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Thermodynamic and commercial analysis of a 600 MW oxy-fired coal unit with a membrane-cryogenic oxygen production system and CO_2 capture installation

Sylwia Berdowska*, Anna Skorek-Osikowska

Institute of Power Engineering and Turbomachinery

Silesian University of Technology, Gliwice, Poland

Abstract

This paper analyzes a 600 MW coal unit with pulverized bed boiler working with oxy-combustion technology with a hybrid, membrane-cryogenic oxygen separation installation and a carbon capture and storage system. A membrane-cryogenic oxygen separator consists of a membrane module and a cryogenic distillation module. The boiler works with oxy-combustion technology, therefore the resulting flue gases are 79% CO_2. In order to increase the concentration of carbon dioxide in the exhaust gas to 95% an installation based on physical separation technology was used. In this work the main results of the calculated energy intensity of each system are presented. A commercial analysis of the coal power plant was performed using the Break-Even Point method. In order to verify the profitability of building a coal unit with a membrane-cryogenic oxygen separation installation, a sensitivity analysis as a function of investment costs and coal price was performed.

Keywords: CO_2 capture, oxy-combustion technology, commercial analysis

1. Introduction

In the EU, more than 50% of electricity is generated from fossil fuels, whereas in the world this index is at the level of 40% [1], therefore new solutions to increase the efficiency of coal-fired units are being developed. In coal units that work with supercritical steam parameters, efficiency levels can be increased to over 50% [2]. The obligation to reduce carbon dioxide emissions to the atmosphere requires the use of separation systems which negatively impact efficiency by 5...9 percentage points [3–5]. The CO_2 sequestration methods developed include technology based on amine absorption, membrane separation systems and combustion in an oxygen enriched atmosphere, where the flue gases generated consist mainly of carbon dioxide and water vapor [6–8]. The subject of the research presented in this article is the commercial aspect of the use of oxy-combustion technology in a power plant.

The analyzed coal unit is integrated with a membrane-cryogenic oxygen plant and with a CO_2separation and compression installation, which is analyzed in detail in [9].

*Corresponding author

Email address: sylwia.berdowska@polsl.pl (Sylwia Berdowska*)

2. Coal unit with pulverized bed boiler integrated with hybrid membrane-cryogenic oxygen separator

In this paper a thermodynamic analysis was performed in respect of a 600 MW coal power plant with pulverized bed boiler working with oxy-combustion technology with live steam parameters at 650°C/31.1 MPa and reheated steam parameters at 670°C/6.15 MPa integrated with an oxygen membrane-cryogenic separator and a carbon capture installation. A model of the oxygen plant and carbon capture installation was built in Aspen software and a model of the boiler in GateCycle software.

The oxygen installation consists of a membrane module and two cryogenic distillation columns. This system use low-temperature polymer membranes, whose main task is to increase the concentration of oxygen in the air stream to about 40% (which is dictated by the lowest energy consumption in the membrane module), then the oxidant is supplied to the section of cryogenic distillation columns. This operation makes it possible to reduce the energy consumption of the oxygen separation process compared to the production of oxygen in the purely cryogenic separator. Influencing energy efficiency in the hybrid oxygen plant are: a fan before the membrane module (F), a vacuum pump on the permeate side (VP), a compressor before the membrane module (for the calculations a 4-section compressor with intercooling was assumed).

The final purity of the resulting oxygen is 95%. An oxygen separator is integrated with the pulverized bed boiler. Exhaust gases produced as the result of combustion in the oxygen enriched atmosphere contain about 79% CO_2, so that their preparation for transport requires only drying excess water and removing unnecessary components such as argon, nitrogen, oxygen and sulfur dioxide. The installation for compression and sequestration of carbon dioxide (Carbon Capture, CC) consists of the following sections: drying, cryogenic distillation and compression. In the drying section, excess water is removed from the flue gas, which is then directed to the cryogenic distillation system, where the excess nitrogen and oxygen is removed. The resulting gas contains 95% CO_2. In the compression section flue gas is compressed to 150 bar for the purpose of pipeline transport.

Table 2: Auxiliary power rate δ of the individual technological installations

Installation	Auxiliary power rate, δ
Air separation installation	0.125
Auxiliary devices of the pulverized bed boiler	0.021
Auxiliary devices of the steam cycle	0.032
CO_2 separation and compression installation	0.075
Total	0.253

A scheme of the analyzed coal unit is shown in Fig. 1. More details concerning the models of the individual technological installations are presented in, e.g. [10–12].

The selected parameters of the oxygen plant and the CC installation are summarized in Table 1.

Using the above assumptions in calculations, the auxiliary power rate is specified for each of the analyzed technological systems. The auxiliary power rate is determined by the formula:

$$\delta = \frac{N_{el,INST}}{N_{al,g}} \tag{1}$$

where:

$N_{el,INST}$—electrical power needed to drive the auxiliary equipment installed in the power unit

$N_{al,g}$—electrical power generated in the analyzed coal unit.

The results of the calculations are summarized in Table 2.

The calculations show that the auxiliary power rate is at its highest for the air separation installation, at almost half the total auxiliary power of the unit.

3. Commercial analysis of the coal unit integrated with a membrane-cryogenic oxygen separator

The commercial analysis was carried out in order to evaluate the profitability of building a coal unit with a pulverized bed boiler working with

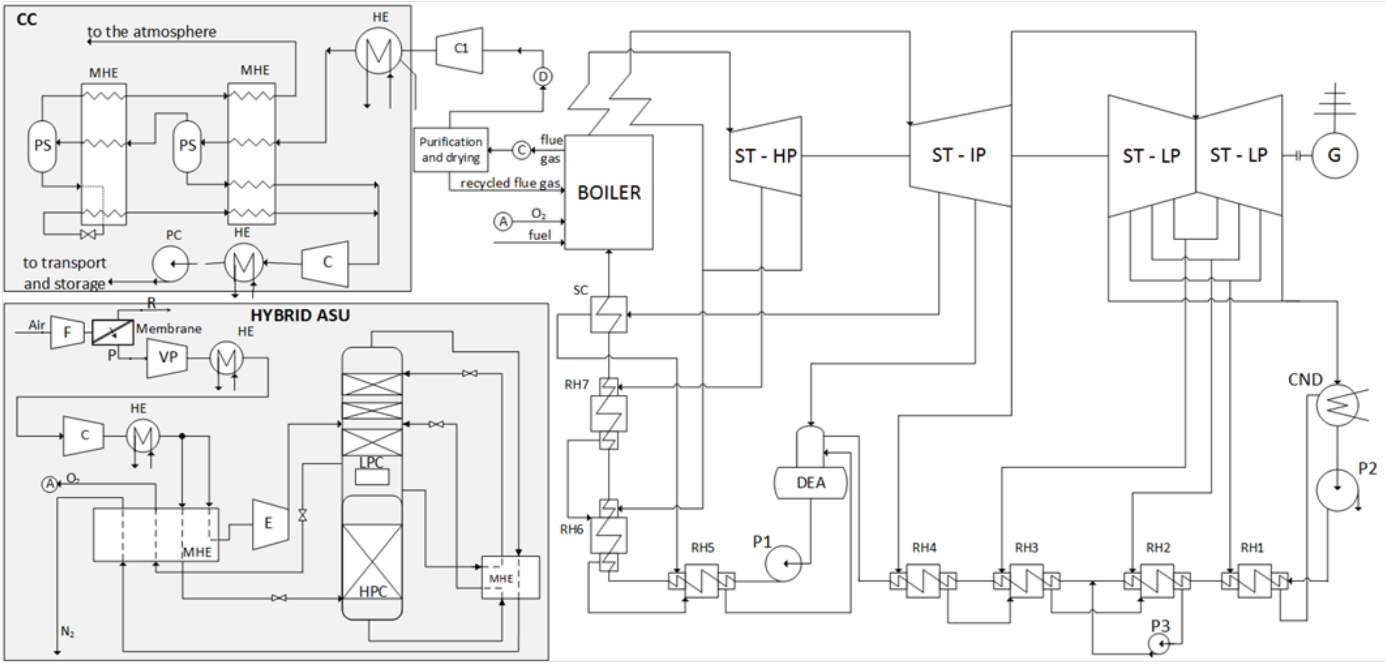

Figure 1: Scheme of a coal unit integrated with a membrane-cryogenic oxygen separator and CC installation; F—fan, VP—vacuum pump, HP—high-pressure, MP—middle pressure, LP—low pressure steam turbine, G—generator, DEA—deaerator, RH—regenerative feat exchangers, CND—condenser, C—compressor, PS—phase separator, MHE—multistream heat exchanger, P—pump, E—expander, P—permeate, R—retentate, HPC—high pressure column, LPC—low pressure column

Table 1: Main parameters of the oxygen separator unit and CC installation

Parameter	Value
Pressure at the inlet to the membrane module, kPa	106.325
Oxygen permeability coefficient, $m_n^3/(m^2 h \cdot bar)$	3.1119
Nitrogen permeability coefficient, $m_n^3/(m^2 h \cdot bar)$	0.2922
Oxygen concentration at the inlet to the cryogenic module, %	41
Pressure behind compressors in the cryogenic installation, kPa	600
Pressure in the high-pressure cryogenic column, kPa	500
Oxygen concentration in the oxidant supplied to the boiler, %	95
Nitrogen concentration in the oxidant supplied to the boiler, %	5
Pressure in the separators of CC installation, kPa	3010
Purity of CO2 at the outlet of the CC installation,%	95

oxy-combustion technology integrated with a hybrid membrane-cryogenic air separation system.

The primary and widely used indicator of commercial efficiency is the Net Present Value (NPV) method [6, 13]:

$$NPV = \sum_{t=0}^{t=N} \frac{CF_t}{(1+r)^t} \quad (2)$$

where : r—the discount rate, t—consecutive year of consideration from the start of the construction system, N—last year of operation of the system.

Cash flow CF_t is determined from the relationship:

$$CF_t = \left[S - J - \left(C_{op} + T_{in} + C_{wc}\right) + A + F + L\right]_t \quad (3)$$

where: S—revenues from sale,J—investment costs, C_{op}—operating costs, T_{in}—income tax, C_{wc}—change of the working capital, A –depreciation, L—salvage value, F—the cost of financing

Commercial analysis based on the Break Even Point (BEP) method is performed for the considered cases. BEP was used to determine the break-even point of the project, which is the point at which revenue from the sale of electricity equals the cash outlays. In this method the limit value of one of the components of the net cash flowCF_t is set. The selected value is nominated for the condition $MPV = 0$. For the calculations the break-even price of electricity was chosen.

One important commercial indicator used in the evaluation of energy systems is the cost of avoided CO_2 emissions C_{AV}, which is determined by the following equation:

$$C_{AV} = \frac{C^{gr}_{CRYO} - C^{gr}_{REF}}{E_{AV}} \quad (4)$$

$$E_{AV} = E_{REF} + E_{CRYO} \quad (5)$$

where: C^{gr}—break-even price of electricity, index ”CRYO” denotes coal unit with cryogenic oxygen separator, ”REF”—reference unit, E—unit emission of CO_2 for particular units.

Commercial analysis was performed for three variants of the coal unit:

- the reference unit with an air-fired pulverized bed boiler without a CO_2 separation and compression installation,
- coal unit with an oxy type pulverized bed boiler integrated with a cryogenic oxygen production system and CC installation,
- coal unit with an oxy type pulverized bed boiler integrated with a membrane-cryogenic oxygen separator and CC installation.

According to the literature, the unit investment costs for particular power plants are as follows:

- a reference coal unit €942...1275/kW$_{gross}$ [14–16],
- a unit with a cryogenic oxygen plant €1615...1963/kW$_{gross}$ [14, 15, 17]
- a unit with a membrane-cryogenic air separator: based on the literature [18, 19] the cost of cryogenic installation was €65.8/kW; the cost of the membrane installation was calculated as being €294.12/kW using the equations 6, 7, 8.

For the unit integrated with a membrane-cryogenic oxygen separator, the cost of particular components of the membrane installation was calculated using the following equations:

$$K_M = k_M \cdot A_M + 250,000 \cdot \left(\frac{A_M}{2000}\right)^{0.7} \quad (6)$$

$$K_{VENT} = 1.051 \cdot \frac{39.5 \cdot m}{0.90 - \eta_{i,VENT}} \beta_{VENT} \cdot ln\beta_{VENT} \quad (7)$$

$$K_{VENT} = 4 \cdot 1.051 \cdot \frac{39.5 \cdot m}{0.90 - \eta_{i,VP}} \beta_{VP} \cdot ln\beta_{VP} \quad (8)$$

where: K_M—unit cost of membrane module, €; K_{VENT}—unit cost of fan, €; K_{VP} —cost of vacuum pump, €; K_M—cost of membrane, €/m^2; A —membrane area, m^2; m—mass flow, kg/s; η_i—isentropic efficiency; B—pressure ratio.

In Table 3 the main assumptions for the commercial calculations are summarized.

On the basis of the assumptions made, the break-even price of electricity for each of the analyzed cases was calculated at:

Table 3: Main assumptions for the commercial analysis

Specification	Value
Annual working time, h/a	8000
Reference unit investment costs, €/kW	1083
Investment costs for the unit with cryogenic ASU, €/kW	1842
Investment costs for the unit with membrane-cryogenic installation, €/kW	2013
Construction time, years	3
Share of own funds, %	20
Share of commercial credit, %	80
Actual interest of commercial credit, %	6
Payback time of commercial credit, years	10
Operation time, years	20
Discount rate, %	6.2
Operating costs, €/MWh	5.8
Operating costs of CC, €/MgCO_2	4.6
Coal price, €/GJ	3.5
CO_2 emission allowances price, €/Mg	46.5
Employment in the reference unit, pers./MW	0.4
Employment in the unit with a cryogenic and hybrid air separator, pers./MW	0.5
Monthly salary including related costs, €/post/month	1163
Average depreciation rate, %	6.67
Income tax rate, %	19
CO_2 emission impacting a unit of coal chemical energy, kg/MJ	0.0927
CO_2 emission impacting a unit of coal chemical energy in the unit with cryogenic air separation installation, kg/MJ	0.0027

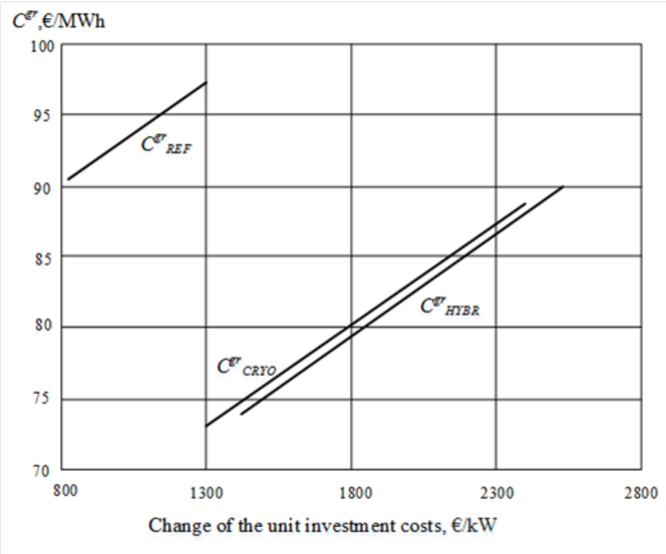

Figure 2: The influence of unit investment cost on the break-even price of electricity C^{gr}(C^{gr}_{REF}—reference unit, C^{gr}_{CRYO}—unit with cryogenic installation, C^{gr}_{HYBR}—unit with membrane-cryogenic system)

- for the reference unit: €94.5/MWh
- coal unit with cryogenic oxygen plant: €81.2/MWh
- coal unit with membrane—cryogenic oxygen plant: €82.8/MWh

The price of electricity is at its highest for the reference coal unit, which is caused by the need to purchase CO_2 allowances. The difference between the energy produced in a unit with a cryogenic oxygen plant and the unit with a hybrid air separator is €1.6/MWh. This difference is due to the higher investment cost of the membrane-cryogenic oxygen plant.

In order to determine the profitability of particular investments, sensitivity analyzes were made in light of variable unit investment costs, coal costs, effect of CO_2 allowances on the break-even price and avoided CO_2 emissions.

In the first case, the effect of changes in the coal unit investment cost on the break-even price of electricity for the reference power plant and units with a cryogenic and a membrane-cryogenic installation was examined. Results of the analysis are shown in Fig. 2.

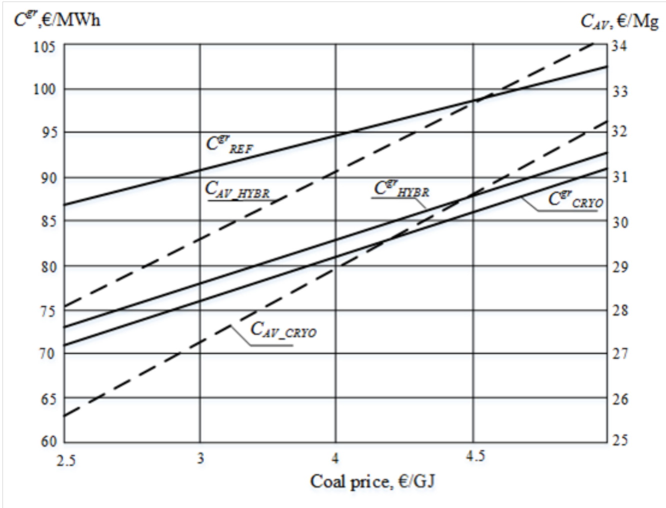

Figure 3: Break-even price of electricity as a function of a change in the coal price (solid line—break-even price of electricity, dashed line—cost of avoided emissions

The price of electricity increases with the increase in investment cost of each power unit. Investment costs are at their lowest for the reference unit, but the high cost of CO_2 emissions to the environment caused an increase in the cost of generated energy of approximately €13.3/MWh compared to the unit with the cryogenic oxygen plant and by €11.7 compared to the unit with hybrid technology.

In the second case the impact of the cost of coal on the break-even electricity price and the cost of avoided emissions of carbon dioxide was examined. The results are illustrated in Fig. 3. A graph was made for a change in fuel price by about 30% from the nominal value of €3.5/GJ. Changing the price of coal by 30% affects the price of electricity by about €10/MWh. The cost of avoided CO_2 emissions changes by about €3.5/MWh.

In the third case, it was analyzed how the cost of emission allowances influences the break-even price of electricity. In the calculations it was assumed that CO_2 emission allowances are purchased for the whole carbon dioxide emission from the reference unit and only for a part of the CO_2 which is emitted to the atmosphere for the units with the oxy boiler and CC installation. The results are shown in Fig. 4. A change in allowance prices by 30% results in a rapid increase in electricity prices for the reference unit by about €10/MWh, whereas for units with hybrid and cryogenic oxygen plant this increase

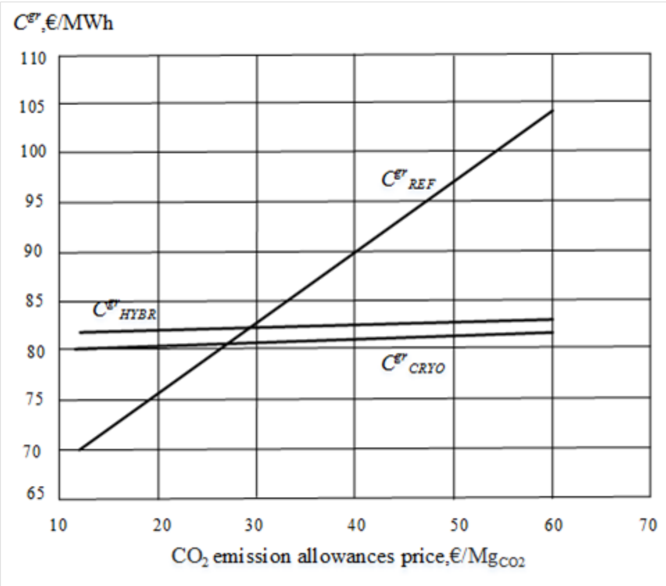

Figure 4: Break-even price of electricity as a function of a change in CO_2 emission allowances

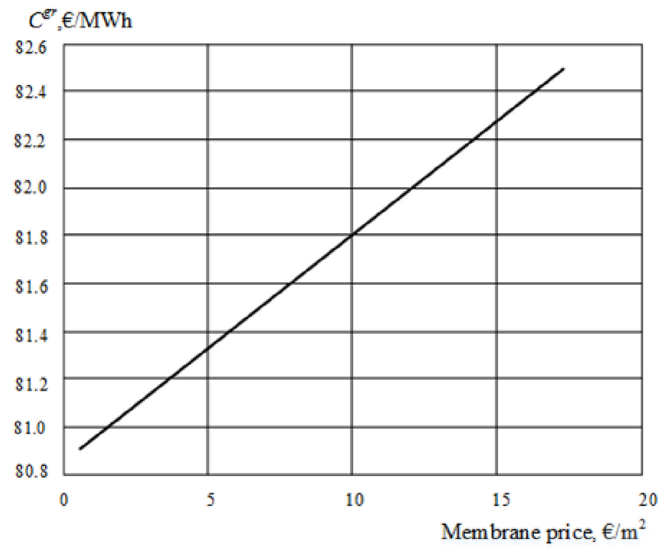

Figure 5: The influence of the membrane price on break-even price of electricity

is minimal: in the order of about €0.25/MWh.

The influence of changes in membrane prices on the break-even electricity cost in the unit with a hybrid oxygen plant was also calculated. The results are shown in Figure 5. The assumed membrane price for previous calculations was €17.2/m^2, but its reduction to €0.7/m^{2}causes a decrease in the electricity cost by €1.6 and the break-even price of electricity is €81.2/MWh.

4. Conclusions

This paper presents the results of a commercial analysis of a coal unit with an oxy-type boiler integrated with a membrane-cryogenic oxygen plant and CO_2 capture and compression installation.

The results of the commercial evaluation of the above system were compared with a reference unit without CO_2 capture and a system integrated with a classical cryogenic oxygen plant and carbon capture installation. The most important element of the commercial analysis was to ascertain the break-even price of electricity for each of the examined systems and to determine the cost of avoided CO_2 emissions.

The break-even price of electricity for the reference unit is €94.5/MWh, for the unit with a cryogenic oxygen plant €81.2/MWh and for the unit with a hybrid air separator €82.8/MWh. The cost of avoided CO_2 emissions for the unit with a cryogenic oxygen plant is €28.9/Mg$_{CO_2}$ and for hybrid technology €31.3/Mg$_{CO_2}$.

Since the cost of electricity production in a unit with a hybrid oxygen plant is higher than in a unit with cryogenic oxygen production technology, the impact of changes in membrane price on the break-even price of electricity was calculated. The break-even price of electricity for the two analyzed technologies is €81.2/MWh for a membrane costing €0.7/m^2. It should be underlined that the choice of membrane has a big influence on the performance of the hybrid unit. The better the membranes (permeability and selectivity for oxygen), the better the system works—and at lower operating costs. The advances in membrane technology expected in the near future will improve the profitability of hybrid systems.

The biggest impact on changes in the price of electricity for each of the analyzed systems was changes in coal price. A 30% reduction in the coal price can cut the break-even price of electricity by 12.5%. The investment costs of the coal unit play an important role in achieving favorable electricity prices. A change in investment costs by 30% caused a change in the break-even price of electricity of: for the unit with a hybrid oxygen separator—€8.5/MWh, for the unit with a cryogenic oxygen plant—€7.9/MWh and for the reference unit—€3.1/MWh.

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