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Influence of chosen parameters on economic effectiveness of a supercritical combined heat and power plant

J. Kotowicz*, P. Łukowicz

Silesian Univerity of Technology, ul. Konarskiego 18 Gliwice, 44-100, Poland

Abstract

The article presents an economic analysis of a supercritical combined heat and power plant integrated with a carbon dioxide chemical absorption unit. The authors describe first the thermodynamic performance boundaries that result from the integration with a carbon capture unit as a function of its heat and electric power consumption rate. These limits refer to the heat and electric power annual production which is essential in the economic analysis. Secondly, the influence of a set of different parameters on the break-even price of electricity is studied. The main focus for examination is the effect on the break-even price of electricity of: carbon dioxide emission allowance price, fuel price, investment costs, overhaul and other maintenance costs.

Keywords: economic effectiveness, CHP, supercritical power plants

1. Introduction

The CO_2 emission cutting policy of many countries and supra-national associations are posing new challenges for the power sector, as this heavy user of fossil fuels is the biggest CO_2 emitter of all industrial sectors. Out of climate change concerns much research is being directed at Carbon Capture and Storage technology (CCS), to reduce emissions of CO_2 into the atmosphere by power units that utilizing fossil fuels [2, 3]. There are a number of proposed CCS techniques, which can be split into pre- and post-combustion methods and further into chemical absorption, membrane separation and even less conventional such as for example acoustic separation. The most mature post-combustion technology at this time is the chemical absorption method. Due to its availability it was chosen to be integrated with the analyzed plant. The integration requires heat and work input (the work input of the capture unit itself can be ignored in the case of chemical absorption because of its small contribution to the overall power consumption). Heat must be provided to a desorption column for the sorbent regeneration process, whereas work is needed by CO_2 compressors. This new parasite consumption will reduce plant net efficiency and hence lead to higher operating cost. Additionally, investment costs will rise significantly. Therefore it is critical to perform a thermo-economic analysis in order to estimate the possible economic consequences of CCS integration.

2. Structure of analyzed plant

The subject of the thermo-economic analysis presented in this paper is the heating unit of the structure shown in Fig. 1. The system consists of a boiler (K), fired with pulverized coal, which produces live steam. Part of the steam returns from the high-

*Corresponding author

Email address: janusz.kotowicz@polsl.pl (J. Kotowicz*)

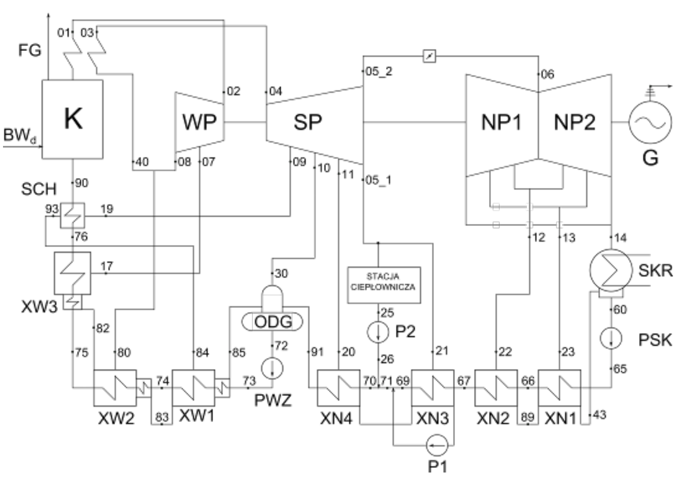

Figure 1: Scheme of the analyzed plant

pressure turbine and is reheated. The steam turbine contains three parts: high-pressure (WP), medium-pressure (SP) and double-flow low-pressure (NP1 and NP2). The high-pressure part of the steam turbine has one regenerative bleed, which guides the bleed steam to a regenerative low-pressure heat exchanger (XW3). At the outlet of the low-pressure part of the turbine, a portion of steam flows into the regenerative low-pressure heat exchanger (XN2), and the rest goes through secondary reheating. After reheating, the steam flows to the medium-pressure part of the turbine, where the first steam extraction goes to the regenerative high-pressure heat exchanger (XW1), passing through the steam cooler (SCH). The steam from the second bleed flows to a deaerator (ODG). The third steam bleed directs steam to the regenerative low-pressure heat exchanger (XN4). At the outlet of the medium-pressure part of the turbine steam flows to the regenerative low-pressure heat exchanger, subsequently to the heating station, and then onto the low-pressure part of the turbine through a crossover pipe. Each part of the low-pressure turbine has two bleeds. The first bleed of the first part is connected with the first bleed of the second part, guiding steam afterwards to the regenerative low-pressure heat exchanger (XN2). Likewise two more bleeds are connected, supplying steam to the regenerative low-pressure heat exchanger (XN1). The outlet steam of the low-pressure parts of turbine flows to a single condenser (SKR).

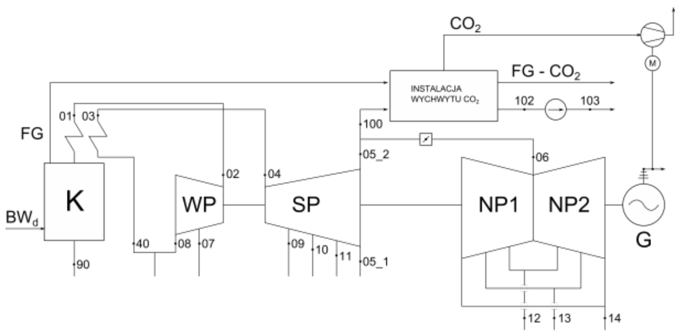

Figure 2: Scheme of carbon capture unit integration

2.1. Integration of power plant with CO_2 capture unit

It was decided that the analyzed thermal power plant would be integrated with a CO_2 capture installation based on chemical absorption. The main parameter that characterizes this type of technology is the energy consumption of the CO_2 capture process, defined as the MJ of heat per unit mass of CO_2. This quantity results mainly from the heat of reaction of the CO_2 sorbent, and the CO_2 capture rate. Detailed analysis of the operation of the CO_2 capture installation would require chemical calculations. Therefore, it was decided that on the basis of literature data, the energy consumption of the sorption process is: 2, 3 and 4 MJ per kg of captured CO_2. The value 0 is assigned for the power plant not utilizing any capture process. The heat required for the sorbent regeneration is supplied with steam taken from the crossover piping of the turbine (pt 100, Fig. 2). After giving away the heat, the steam condenses and the saturated condensate returns to the cycle, pumped by a pump to the deaerator (pt 103).

3. Design parameters

The boiler is fed with fuel of a lower heating value: 23 MJ/kg and of composition: c=0.599, h=0.038, s=0.01, n=0.012, o=0.05, p=0.2, w=0.09. The thermal efficiency of the boiler is 94.5%. Live steam pressure is 30.3 MPa and the temperature 653°C. The secondary steam temperature at the boiler outlet is 672°C. More parameters are presented in Table 1. Detailed figures are given in [4].

Table 1: Basic design data

Quantity	Value
Fresh steam pressure at boiler outlet, MPa	30.3
Fresh steam temperature at boiler outlet, °C	653
Fresh steam pressure at turbine inlet, MPa	30
Fresh steam temperature at turbine inlet, °C	650
Reheat steam pressure, MPa	6
Reheat steam temperature at boiler outlet, °C	672
Reheat steam temperature at turbine inlet, °C	670
Feed water temperature, °C	310

4. Results of thermodynamic calculations

Table 2 presents the main results of thermodynamic calculations required for the economic analysis. The key to calculating the minimum price of electricity energy is ascertaining annual net production and annual production of heat. Other important parameters influencing the price of electricity are: annual fuel consumption and the amount of CO_2 emitted, for which emission allowances must be purchased. The table shows the annual amount of CO_2 produced in the boiler (assuming annual operating time of 7,500 hours), the recovery rate of CO_2 is assumed to be 90%. The costs of emissions are proportional to 10% of the CO_2 produced in the boiler. In the case of a combined heat and power plant calculations should take into account varying operating conditions due to the requirement to satisfy the changing demand for heat during the year. In the calculations, the required amount of heat is determined by the characteristics of the district heating network [4].

5. Economic calculations

The economic calculations were performed by NPV analysis (Net Present Value). This method compares the annual cash flow in the assumed operating time of the power plant, yielding the NPV ratio.

Table 2: Results of thermodynamic calculations to be used in the economic analysis

Sorbent heat consumption rate	0	2	3	4
Annual gross production of electricity	2.16	2.18	2.21	2.26
Annual net production of electricity	1.82	1.83	1.85	1.89
Annual production of heat	1.35	1.26	1.14	0.94
Annual production of CO_2	1.73	1.87	1.96	2.05
Annual fuel consumption	7.92	8.59	8.96	9.37

One of the input assumptions is the sale price of electricity. If we assume that NPV is equal to zero, there is a specified value for the sale price of electricity, which is called the breakeven price of electricity.

The net present value ratio (NPV) is given by:

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

where: t=0—the year of the start of construction; t=N—the last year of operation, r—discount rate

$$CF_t = [-J_{sz} + S - K_{op} + P_d + K_{obr} + K_a + L] \tag{2}$$

where: J_{sz}—investment costs to build the power unit; S—revenues from sales of electricity; K_{op}—operating costs; P_d—income tax; K_{obr}—change in working capital (in the analysis, the value is 0); K_a—amortization costs; L—liquidation value, occurring in the last year of the power plant's operation.

6. Results of economic calulations

Fig. 3 shows the breakeven price of electricity as a function of the sorption heat consumption process. The graph shows that the use of chemical absorption lowers the breakeven price of electricity as it decreases heat consumption in the CO_2 capture. Clarification of this relationship is described in detail in the next section.

Table 3: Results of thermodynamic calculations to be used in the economic analysis

Quantity	Value
MACROECONOMIC AND BASIC ASSUMPTIONS	
Equity contribution in financing of investment, %	0.25
Contribution of credit bank in financing of investment, %	0.75
Annual interest rate of credit bank, %	6
The period of repayment of credit bank, years	10
Period of construction of the power unit, years	3
Period of operation of the power unit, years	20
Percentage distribution of investment costs in subsequent years of construction, %	20/30/50
Discount rate, %	5
Average depreciation rate, %	6.67
Income tax, %	19.0
Liquidation value, %	20
Polish zloty / Euro exchange rate, PLN/€	-
Polish zloty / Dollar exchange rate, PLN/$	3.23
ELEMENTS RELATED WITH CONSTANT COSTS	
The costs of repairs (in relation to investment costs) in the subsequent years of operation—varying in time, %	0.5 . . . 2.5
Unitary employment rate, person/MWb	1.5
Unitary monthly employment costs (with overheads), PLN/person/month	4500
ELEMENTS RELATED WITH VARIABLE COSTS	
Annual working time of a power unit, h/a	7500
Unit price of fuel, PLN/ Mg (PLN/GJ)	220 (9.57)
Price of CO_2 emission allowances, PLN/Mg	90

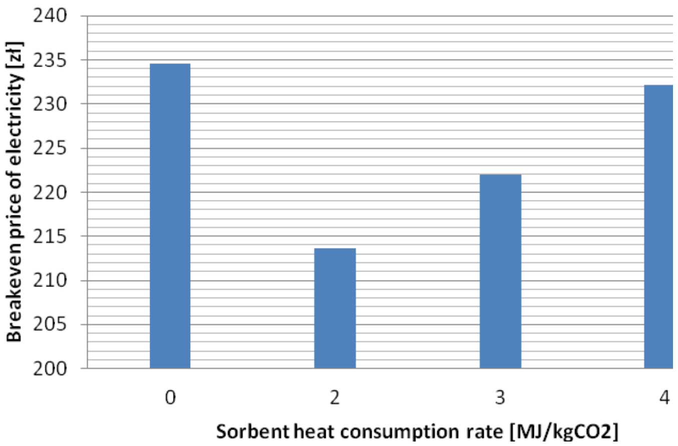

Figure 3: Breakeven price of electricity in function of SHC

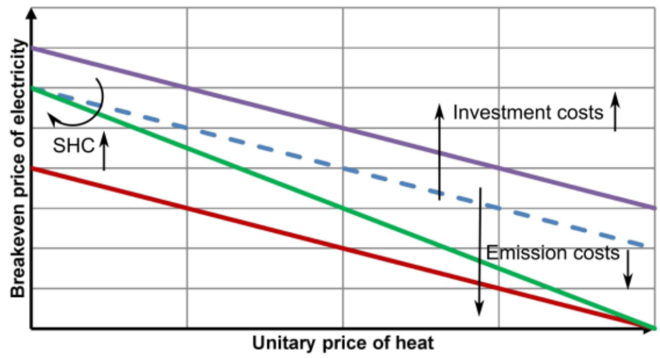

Figure 4: Pictorial illustration of the influence of chosen parameters on the breakeven price of electricity

6.1. Influence of selected parameters on the breakeven price of electricity

The previously mentioned relationship between the breakeven price of electricity and the energy consumption of the sorption process, can be explained by analyzing the influence of basic parameters. If one analyzes how the value of the unit price of heat affects the breakeven price of electricity, one may observe a linear relationship: the breakeven price of electricity decreases with an increase in the sales price per unit heat (dashed lines in Fig. 4). This is due to the fact that to keep NPV equal to zero by higher income from the heat sale, the breakeven price of electricity must go down. The position and angle of each line is determined for a given economic parameter, while keeping all other parameters equal (except the price of heat). When changing one parameter, such as investment costs or emission costs, a line moves parallel to its initial position. If the emission or investment costs go up, the line moves

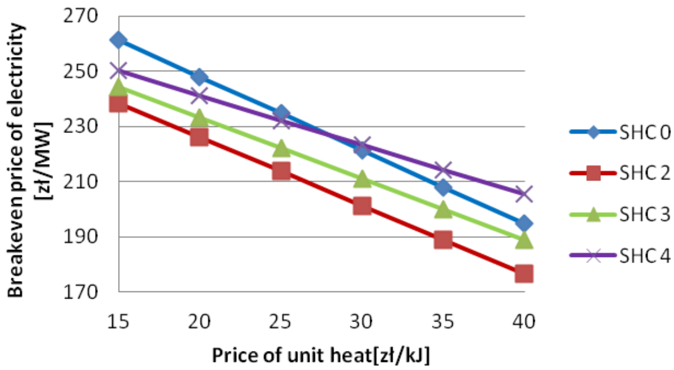

Figure 5: Breakeven price of electricity in function of SHC and unitary price of heat

up, i.e. for the same price of heat, the breakeven price of electricity will be higher. The energy consumption of the sorption process causes a drop in the heat available for sale. Graphically, it is be depicted by a steeper incline. The larger the power consumption of sorption, the greater the incline is.

The scheme shown in Figure 5 is a result of the relationship discussed above. It shows that the line of the breakeven price of electricity of heat and power plants operating without CO_2 capture intersects the other lines, which characterize plants integrated with a chemical sorption installation operating with different SHC. This means that the conclusion about the influence of the sorption process on reducing the price of electricity comes with a corollary that this occurs in a given range of the price of heat. The first intersection (following from the beginning of the axis in the direction of increasing price of heat from the beginning of the axis) will be present for a characteristic line for a system without any CO_2 capture installation with the characteristic line representing a system with the highest energy consumption of the sorption process. Subsequently the characteristic line of SHC=0 will intersect lines with a lower SHC value at points corresponding to higher unit prices of heat.

Two ranges can be seen. The first is when the breakeven price of electricity for a combined heat and power plant with a CCS unit is lower than the price for a plant without a CCS unit. The second is when the opposite happens. Based on the previous considerations on the impact of various quantities on the breakeven price of electricity, two ranges can be deduced (to the intersection of lines and from

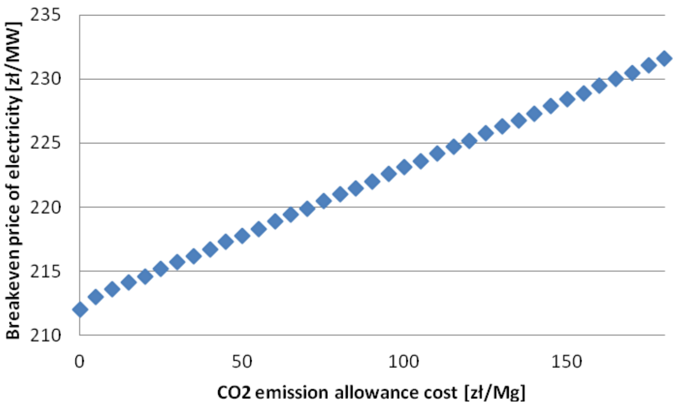

Figure 6: Breakeven price of electricity as a function of SHC and unitary price of heat

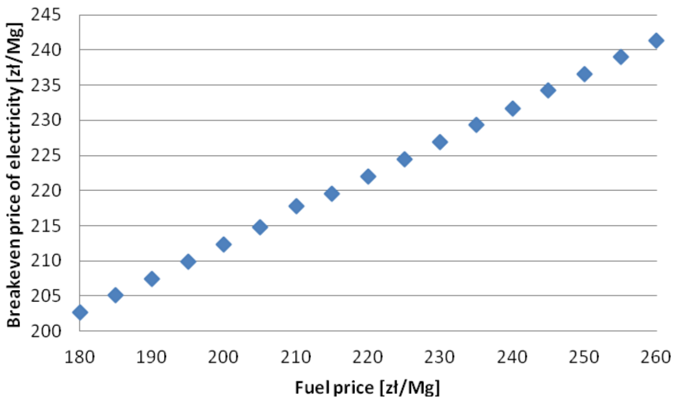

Figure 7: Influence of fuel price on the breakeven price of electricity

the intersection of lines). In the first range the breakeven price of electricity for the heat and energy power plants with a chemical absorption installation is lower than for plants without. This is due to the fact that the benefit of not paying for the CO_2 emission allowances is higher than the loss of profit from the sale of heat (which the heat and power plant with the CO_2 capture installation must consume to regenerate the sorbent). In the second range, above a certain critical price of heat, the revenue from sales of heat compensates the cost of the CO_2 emission allowances. This happens because the power plant without the CO_2 capture installation has more heat to sell.

6.2. *Results of sensitivity analysis*

The main indicator of economic efficiency for the heat and power plant is the breakeven price of electricity. Unfortunately, in the economic calculations, the quantities assumed as input variables are subject to considerable uncertainty, both in execution and in the time from the start to the end of operation of the power plant. Therefore, it is important to perform a sensitivity analysis with respect to the parameters which have the greatest impact. The discussion below presents the influence of selected parameters for a heat and power plant with CO_2 capture with energy consumption for absorption of 3 MJ per kg of CO_2 captured (SHC 3). While changing one parameter, all other parameters were kept equal. Fig. 6 presents the influence of unit price of CO_2 emission on the breakeven price of electricity. The initial price of CO_2 emission allowances is 90 PLN/MgCO_2. This parameter varied in the range 0 to 180 PLN. A change in CO_2 emission allowance cost by 1 PLN/Mg$_{CO_2}$ causes a change in the breakeven electricity price of 0.11 PLN/MWh.

Fuel price is another key parameter which has a significant impact on the breakeven price of electricity. The initial fuel price is assumed to be 220 PLN/kg. In the sensitivity analysis, the fuel price varied in the range 180 to 260 PLN/kg. A change of 1 PLN/Mg in the unit price of fuel affects the breakeven price of electricity by 0.48 PLN per MWh.

The big unknown in these economic calculations is the unit cost of investment for a "zero-emission" power plant. In this paper its value is based on literature data [1], increased by 30% to reflect changes in the time since the publication appeared (2007). The influence of the investment cost is examined in the range 2,000 to 3,400 $/kWb with a nominal value of 2,800 $/kWb. A change of 100 PLN/kW in the investment costs will change the breakeven price of electricity by 5 PLN.

The influence of repair costs on the breakeven price of electricity was also examined for the three variants. Repair costs were related to investment costs as percentage values. Operation time was divided into intervals, for each interval a value of repair costs was assumed. It is characteristic for each subsequent interval to have higher repair costs than the previous one. The influence of repair costs is analyzed by changing the values in the intervals from those established in the assumptions, for each variant. Variant 1 (Fig. 9) contains starting values: 0.5% of the investment in years 1...3, 1.0% in years 4...10,

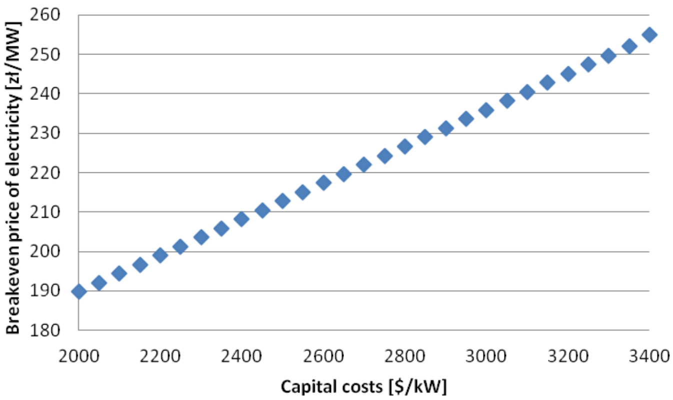

Figure 8: Influence of fuel price on the breakeven price of electricity

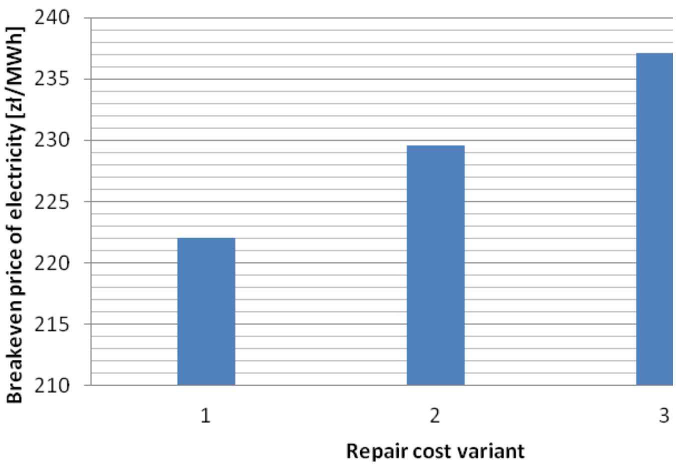

Figure 9: Influence of repair costs on the breakeven price of electricity

1.5% in years 11...15, 2.0% in years 16...20, 2.5% in years 21...25. In the second variant, maintenance costs were increased by 0.5 percentage points in each period.

7. Summary

Justification for building a heat and power plant with "low- / zero-emission" technology can be supplied by means of thermo-economic analysis, using for example the NPV ratio method. Individual thermodynamic and economic parameters have a strong influence on the breakeven price of electricity. The high costs of building and operating CO_2 capture units can be compensated by high prices of CO_2 emission allowances. Heat and power plants without a CO_2 capture installation will be able to avoid these costs, but only to a certain critical sales price of heat.

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