Open Access Journal

Journal of Power Technologies 93 (5) (2013) 314–321

journal homepage:papers.itc.pw.edu.pl

The impact of CO_2 capture and compression on the economic characteristics of a combined cycle power plant

Janusz Kotowicz, Mateusz Brzęczek*

Silesian University of Technology, Institute of Power Engineering and Turbomachinery, Konarskiego 18, 44-100 Gliwice, Poland

Abstract

This paper presents the results of an economic analysis of a triple-pressure combined cycle power plant with a steam reheater (3PR). The economic analysis was performed for two variants of the power plant - with and without integration of the system with a CO_2 capture and compression installation. The structures of the triple-pressure combined cycle power plant with the steam reheater and CO_2 capture and compression installation (CCS) are presented. The characteristic values of systems and the economic assumptions are summarized. An analysis was performed of the break-even point (BEP), i.e., the minimum selling price for electricity. Sensitivity analyses were performed for individual components of the break-even price of electricity and the impact of degradation of the efficiency and the power characteristics of the combined cycle power plant.

Keywords: combined cycle power plant, economic optimization, CO_2 capture and compression, carbon capture

1. Introduction

One of the most effective power technologies based on fossil fuels are combined cycle power plants (CCPP), consisting of a gas turbine and a heat recovery steam generator. The development of gas turbines and the steam cycle drove the development of CCPP, which has now reached net electrical efficiencies of over 60% [1, 2].

CCPP demand relatively low levels of investment. However, a major obstacle in adaptation of CCPP in Poland is the high price of gaseous fuel. New challenges for the Polish energy sector from the EU relating to cutting CO_2 emissions can solve this problem. A combined cycle power plant has CO_2 emissions of 330 kg_{CO_2}/MWh at net efficiency of about 60%. Coal-fired power plants with efficiency of 45% have an emission rate of about 860 kg_{CO_2}/MWh [3–5].

*Corresponding author

To help achieve the CO_2 emissions objectives set by the EU for the Polish energy sector, a CO_2 capture system(s) must be used (CCS—Carbon Capture and Storage). Installing a CO_2 capture and compression system is associated with a significant drop in net efficiency and an increase in investment expenditures [6, 7]. The impact of installing a CO_2 capture and compression system on the economic characteristics of the CCPP is presented in this paper.

2. Combined cycle power plant with a CO_2 capture and compression installation

An economic analysis was made for the three-pressure combined cycle, equipped with a class G gas turbine with 260 MW of net electrical power. The unit was analyzed in two versions: with and without integration with a CO_2 capture and compression installation. In order to integrate the combined

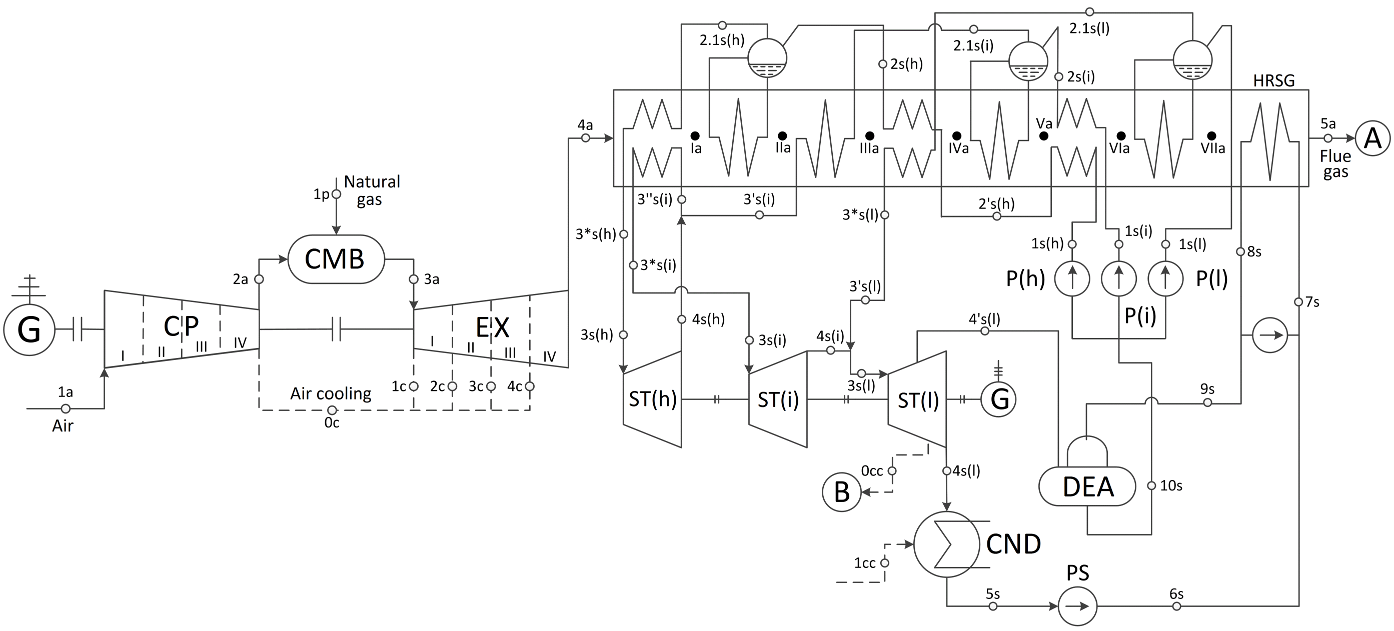

Figure 1: Schematic structure of the three-pressure combined cycle power plant with steam reheating (G—generator, CP—air compressor, EX—expander, CMB—combustor, HRSG—heat recovery steam generator, CND—condenser, DEA—deaerator, SP—steam turbine (h—high-pressure part, i—intermediate-pressure part, l—low-pressure part), P—pump, PS—condensate pump, A—the exhaust gas stream directed to CCS, B—the steam flow directed to CCS) Table 1. The characteristic values of the CCPP with and without CCS

cycle with the CO_2 capture installation a steam bleed into the low-pressure steam turbine was introduced. A schematic of the three-pressure combined cycle is presented in Fig. 1. The characteristic values of the power unit are summarized in Table 1.

The process of CO_2 capture from the flue gases takes place in the absorber—stripper installation, shown in Fig. 3. Absorption based on chemical sorbents is at present the optimal method of CO_2 capture from flue gas in post-combustion technology [8, 9]. The sorbent used in the CO_2 capture installation here is a 30% solution of monoethanolamine (MEA). The energy consumption of the sorbent was set at 4 MJ/kg_{CO_2}. The degree of recovery of CO_2 from flue gas is 90%. The rate of energy consumption of the CO_2 compression installation is 0.1 kWh/kg_{CO_2} which is equivalent to 360 kWh/kg_{CO_2}. The use of steam bleeding in a steam turbine to regenerate the sorbent causes a drop in the net power of the steam turbine and therefore, a drop of 44.55 MW in the net power of the power unit, which corresponds to a 6.7% drop in net efficiency.

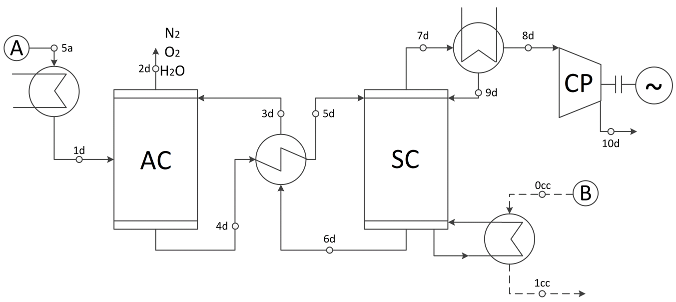

Figure 2: The system of CO_2 separation and preparation for transport (AT—-absorber column, DT—-stripper column, CP—-CO_2 compressor, A—the exhaust gas stream directed to CCS, B—the steam flow directed to CCS)

3. The assumptions for the economic analysis

Table 2 presents the detailed assumptions for the economic analysis of the analyzed unit. It also summarizes the parameters concerning the operating costs and the capital expenditures of the unit. The economic analysis was performed using an algorithm created in Microsoft Excel(R). Thermodynamic optimization of the analyzed CCPP is shown in the literature [10].

Table 2: Detailed economic assumptions

Parameter	without CCS	with CCS
Share of internally-funded investments/commercial credit, %		20/80
Actual annual interest rate on commercial credit, %		6
Repayment period of commercial credit, years		10
Construction period, years		20
Operational life of the plant, years		30/50/20
Share of capital costs for the consecutive years of construction, %		6.2
Discount rate, %		6.67
Average rate of depreciation, %		19
Rate of income tax, %		20
Salvage value, %		4.185
Polish zloty/Euro exchange rate, PLN/EUR, [11]		3.257
Polish zloty/Dollar exchange rate, PLN/USD, [11]		0.5/1.0/1.5/2.0
Repair costs (as % of investment expenditures) in the consecutive years of plant operation, %		0.2
Unit employment rate, person/MW_b		5000
Unit monthly costs of employment (with charges), PLN/person/month		8000
Operating time of the power plant per year, h/a		1.3808(1)/37.9609(2)
Unit price of fuel, PLN/m^3_n(1), PLN/GJ(2), [12]		28.7
Unit cost of operation of the power plant, PLN/MWh_n	0	20
Unit operating costs of CCS, PLN/Mg_{CO_2}	257.90	417.66
Total investment costs, USD millions	656.7(3)	1164.6(3)
Unit investment costs, USD/kW_h(3), USD/kW_n(4)	677.0(4)	1241.6(4)

Table 1: The characteristic values of the CCPP with and without CCS

Parameter	Value	
	without CCS	with CCS
Gross electrical power, MW	392.72	358.62
Net electrical power, MW	380.94	336.39
Net electrical efficiency, %	57.32	50.62
Rate of auxiliary power demand, %	3.00	
Power demand of CO_2 compression, MW	11.47	
Chemical energy of fuel, MW	664.50	
Unit CO_2 emission, kg/MWh_h	325.61	35.66

4. The economic analysis

The economic analysis presented in this paper is a break-even point analysis, which is widely used in commercial planning. In this case, the BEP is the minimum selling price of the generated electricity. The selling price was changed up to the point at which the net present value (NPV) was equal to zero. According to the definition of NPV, it depends on the discount rate (r) and the annual net cash flow (CF_t). Cash flows are calculated for the consecutive years of plant operation (t) and then discounted. The discounted cash flows of each year are summed together, using the formula:

$$NPV = \sum_{t=0}^{t=n} \frac{CF_t}{(1+r)^t} \quad (1)$$

Cash flows (CF_t) depends on the salvage value occurring in the last year of operation of the unit (L), depreciation (A), working capital (K_{obr}), income tax (P_d), operating costs (K_{op}), income from sales of electricity (S), unit investment costs and construction of the power unit (J_{BE}), as follows:

$$CF_1 = \left[-J_{BE} + S - (K_{op} + P_d + K_{obr}) + A + L\right]_t \quad (2)$$

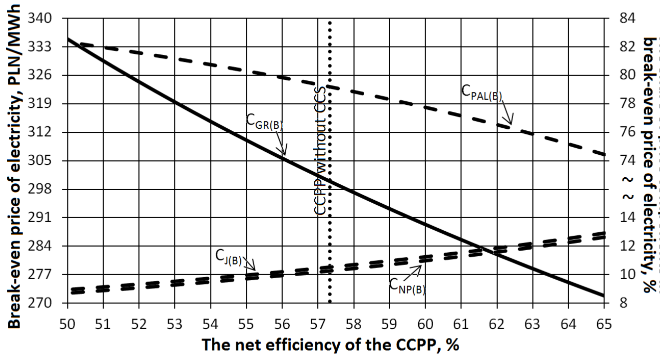

Figure 3: Break-even price of electricity as a function of net efficiency of the CCPP (3PR) without CCS ($C_{GR(B)}$—break-even price of electricity for a unit without CCS, $C_{PAL(B)}$—the fuel component for a unit without CCS, $C_{NP(B)}$—the non-fuel component for a unit with CCS, $C_{J(B)}$—the investment component for a unit without CCS)

The break-even price of electricity for the CCPP without CO_2 capture and compression is 300 PLN/MWh. For the CCPP integrated with the CO_2 separation and compression installation, the break-even price of electricity is 364.40 PLN/MWh. The remainder of this article presents the influence of individual quantities on the break-even price of electricity. The break-even price of electricity is made up of three components: the non-fuel component (c_{NP}^{gr}), the investment component (c_J^{gr}) and fuel component (c_{PAL}^{gr}). The components are defined by the formulae:

$$c_{NP}^{gr} = \frac{\sum_{t=0}^{t=n} \frac{[K_{NP}]_t}{(1+r)^t}}{\sum_{t=1}^{t=N} \frac{E_{el,N}}{(1+r)^t}} \quad c_J^{gr} = \frac{\sum_{t=0}^{t=n} \frac{[J_{BE}]_t}{(1+r)^t}}{\sum_{t=1}^{t=N} \frac{E_{el,N}}{(1+r)^t}} \quad (3)$$

$$c_{PAL}^{gr} = \frac{\sum_{t=0}^{t=n} \frac{[K_P]_t}{(1+r)^t}}{\sum_{t=1}^{t=N} \frac{E_{el,N}}{(1+r)^t}}$$

Fig. 3 shows the effect of the net efficiency of the CCPP (3PR) without a CO_2 capture and separation installation on the break-even price. The function of the break-even price of electricity ($C_{GR(B)}$) is marked with a solid line and is related with the left vertical axis of the graph. Shown in dashed lines are the individual components that comprise the break-even price of electricity and they refer to the right axis on the graph. Shown with the dotted line is the efficiency of the unit subject to economic analysis. As the net electrical efficiency of the plant in-

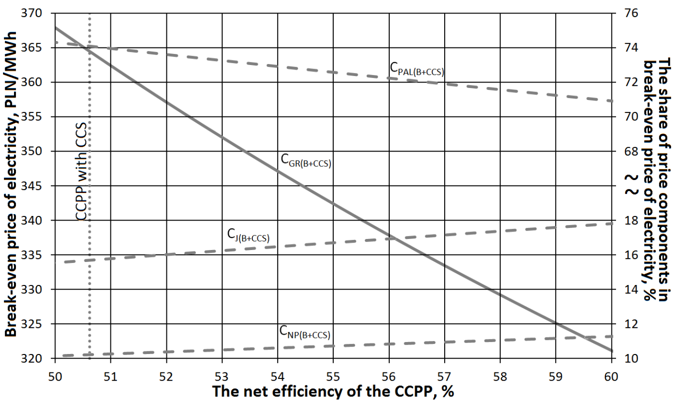

Figure 4: Break-even price of electricity as a function of net efficiency of the CCPP (3PR) integrated with the CCS installation ($C_{GR(B+CCS)}$—break-even price of electricity for a unit with CCS, $C_{PAL(B+CCS)}$—the fuel component for the unit with CCS, $C_{NP(B+CCS)}$—the non-fuel component for the unit with CCS, $C_{J(B+CCS)}$—the investment component for the unit with CCS)

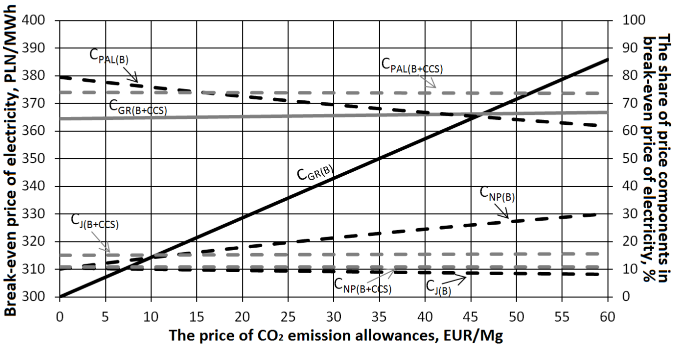

Figure 5: Break-even price of electricity as a function of prices of CO_2 emission allowances for the combined cycle power plant (3PR) with and without CCS

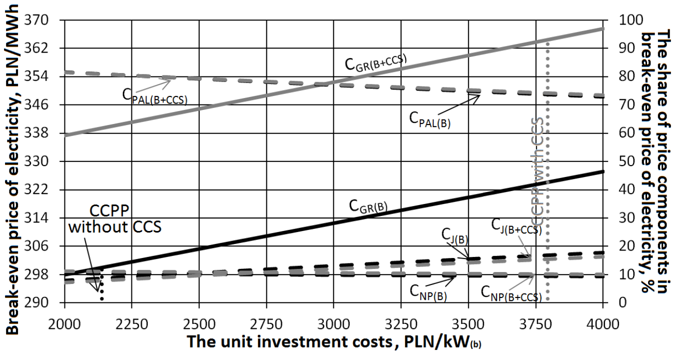

Figure 6: Break-even price of electricity as a function of unit investment cost of the CCPP (3PR) with and without CCS

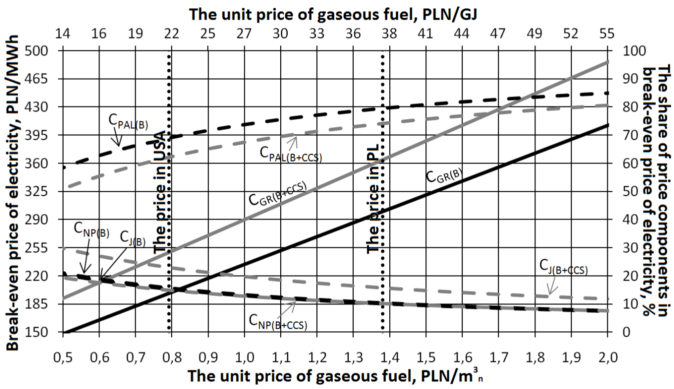

Figure 7: Break-even price of electricity as a function of unit price of gaseous fuel for the CCPP (3PR) with and without CCS

creases, the break-even price of electricity falls: by 4.60 PLN/MWh per 1 percentage point of net efficiency.

Fig. 4 shows the break-even price of electricity ($C_{GR(B+CCS)}$) as a function of the net efficiency of the combined cycle (3PR) integrated with the CO_2 capture and compression installation. As the net electrical efficiency of the unit increases, the break-even price of electricity falls: by 5.3 PLN/MWh per 1 pp net efficiency.

Fig. 5 shows the course of the break-even price of electricity as a function of prices of CO_2 emission allowances for the CCPP with and without a CO_2 capture and compression installation. Functions marked in black are for a unit without CCS, and functions in gray are for a unit with CCS. As the price of CO_2 emission allowances increases, the break-even price of electricity increases: by 1.4 PLN/MWh per 1 EUR/Mg_{CO_2}. Since this price includes the non-fuel component, a significant increase can be noticed (for the price of CO_2 emission allowances at around 40 EUR/Mg the component is about 25% of the break-even price of electricity).

The break-even price of electricity as a function of the investment cost of the CCPP (3PR) is shown in Fig. 6. As the unit investment cost of units with and without CCS increases, the break-even price of electricity increases: by 4.7 PLN/MWh per 100 $USD/kW_{(gross)}$.

The break-even price of electricity as a function of the unit price of gaseous fuel for the CCPP (3PR) is presented in Fig. 7. For a unit price of gaseous fuel in Poland of 1.38 PLN/m^3_n (37.9 PLN/GJ) [13], the break-even price of electricity is 300 PLN/MWh. In addition, the unit price of gaseous fuel in the USA was determined, which is 0.79 PLN/m^3_n (21.7 PLN/GJ) [12], for which the break-even price

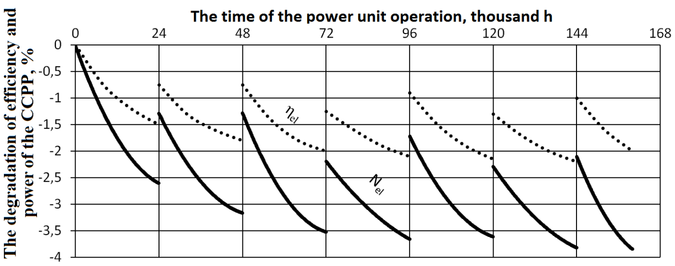

Figure 8: Degradation of efficiency and power characteristics of the CCPP

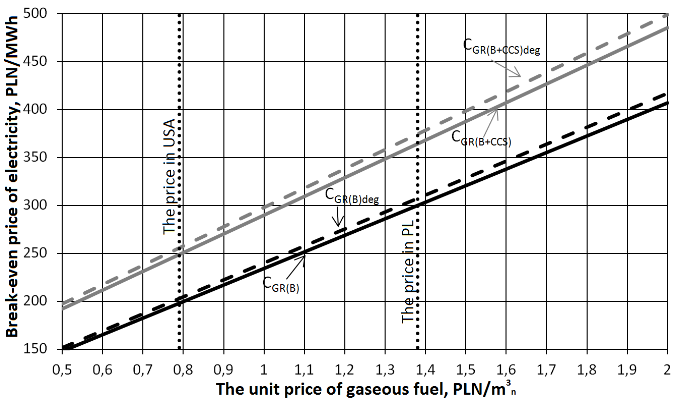

Figure 9: Break-even price of electricity as a function of unit price of gaseous fuel with and without taking into account the characteristics of performance degradation for the CCPP (3PR) with and without CCS

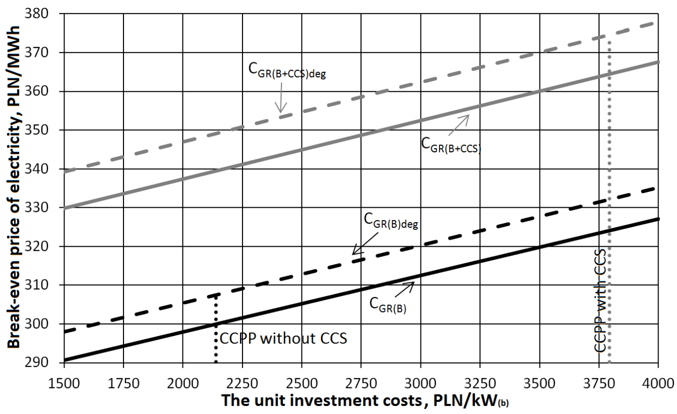

Figure 10: Break-even price of electricity as a function of unit investment cost with and without taking into account the characteristics of performance degradation for the CCPP (3PR) with and without CCS

of electricity is 198.50 PLN/MWh. As the fuel price component increases, the break-even price of electricity increases: by 16.2 PLN/MWh to 0.1 PLN/$m^3{}_n$ (equivalent to 5.1 PLN/MWh per 1 PLN/GJ) for both analyzed variants of the power plant.

The degradation of performance efficiency of the CCPP (dotted line) shown in Fig. 8 was determined on the basis of the literature [3], as the average decrease in net efficiency of the unit in a given year (1 year = 8000 h). The degradation of the power characteristic of the CCPP was determined based on the average performance declines in the year x ($\Delta\eta_{el,x}$), the nominal net efficiency of the unit ($\eta_{el.3PR}$ = 57.32%) and the stream of chemical energy of fuel ($E_{chp} = 664.5\ MJ/s$) in accordance with the formula:

$$N_{el.n} = \left[\left(\Delta\eta_{el.x} + \eta_{el.3PR}\right)/100\right] \cdot E_{chp} \quad (4)$$

The net power of the power unit (3PR) for each year of operation was obtained. These powers were included in the economic calculations.

The break-even price of electricity as a function of the unit price of gaseous fuel for the combined cycle power plant (3PR) was determined with and without taking into account the degradation of the performance and power characteristics of the system (Fig. 9). For the price of gas in Poland at the level of 1.3808 PLN/$m^3{}_n$ (37.9609 PLN/GJ), the break-even price of electricity taking into account the degradation characteristics of the unit without CCS is 307.40 PLN/MWh, while for the unit with CCS it is 374.60 PLN/MWh.

The break-even price of electricity as a function of the unit investment cost of the combined cycle power plant (3PR) was determined without taking into account the degradation of the performance and power characteristics of the system. The character of these functions is shown in Fig. 10. Taking into account the degradation of the characteristics of efficiency and power of the units causes an increase in the break-even price of electricity by 7.2 PLN/MWh for the unit without CCS and 9.0 PLN/MWh for the unit with CCS in relation to the function that does not factor in the degradation of the characteristics.

Fig. 11 shows a break-even price of electricity as a function of net efficiency with and without taking into account the degradation of the performance characteristics of the combined cycle power plant (3PR) with and without CCS. Fig. 12 shows the effect of prices of CO_2 emission allowances for the selected values of net efficiency for the unit with and without CCS on the break-even price of electricity.

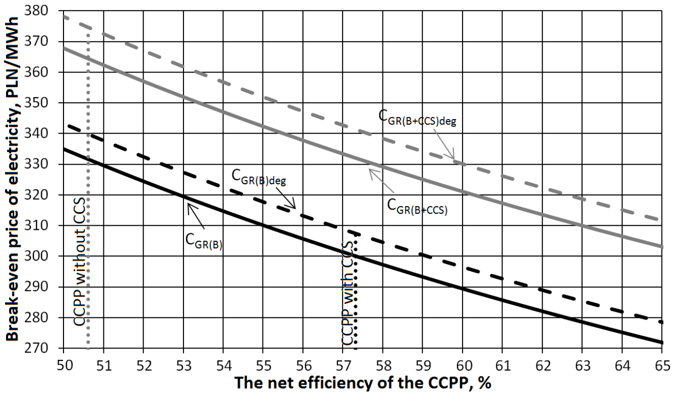

Figure 11: Break-even price of electricity as a function of net efficiency with and without taking into account the characteristics of the performance degradation for the CCPP (3PR) with and without CCS

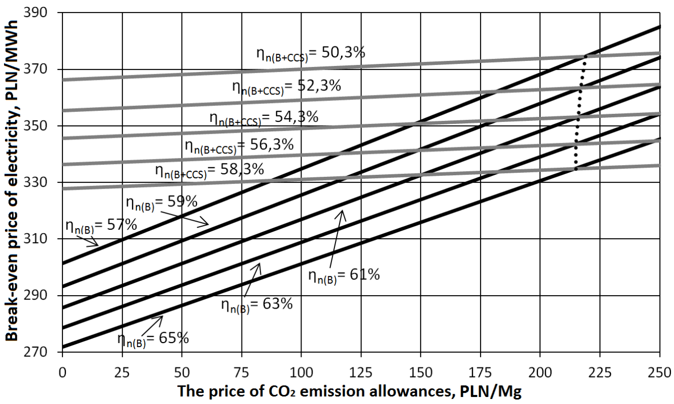

Figure 12: Break-even price of electricity as a function of prices of CO_2 emission allowances for units with and without CCS for selected values of net efficiency of the CCPP

5. Conclusion

Increased net electrical efficiency means a lower break-even price of electricity. For a combined cycle power plant net electrical efficiency is 57.32% and the break-even price of electricity is 300 PLN/MWh. Integration of the unit with a CO_2 capture and compression installation causes a decrease in efficiency of the power plant to 50.62%. At this net efficiency of the unit, value of the break-even price of electricity is increased by 64.40 PLN/MWh. Increasing net electrical efficiency by 1% for the unit without CCS will reduce the break-even price of electricity by 4.60 PLN/MWh (for a unit with CCS: by 5.30 PLN/MWh).

If CO_2 allowances cost 46.30 EUR/Mg the break-even price of electricity of the unit integrated with CCS reaches the same value as in the variant without integration. Higher prices of CO_2 emission allowances result in higher profitability of investment for the unit with CCS. Increasing the price of CO_2 allowances by 1 EUR/MgCO_2 in a unit without CCS increases the break-even price of electricity by 1.40 PLN/MWh (for a unit with CCS: by 0.05 PLN/MWh).

The investment cost is crucial for the break-even point. The increase in the investment expenditures for building a combined cycle power plant increases the break-even price of electricity. The construction of a CO_2 capture and compression installation causes an increase in the break-even price of electricity of 24.40 PLN/MWh. An increase in capital costs of 100 USD/kW$_{(gross)}$ for plants with and without CCS increases the break-even price of electricity by 4.70 PLN/MWh.

A reduction in the price of gaseous fuel can significantly contribute to improving the profitability of investments in combined cycle power plants. A decrease in the price of fuel of 0.1 PLN/m^3_n will cause the break-even price to fall by 16.20 PLN/MWh for both analyzed variants of the power plant (equivalent to 5.10 PLN/MWh per 1 PLN/GJ). For comparison, the same investment in combined cycle power plants for the price of gas in the USA is 101.5 PLN/MWh more profitable than in Poland.

References

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

[2] T.J. Chmielniak, J. Kotowicz, and J. Łyczko. Parametric analysis of a dual fuel parallel coupled combined cycle. *Energy*, 26(12):1063–1074, 2001.

[3] J. Kotowicz. Elektrownie gazowo-parowe, 2008.

[4] L. Remiorz and M. Brzęczek. Wpływ instalacji ccs na sprawność układów gazowo-parowych. *Rynek Energii*, 3(106):81–86, 2013.

[5] Marcin Job, Łukasz Bartela, and Anna Skorek-Osikowska. Analysis of the use of waste heat in the oxy-combustion power plant to replace the steam cycle heat regeneration. *Journal of Power Technologies*, 93(3):133–141, 2013.

[6] J. Kotowicz, A. Skorek-Osikowska, and Ł. Bartela. Economic and environmental evaluation of selected advanced power generation technologies. In *Proceedings of the*

Institution of Mechanical Engineers, Part A: Journal of Power and Energy, volume 225(3), pages 221–232, 2011.

[7] J. Kotowicz and Ł. 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):328–338, 2011.

[8] A. Skorek-Osikowska, J. Kotowicz, and K. Janusz-Szymańska. Comparison of the energy intensity of the selected CO_2-capture methods applied in the ultra-supercritical coal power plants. *Energy & Fuels*, 26(11):6509–6517, 2012.

[9] J. Kotowicz and K. Janusz. Sposoby redukcji emisji CO_2 z procesów energetycznych. *Rynek Energii*, 1:10–18, 2007.

[10] J. Kotowicz and M. Brzęczek. Wpływ instalacji ccs na optymalne parametry układów gazowo - parowych. In *V Konferencja Naukowo - Techniczna Energetyka Gazowa 2013*, Zawiercie, 9-11 października 2013.

[11] Archiwalne kursy walut narodowego banku polskiego. Średnioważone kursy walut obcych w złotych liczone narastająco od stycznia 2012 roku do końca poszczególnych miesięcy. retrieved 30.09.2013.

[12] DOE/NETL 2010/1405 National Energy Technology Laboratory. Advancing oxycombustion technology for bituminous coal power plants: An r&d guide, April 2012.

[13] Taryfy dla paliw gazowych nr 5/2012 z poprawkami obowiązującymi od 1 stycznia 2013 roku. retrieved 30.09.2013.