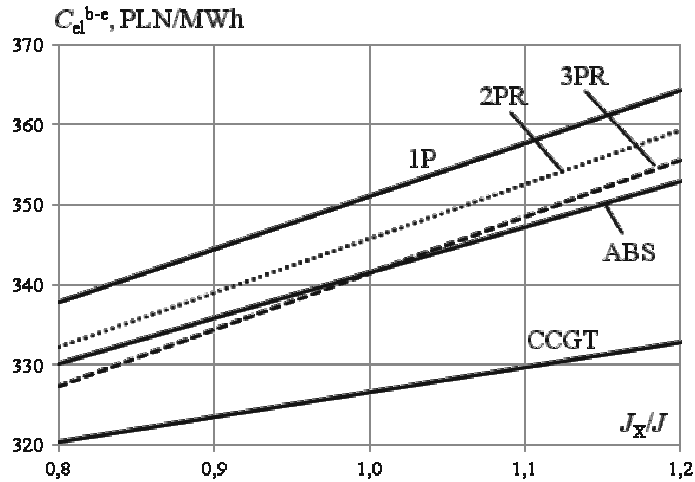Figure 5. Break-even price of electricity C_{el}^{b-e} as a function of fuel price C_F

Figure 6. Break-even price of electricity C_{el}^{b-e} as a function of investment costs J.

the gas turbines with air combustion achieves the efficiency exceeding 40% at lower compression ratios. The oxy-combustion unit is characterized by a large gas turbine outlet heat flow amounting $\dot{Q}_{4a} = 386$ MW, resulting in α ratio equal to $\alpha = (\dot{Q}_{4a}/N_{el.GT}) = 1.93$. The heat flow is feeding the heat recovery steam generator and provides a high electric power in the steam part.
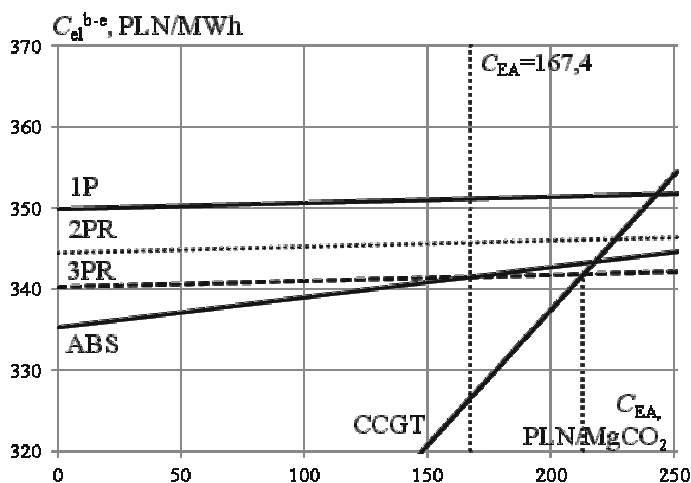
Figure 7. Break-even price of electricity C_{el}^{b-e} as a function of CO_2 emission allowances C_{EA}.

- The thermodynamic optimization by the means of a genetic algorithm for the steam cycles in three variants (1P, 2PR, 3PR) was performed. The limitation of the efficiency growth are minimum temperature differences in heat exchangers, maximum live steam parameters and technical conditions: the HRSG flue gas outlet temperature ($t_{5a\ lim}$) and the steam turbine outlet steam quality ($x_{4s\ lim}$). The obtained unit's gross electric efficiencies (57.38% in 1P, 58.62% in 2PR and 59.98% in 3PR) are comparable with those in currently used units without carbon capture and storage technology, but the high own needs of the cryogenic ASU and of the carbon dioxide compression installation results in the net electric efficiencies lower by 8.9–8.95%, depending on the unit.

- For the analyzed variants of the oxy-combustion plant and for two comparative plants (CCGT and ABS) an economic evaluation was performed by determining the break-even price of electricity (C_{el}^{b-e}). Within the oxy-combustion plants, the 3PR unit achieved the best result (C_{el}^{b-e} = 341.5 PLN/MWh), the 2PR unit achieved result higher by 4.3, and the 1P unit higher by 9.7 PLN/MWh.

- The greatest impact on the break-even price bears the fuel cost (up to 80%), while the investment costs are 17–19% and the remaining part

are nonfuel costs. The results and the cost distribution highlights the importance of CCGT units development to obtain higher efficiency. The higher investment costs in more advanced unit will pay off as the savings in fuel cost and the unit will achieve better ecological characteristics. The huge influence of fuel prices on the break-even price of electricity in comparison to the investment costs shows the sensitivity analysis presented in Figs. 5–6.

- The oxy-combustion units emit minor amounts of carbon dioxide (carbon capture effectiveness 98%) and are almost insensitive to the price of CO_2 emission allowances (C_{EA}). The unit with carbon capture by absorption method (ABS case) has a slight, but higher sensitivity due to the higher CO_2 emissions related to a lower CO_2 capture efficiency (90%). On the other hand, a clear impact of the C_{EA} on C_{el}^{b-e} for CCGT plant without CCS technology can be noted.

- The price of CO_2 emission allowances is particularly important in the assessment of the analyzed units because the EU emissions trading system will be the driving force for the implementation of the CCS technology. Therefore, additionally determined the value of C_{EA}, for which it becomes cost effective, i.e. the C_{el}^{b-e} value for the plant with CCS technology is equal to the plant without this technology. For the 3PR unit the CO_2 emission allowances price is $C_{EA} = 213$ PLN/MgCO$_2$. This price can be simply considered as an information about the cost of CO_2 capture, but it does not include the infrastructure associated with the transport and storage of the captured gas, so the total cost of sequestration would be higher.

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