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# Repowering a coal-fired power plant with a gas turbine to supply heat for the desorption process

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**Abstract**

This paper presents the results of an analysis for a 900 MW supercritical coal-fired power plant integrated with an absorption $CO_2$ separation installation and a gas turbine unit. In this unit the gas turbine with evaporator is the heat source for the desorption process, which is realized in a $CO_2$ separation installation. The aim of the analysis was to determine the thermodynamic, ecological and economic evaluation indicators, which are defined in the paper. Analyzes were carried out for the variable heat demand required for the desorption process. Additionally, the impact of a change in emission allowance price on selected economic evaluation indicators was analyzed.

*Keywords:* $CO_2$ separation, thermodynamic analysis, economic analysis

## 1. Introduction

Poland plans to significantly increase the production of natural gas-fired electricity over the next two decades. The Polish Energy Policy until 2030 [1] is projected to increase the installed capacity of gas sources to about 3,000 MW. These forecasts seem quite realistic when one takes into account the scale of the planned and already launched investments in the country. The statement presented in [2] shows the pace of development of large-scale gas power industry. It has now surpassed the power gains forecasts presented in [1]. An unprecedented, bold investment policy by the energy sector in the field of technology is being driven primarily over concerns about the feasibility of significantly reducing greenhouse gas emissions in systems using coal and lignite. In order to meet the EU policy on reducing anthropogenic greenhouse gas emissions, a substantial decarbonization of economies is needed (the Polish economy in particular). An alternative way ahead is success in the commercialization of efficient $CO_2$ sequestration technologies. The future success of investment directions chosen today by companies will be decided on the one hand by current research and development in the field of $CO_2$ sequestration technology, and on the other hand by relations between usually stable coal prices to less stable gas prices. In the absence of reliable estimates of the mentioned factors, it appears that the only reasonable solution is the creation within corporations of a sustainable mix of gas and coal fueled technologies. Although unprecedented in Poland at this time, one solution is to use both coal and gas in hybrid systems allowing, to some extent, flexible adjustment of charges relating to market trends such as fuel prices or the price of allowances to emit greenhouse gases. Another solution is to create integrated coal units with CCS technology powered by ecological fuels (gas or

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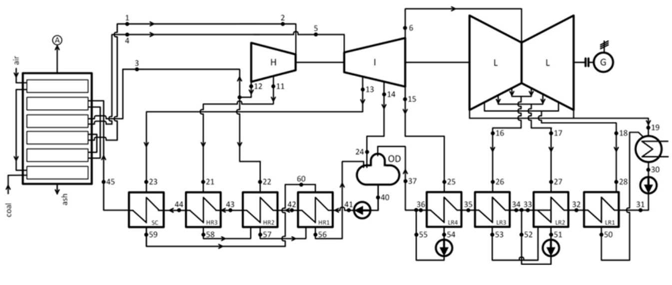

Figure 1: Diagram of the supercritical unit

biomass) to produce the heat required for the process of desorption. Systems of this type are explored in this article.

## 2. Characteristics of a supercritical unit

The analyzed supercritical unit, for which a diagram is shown in Fig. 1, corresponds to the concept of systems that already form part of the national grid. The installed capacity of the unit is 900 MW. The dust boiler working on coal (calorific value of 23.93 MJ/kg, moisture: 0.090, ash: 0.200, C: 0.599, H: 0.038, O: 0.050, N: 0.012, S: 0.010) is equipped with a steam reheater. The condensing-extraction steam turbine consists of a high, medium and two-pass low-pressure part. The secondary steam parameters can be considered forward-looking: 650°C/30 MPa and 670°C/5.9 MPa. The vapor pressure in the condenser is set at 5 kPa. The model of the unit was built using the GateCycle program. The most important characteristic values used in the calculation are summarized in Table 1.

## 3. Characteristics of the integration of the unit with a $CO_2$ separation installation and a gas turbine

The most advanced method of separating $CO_2$ from flue gases is chemical absorption using aqueous monoethanolamine (MEA) as a sorbent. The standard installation mainly consists of two columns: the first column, i.e. the absorber, wherein the $CO_2$ reacts with the exhaust gas scrubbing solution of MEA and the second column, i.e. a stripper where a saturated MEA solution is subjected to heat for regeneration. This heat must be supplied to the installation from the outside. In the absorber column, the MEA solution absorbs $CO_2$. Exhaust devoid of gas (assumed 90%) leaves the column and is discharged to the atmosphere. Deep cleaning, including deep desulfurization, is needed prior to feeding the flue gas into the installation. Sulfur compounds interacting with monoethanolamine form stable salts, which contributes to material losses of the solution which has to be supplemented in the system. A saturated solution of MEA with $CO_2$ leaves the absorber column at its lower part, and goes through the pump and heat exchanger to the stripper column. Here, after the solution has reached a temperature of 125°C, it releases $CO_2$, which leaves the column from the top, together with a substantial amount of water vapor. The final separation of $CO_2$ is performed in the condenser (CND-ABS) and the separated $CO_2$ goes to the compression installation, whose role is to compress the $CO_2$ to a pressure of 15 MPa. After cooling, the gas is condensed and transported to the place of storage. To implement the desorption process, the stripper column requires significant amounts of heat (indirectly through the re-boiler). In the classical solutions, analyzed by authors in [3, 4], heat is supplied with steam taken from bleeding the steam turbine power unit. Undoubtedly, the great advantage of this solution is its lower investment costs due to the lack of additional systems to produce heat. However, the disadvantage is the need to design a steam turbine for a significant extraction of steam with appropriate parameters for the work of the re-boiler in the $CO_2$ separation installation. Reducing the double-flow low-pressure part of the steam turbine, providing high efficiency at a minimum flow of steam, excludes large flows in the event of discontinuance of the $CO_2$ separation process, which would take place in a situation where the European Union withdraws the policy of limiting emissions of primary greenhouse gas. The literature examines alternative ways to supply heat to the stripping process. In [5] the authors analyze the production of heat in an external source powered by a biomass boiler. However, in [6] a variant is analyzed in which heat is extracted from the flue gas leaving the gas turbine unit. This variant is also the subject of analysis in this article. Similar analyses were presented in [7–9], where they relate to the integration of a CCS installation with a supercritical coal-fired combined heat and power plant.

For the purposes of analysis it is assumed that

Table 1: Assumptions for calculations

| Quantity | Value |
|---|---|
| Deaerator operating pressure, MPa | 360.3 |
| Condenser operating pressure, MPa | 291.8 |
| Pressure at outlet of condensate pump, MPa | 201.9 |
| Feed water temperature, °C | 166.6 |
| Internal efficiency of stage groups of steam turbine part H, % | 997.5 |
| Internal efficiency of stage groups of steam turbine part I, % | 0.856 |
| Internal efficiency of stage groups of steam turbine part L, % | 0.361 |
| Internal efficiency of last stage groups of steam turbine part L, % | 0.293 |
| Efficiency of the generator, % | 2024 |
| Mechanical losses of turbine, MW | 0.681 |
| Internal efficiency of pumps, % | 0.240 |
| Pressure drop in steam pipe between steam cooler and regenerative heat exchanger HR1, % | 1.0 |
| Pressure drop of water in regenerative heat exchangers and steam cooler, % | 1.0 |
| Pressure drop of working medium in steam boiler, MPa | 4.2 |
| Pressure drop of steam in reheater, MPa | 0.3 |
| Pressure drop in reheated steam pipes, % | 1.7 |
| Temperature increase of condensate in low-pressure regenerative heat exchangers, K | 120.7 |
| Temperature increase in regenerative heat exchanger HR1, K | 41.9 |
| Temperature increase in regenerative heat exchanger HR3, K | 28.4 |
| Temperature increase in steam cooler, K | 5.0 |
| Terminal temperature difference in regenerative heat exchangers LR1, LR2, LR3 and LR4, K | 3.0 |
| Terminal temperature difference in regenerative heat exchangers HR1, HR2 and HR3, K | 2.0 |

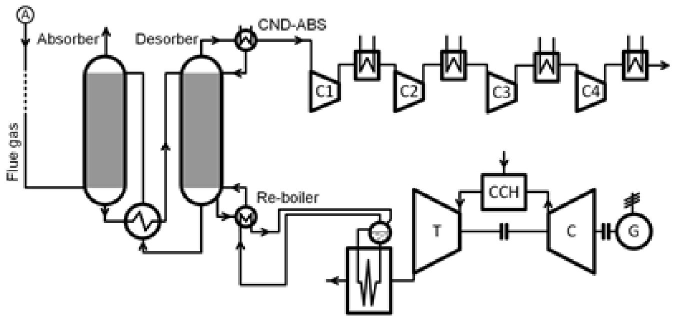


Figure 2: Diagram of $CO_2$ separation unit

the integration of the power unit characterized in Section 2 involves only the flue gases leaving the boiler that are brought to the $CO_2$ separation plant (the link between the two systems is indicated in Fig. 1 and 2 with the letter A). It was assumed that in separation unit four a sectional compressor is installed with built-in coolers between the sections. It was assumed that between the sectional exchanger the gas is cooled to a temperature of 40°C, and the heat is dissipated in the atmosphere. For increased efficiency it may be considered useful to use the heat or cooling of the compressed $CO_2$, for example to replace the low-pressure regenerative heat exchangers of the steam cycle. Finally pressurized to a pressure of 15 MPa, $CO_2$ is cooled in a heat exchanger built up at the outlet of the compressor. The gas turbine unit itself includes a gas turbine and a heat exchanger constituting the evaporator, wherein the medium circulates in the circuit between the re-boiler and a gas turbine heat exchanger, where it is evaporated. The turbine that was selected for cooperation with the evaporator is characterized by a pressure ratio equal to 20 and exhaust gas temperature in the combustion chamber of 1430°C. The gas turbine is supplied with natural gas having the following characteristics: calorific value of 48.8 MJ/kg, $CH_4$: 0.973, $N_2$: 0.0086, $C_2H_6$: 0.0081, $C_3H_8$: 0.0046, $CO_2$: 0.0028, $C_4H_{10}$: 0.0026. The gas turbine efficiency obtained is 41.38%.

The basic quantity characterizing the energy consumption of the separation system is the unit rate of heat demand required for the desorption process ($q_{des}$). In the literature, these values generally range from 2 to 4 $MJ/kg_{CO_2}$ separated. Values in this range were analyzed and formed the basis for preparing this paper. Ratio $q_{des}$ determines the flow of heat which must be taken in the evaporator assembly of a gas turbine according to the relation:

$$\dot{Q}_{TG} = \frac{\dot{Q}_{des}}{\eta_{reboiler}} = \frac{1}{\eta_{reboiler}} \cdot \dot{m}_{sp} \cdot \frac{M_{CO_2}}{M_{sp}} \cdot z_{CO_2} \cdot R_{CO_2} \cdot q_{des} \tag{1}$$

where: $\dot{Q}_{TG}$ – heat flux required for the process of desorption, MW, $\eta_{reboiler}$ – efficiency of the reboiler heat exchanger (99%), $\dot{m}_{sp}$– exhaust stream brought to the separation plant, kg/s, $M_{CO_2}$, $M_{sp}$– molar number of $CO_2$ and gas brought to the installation, kg/kmol, $z_{CO_2}$ – the molar fraction of $CO_2$ in the flue gases, $kmol_{CO_2}/kmol_{flue\,gas}$,$R_{CO_2}$ – the degree recovery of $CO_2$ (90%).

In proportion to the heat which is obtained in the evaporator for the purpose of realizing the desorption process, the power of the gas turbine is also changed. The analyses assumed that there is a possibility of using a gas turbine system of any output, which means that it did not use a series of types of machine available on the market. Other characteristic values of the gas turbine remained unchanged regardless of the required size of the machine.

## 4. Thermodynamic and ecological analysis

### *4.1. Indicators*

During the analysis the gross efficiency of electricity generation was determined, defined by the following relation:

$$\eta_{el,n} = \frac{N_{el,ST} + N_{el,GT}}{\dot{E}_{chc} + \dot{E}_{chg}} \tag{2}$$

where:$N_{el,ST}$– power from the generator terminals of steam turbine (900 MW), $N_{el,GT}$– power from the generator terminals of the gas turbine, MW, $\dot{E}_{chc}$,$\dot{E}_{chg}$– streams of the chemical energy of coal and gas, MW.

$$\eta_{el,n} = \frac{N_{el,ST} + N_{el,GT} - \sum N_{pn}}{\dot{E}_{chc} + \dot{E}_{chg}} \tag{3}$$

where: $\sum N_{np}$ – sum of the auxiliary powers of their individual parts operating in the power plant (including the installation of $CO_2$ separation and compression), MW.

The use of a gas turbine to power the desorption process eliminates the need to extract steam from the steam turbine. Thus, the introduction of the gas turbine system results in additional power being generated. An important characteristic quantity used for assessing the dual fuel system is called incremental efficiency, defined by the equation:

$$\eta_{\triangle} = \frac{N_{el,GT} + \beta \cdot \dot{Q}_{des}}{\dot{E}_{chg}} \tag{4}$$

This quantity reflects the power gain obtained through introducing the gas turbine system, i.e., the sum of: the power of the gas turbine $N_{el,GT}$ and steam turbine power increase $\Delta N_{\mathrm{el,\,ST}}$, which in this case results from the heat flux required for the desorption process and the ratio of the power loss which would be the consequence of extracting the steam from the steam turbine to supply heat for desorption process $\beta = \triangle N_{el,ST}/\dot{Q}_{des}$ . The denominator in equation (4) is a stream of additional chemical energy of the fuel fed into the gas turbine, with the result that the incremental efficiency may be compared with the values of the efficiency of the other systems of converting chemical energy of gas into electricity.

To determine the coefficient $\beta$ analysis was carried out to determine the steam turbine power loss associated with extracting the steam required for the realization of the desorption process. For the assumptions, a value of 0.229 MW/MW was given.

The indicator most commonly used in the literature for assessing energy systems in the context of $CO_2$ emission is a unit $CO_2$ emission factor that specifies the amount of gas emitted per unit of electricity resulting net:

$$\varepsilon_{CO_2} = \frac{(1 - R_{CO_2}) \cdot \dot{m}_{CO_2c} + \dot{m}_{CO_2g}}{N_{el,ST} + N_{el,GT} - \sum N_{pn}} \tag{5}$$

where: $\dot{m}_{CO_2c}$, $\dot{m}_{CO_2g}$—streams of $CO_2$ generated from the combustion of coal and natural gas, kg/s.

*4.2. Results of analyzes*

The results are reported in this section relate to analyzes carried out when changing the values of the heat demand for desorption. The characteristics obtained during the analysis of the integrated system containing a supercritical coal-fired power unit, the

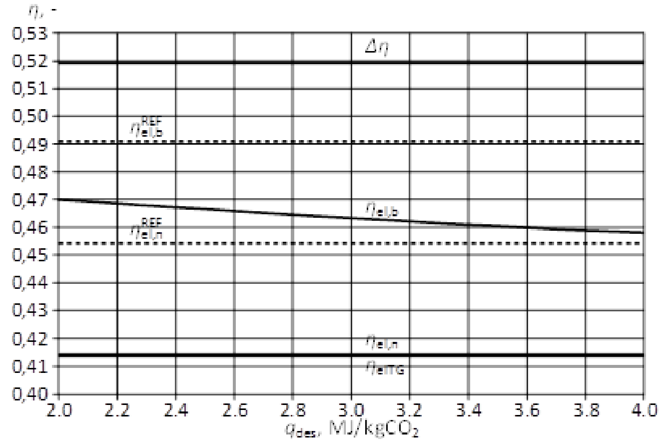


Figure 3: Efficiency characteristic as a function of heat demand for the desorption process

$CO_2$ separation installation and gas turbine are summarized in comparison with characteristic values obtained for the reference unit, which is a supercritical coal-fired power unit functioning without a separation unit. These characteristics are plotted by a dotted line in the charts.

Fig. 3 summarizes the characteristics of performance: gross and net efficiencies, gas turbine efficiency and incremental efficiency. Gross efficiency is the only performance in Fig. 3 which substantially depends on the ratio of $q_{des}$. The decrease in efficiency accompanying the growth rate is caused by the growing importance of the efficient use of natural gas in the system, which is lower than the efficiency of the use of coal (the higher the power of the gas turbine, the lower the efficiency of the gross electricity generation). Obtaining a roughly constant distribution of the net efficiency of electricity production with changing $q_{des}$ is a result of the minor effect of this ratio on the amount of power used for the system's own needs, which is the sum of the needs of the steam cycle, separation plant and the $CO_2$ compression installation. In addition, due to the value of the gas turbine efficiency (0.4138), change in the power of the gas turbine does not contribute to the change in net efficiency of the whole unit.

Reported declines in gross efficiency and net efficiency of the analyzed system compared to the reference system with heat supplied from the steam circuit show that the drop in efficiency is much lower for the system with a gas turbine. With gross efficiency

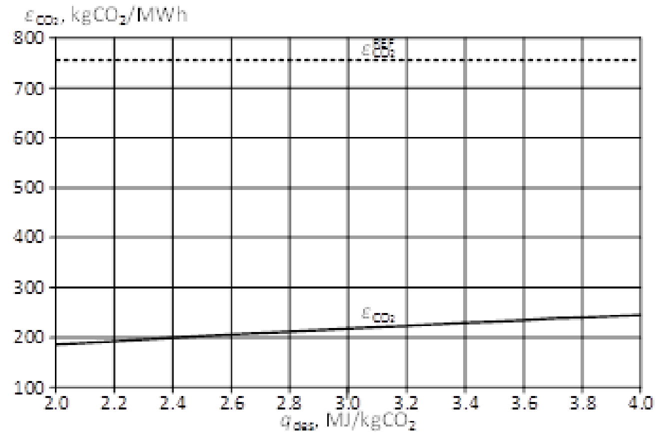


Figure 4: Emission factor of $CO_2$ per unit as a function of rate of heat demand for the desorption process

depending on the values of heat demand for desorption, the drop in efficiency (relative to the gross efficiency of the power unit with no $CO_2$ separation) ranged from 2.1 to 3.3 percentage points (see Fig. 3). With the classical way of integrating a $CO_2$ desorption unit, the corresponding decrease in gross efficiency would be 3.9 to 7.8 percentage points. Since the decline in net efficiency practically does not depend on the values of $q_{des}$ its value was constant, at 4 percentage points (see Fig. 3). With the classical solutions of integrating the power unit with the $CO_2$ separation and compression installation, the decrease in net efficiency would be, depending on $q_{des}$, from 9.5 to 13.5 percentage points.

Incremental efficiency calculated for the analyzed power unit does not depend on the ratio of heat demand for the desorption process. The value obtained here, 0.5191, indicates a much higher efficiency of use of natural gas than is achieved in a stand-alone gas turbine. However, this efficiency is much lower than the efficiency of newly constructed gas turbine combined cycles (currently over 60%).

Fig. 4 shows the characteristics of the unit ratios of the $CO_2$ emission obtained for the analyzed system and the reference system. Emission in the case of the unit with supercritical parameters with no separation of $CO_2$ is 755 kg/MWh. With separation including the use of a gas turbine system, a significant reduction in the emission factor can be achieved, but the effect is limited due to the lack of separation of the greenhouse gas from the gas turbine exhaust. This ratio is much higher than it would be the case if the power plant was integrated with a separation installation in the conventional way.

## 5. Economic analysis

### *5.1. Indicators*

The economic analyzes included two variants of the power unit, i.e. a variant of reference, and therefore without CCS, and a variant integrated with the installation as per the idea presented in section 3. The economic analysis was carried out using the break-even price of electricity. This quantity is the theoretical price at which the electricity would be sold to provide profitability for the investment. The break-even price of electricity is determined from the condition:

$$C_{el}^{b-e} = C_{el}(NPV = 0) \tag{6}$$

where NPV is the net present value, a popular indicator of economic efficiency obtained from the relation:

$$NPV = \sum_{t=0}^{t=N} \frac{CF_t}{(1+r)^t} \tag{7}$$

where: $r$ – discount rate, $t$ – successive year of consideration from the time of starting construction of the system.

The chosen method requires the determination of cash flows ($CF$) for each year ($t$) associated with the investment period:

$$CF_t = [-J + S - (K_{op} + P_d) + A + L]_t \tag{8}$$

where: $J$ – investment cost, $S$ – sales, $K_{op}$ – operating costs, $P_d$ – income tax, $A$ – depreciation, $L$ – liquidation value.

Investment cost ($J$) in this variant was determined using the reference unit investment ($i$), which determines the rate of total investment outlay per 1 kW of installed capacity of gross electricity:

$$J_{REF} = i_{REF} \cdot N_{el,ST} \tag{9}$$

In the case of the variant with the plant integrated with a separation unit the investment rate is higher than the reference variant due to the extra outlay

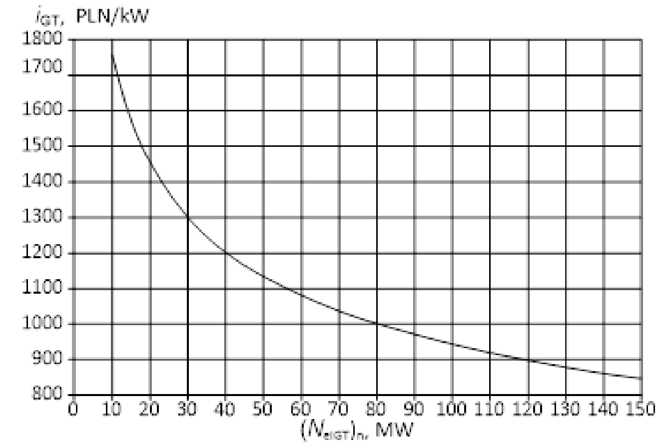


Figure 5: Unit cost of purchasing the gas turbine as a function of its nominal electrical power

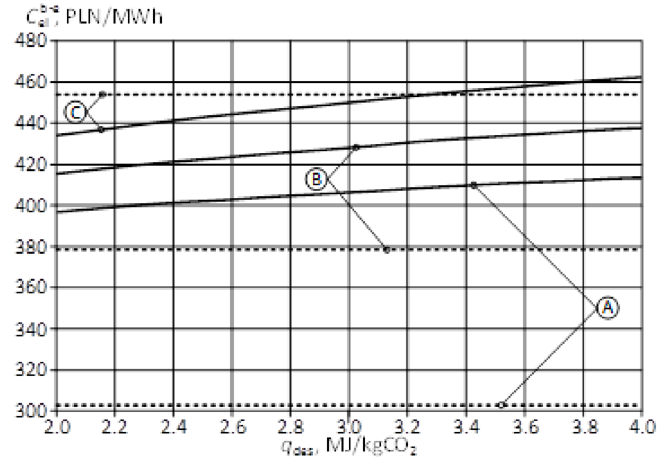


Figure 6: Break-even price of electricity as a function of the heat demand for the desorption process, obtained for three values of the prices for emission allowances; A: 100 PLN/Mg$CO_2$, B: 200 PLN/Mg$CO_2$ and C: 300 PLN/Mg$CO_2$

for components associated with separation and compression of $CO_2$. In the case of the reference unit, investment expenditure was assumed at the level of 5050 PLN/kW$_b$. If the unit is integrated with CCS, the value of the index was set at the level 8650 PLN/kW$_b$. In the case of the variant unit integrated with CCS, the investment expenditure included additional outlay on the gas turbine system ($J_{GTU}$). Accordingly, in this case, the investment outlay was:

$$J = i \cdot N_{el,ST} + J_{GTU} \tag{10}$$

The effort was made considering the values characterizing the gas turbine and the evaporator and was determined using the equation:

$$J_{GTU} = B[l_{GT} \cdot i_{GT} \cdot N_{el,GT} + 44204 \cdot (kA)^{0.6}] \tag{11}$$

where: $B$ – building cost factor [10] (assumed $B = 2$), $l_{GT}$ – the number of installed gas turbines, $i_{GT}$ – unit cost of purchasing gas turbine, $(N_{elGT})_n$ – nominal electric power of the gas turbine, $kA$ – thermal conductivity, W/K.

The values of unit investments were based on the literature [10–16]. On the basis of the same literature sources, the unit costs of operation and maintenance of individual systems were determined (see Table 2).

$$i_{GT} = 21346 \cdot (N_{el,GT})_n^{-0.271} \tag{12}$$

In addition, other investment flows identified according to Eq. (8) depend to a lesser or greater extent on the thermodynamic characteristics of the unit. Prior to the analysis, it is important to make assumptions for the economic environment in which the energy system is functioning. The key assumptions used in the analysis are summarized in Table 2. It is worth noting that some of the values recorded in the table (in addition to unit investment, as mentioned earlier) differ significantly for the reference system and the installation of an integrated CCS. The economic disadvantages of integrated systems are higher investment costs. However, the economic analysis assesses the validity of the integration of the CCS the installation, especially by evaluating the possibility of higher compensation of expenses and costs by reducing the costs associated with greenhouse gas emissions.

### 5.2. Results of the analysis

Fig. 6 presents the characteristics of the break-even price of electricity as a function of heat demand for the desorption process. The characteristics relate to the three cases, in which the assumed prices for allowances for greenhouse gas emissions are different:

A: $C_{ea} = 100$ PLN/Mg$CO_2$,
B: $C_{ea} = 200$ PLN/Mg$CO_2$,
C: $C_{ea} = 300$ PLN/Mg$CO_2$.

Table 2: Key assumptions for the economic analysis

| Specification | Reference | Integrated system |
|---|---|---|
| Annual operation time, h/a | 8000 | |
| Unit investment costs, PLN/kW gross power | 5050 | 8650 |
| Construction time, Years | 3 | |
| Investment cost split per years of construction, % | 30/50/20 | |
| Share of internally generated funds in investment costs, % | 20 | |
| Share of funds obtained from commercial loan, % | 80 | |
| Actual interest rate for the loan, % | 6 | |
| Repayment time, Years | 10 | |
| Operation time, Years | 20 | |
| Discount rate, % | 6.2 | |
| Unit operations and maintenance costs, PLN/MWh | 25 | 58 |
| Price of coal, PLN/GJ | 15.22 | |
| Price of natural gas, PLN/GJ | 39.10 | |
| Unit employment, Person/MW | 0.5 | 0.2 |
| Monthly salary, PLN/person/month | 5000 | |
| Depreciation rate, % | 6.67 | |
| Salvage value in relation to investment costs, % | 20 | |
| Income tax rate, % | 19 | |

The characteristics indicated by dashed lines refer to the reference system.

The effect of values of heat demand on the evaluation index of economic effectiveness is relatively small. Of the three cases taken into account, only the case where the price of the allowances is the highest could provide an opportunity to compete with the system in which separation is not conducted. Integration of the system seems to be justified only when the values of heat-demand indicator are lower than about 3.3 MJ/kg$CO_2$.

Fig. 7 summarizes the characteristics of the break-even price of electricity obtained for a variable price of emission allowances. The three solid lines refer to the characteristics obtained during the analysis of the integrated unit with the $CO_2$ separation installation on the assumption that we are dealing with three different values of the heat-demand indicator for the desorption process: I: $q_{des} = 2\,\mathrm{MJ/kgCO_2}$, II: $q_{des} = 3\,\mathrm{MJ/kgCO_2}$, II: $q_{des} = 4\,\mathrm{MJ/kgCO_2}$,. The values of the economic effectiveness obtained for the variant of the unit with an integrated $CO_2$ separation and compression installation depend to a much lesser extent on the price of emission allowances than is the case with the reference system (dashed line in Fig. 7). The intersection of individual characteristics obtained for an integrated system with the characteristics of the reference point on the price of allowances, beyond which it is more cost-effective to invest in an integrated unit. The high prices at this

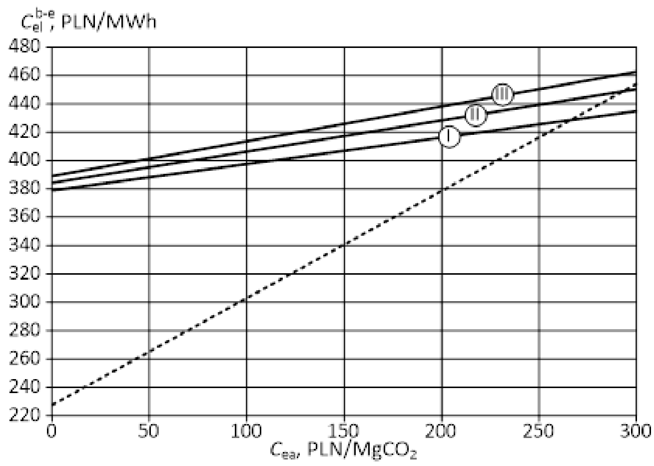


Figure 7: Frontier sale price of electricity as a function of price allowances for greenhouse gas emissions obtained for three values of heat demand for the desorption process; I: 2 MJ/kg$CO_2$, II: 3 MJ/kg$CO_2$ and III: 4 MJ/kg$CO_2$

point show limited competitive potential in the near future for the integrated systems with a separation installation and gas turbines.

## 6. Conclusions

Based on the results of the analyses the following conclusions can be drawn:

- In light of the expected price of allowances for greenhouse gas emissions in the coming years, the competitiveness of including a $CO_2$ separation plant in the power system may be too low compared to solutions without integration.

- The economic effectiveness of the analyzed variants is determined to some extent by heat demand for the desorption process, which is expected to gradually decrease in the coming years with progress in methods of chemical absorption.

- It is very important from the point of view of competitiveness of units with integrated CCS to use the heat recovered within the separation plant and to conduct optimization in this regard. Effective use of this potential can contribute to a significant improvement in the economic characteristics of the solutions studied.

- In addition to the consequences of the growth rates in the emission of greenhouse gases, the competitiveness of integrated CCS systems might be strengthened by reducing the capital expenditure incurred on construction and by reducing the costs of operation and maintenance of the units through the development of separation technology, much of which relates to separation installations, transport and storage of $CO_2$.

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