Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

THE THERMODYNAMIC AND ECONOMIC ANALYSIS OF THE SUPERCRITICAL COAL FIRED POWER PLANT WITH CCS INSTALLATION

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Abstract

In the paper the results of the thermodynamic and economic analysis of the supercritical coal fired power plant integrated with the carbon dioxide capture installation was shown. The paper presents the algorithm for determining the power of power plant and its efficiency losses due to the membrane separation of CO_2 *from the flue gases and* CO_2 *compression. For the purpose of separating* CO_2 *a membrane technology was applied. Calculations concerning the membrane separation of* CO_2 *were carried out with the program Aspen. For the assessment of the separation process two indices were applied: the mole fraction of* CO_2 *in the permeate and the recovery ratio of* CO_2*. The decision variables in the calculation were the pressure on the feed side and on the permeate side. The pressure on the permeate side is generated by a vacuum pump and on the feed side by a compressor. The power rating of require components determines the energy consumption of the separation and compression processes. The way of determining the minimum losses of the power rating and efficiency of the power plant in membrane separation process and compression* CO_2 *using calculated indices were shown. The power rating losses and efficiency of the power plant were determined for both processes. The economic analysis was calculated for power unit, taking into account investments and costs connected to the* CO_2 *capture installation. For the conducted analysis it is essential to determine the unit sale price of electricity as well as the cost of avoided emission* CO_2*.*

Keywords: *supercritical power plant, capture* CO_2*, membrane separation*

1. Introduction

One of the priority operations in the UE is environmental protection. Poland as a members country has the task of reducing of the anthropogenic emissions of greenhouse gases, mainly CO_2 connected with the energy production from fossil fuels. The reduction of CO_2 emission prevents global climate change. Also, Improved energy efficiency, effective burning of fossil fuels and the use of alternative energy sources will help to reduce this emission. A technique that could make it possible to faster achieve large reduction of greenhouse gases emission is CO_2capture from power generation processes.

There are many possibilities of reducing the emission of CO_2 in energy processes [7]. The main methods are pre-combustion capture, post-combustion capture and oxy-combustion.

In the presented a paper use of a post-combustion process, including the membrane separation of carbon dioxide from combustion gases is described [8].

2. Thermodynamic analysis and the results of calculations

High efficiency of the electricity production has a connection to these technologies, which that influence more effective and efficient use of fuels. A modern power engineering rely on supercritical coal fired plant. Various structures and parameters with electric power of $N_{el,REF}$ = 600 MW are presented in the paper [2]. These are reference systems for the Polish power engineering after the year 2010. The model of the supercritical coal power plants integrated with CCS installation was applied for the analysis. The diagram of such an installation is presented in fig.1.

Characteristic parameters of this block are [6]:

- Temperature and pressure of live steam – 600˚C/28.5 MPa,
- Temperature of resuperheated steam – 620˚C,
- Pressure in the steam condenser – 5 kPa,
- Isentropic efficiency of all turbine stage – 0.9,
- Mechanical efficiency and efficiency of the generator – 0.99 i 0.988,
- Efficiency of the boiler – 0.95,
- Efficiency of the electricity production – 0.4878,
- Lower Heating Value – 24500 kJ/kg.

Such a systems emits 2.086 Mg/h of flue gases of the mole fraction of CO_2 amounts to 14.05%, which gases CO_2 emission equal to 121.3 kg/s [6]. Assuming that the block annual work for 8000h, the CO_2 emission would amount to 3 493 440 Mg.

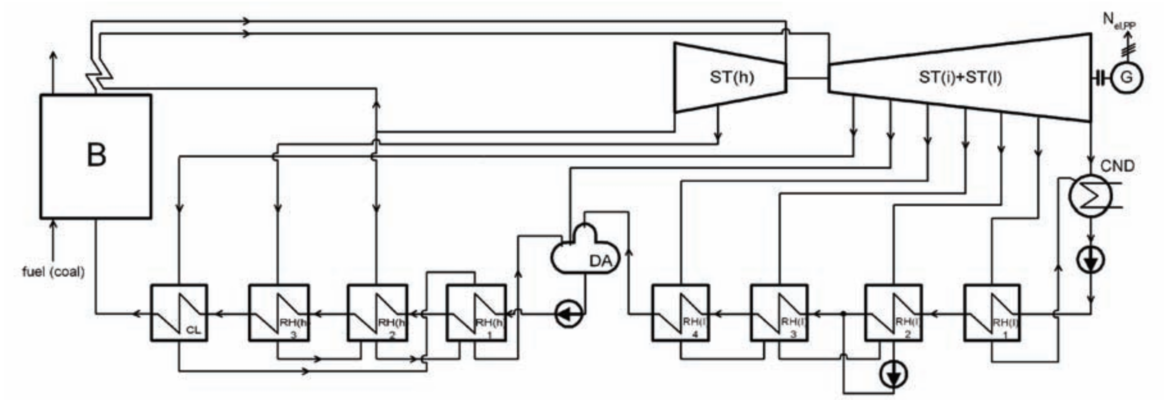

Fig.1 Reference systems of supercritical carbon blocks (B- boiler, ST – steam turbine, G – generator, CND – condenser, DA – deaerator, CL – cooling steam, RH – reheater, h, i, l – stage of turbine (high, intermediate, low)

For these reference systems of supercritical carbon blocks is characterizing by high efficiency of electricity generation, the separation of CO_2 from flue gases was applied in order to lower its emission. Diagram of the installation of membrane separation and compression of CO_2 from flue gases are presented in fig.2. This system consists of membrane module (M), flue gases compressor (C), vacuum pump (VP), CO_2 compressor (C1) and heat exchangers HE1 and HE2. The aim of membrane module is to separate CO_2 flow from the flue gases (so-called permeate). The permeate is this part of the solution flue gases which penetrates the membrane. The driving force of the process is the difference of partial pressures on both sides of the membrane.

There are two essential quantities used for the assessment of the process of separating CO_2 from flue gases: the mole fraction of CO_2 in the permeate $(Y_{CO2})_P$ (purity of permeate) and carbon dioxide recovery ratio R, determining how much of CO_2 in the flue gases leaving the boiler is contained in the permeate flow; second one is expressed by the equation:

$$R = \frac{n_{5a}\left(Y_{CO_2}\right)_P}{n_{1a}\left(X_{CO_2}\right)_{1a}}, \tag{1}$$

where:
n-flux of the flue gas, kmol/s, R-carbon dioxide recovery ratio, X,Y-mole fraction.

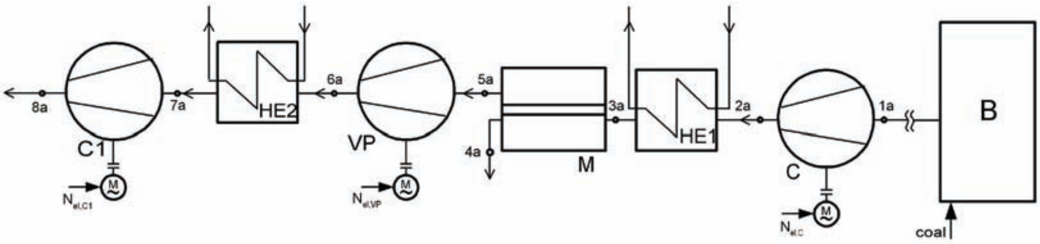

Fig.2 Diagram of the system of membrane separation and compression CO_2 from flue gases emitted by the power plant presented in Fig.1 (HE – heat exchanger, C – compressor,C1 – CO_2 compressor, VP – vacuum pump, B – boiler, M – membrane module).

Calculations concerning the membrane separation of CO_2 were carried out using Aspen software. The model of this process was developed basing on the following assumptions. The analysis was carried out in the membrane module consisting of cross-flow capillaries. The gases are considered as semi-ideals. Furthermore, constant temperature of the process at 40˚C was assumed (hence, it is necessary to use the heat exchanger HE1 which is shown in fig.2). It permitted to use the constant coefficients of permeability for the gases. It was also assumed that the flow of 900kmol/h was passing through the membrane module with a surface area of 18000 m^2. The decision variables in the calculation were the pressure of the flue gases and of the permeate [4].

For the analysis a hybrid membrane which permits the following properties i.e. the CO_2 permeability equals to 20 m^3(STP)/(m^2·h·bar) and the ideal coefficient of selectivity equals to 200 was used. The pressure of the flue gases was changed in the range $1\ \text{bar} \geq p_{2a} \geq 1.35\ \text{bar}$ and the permeate pressure was changed in the range $0.005\ \text{bar} \geq p_{5a} \geq 0.08\ \text{bar}$. The pressure on the permeate side was generated by a vacuum pump and on the flue gases side by a compressor. The power rating of require components determines the energy consumption of the membrane separation process.

The power station internal load rate, including the power demand devices connected to the CO_2 separation from flue gases of reference to the power of the power plant, is mark by the symbol δ_1 and it is expressed by the equation:

$$\delta_1 = \frac{n}{\eta_{el,REF}\eta_{em}m_f \cdot LHV}\left\{\left\{T_{1a}\left(Mc_p\right)_C\left[1+\frac{\left(\frac{p_{2a}}{p_{1a}}\right)^{\frac{\kappa_C}{z_C}}-1}{\eta_{i,C}}\right]^{z_C}-1\right\}+T_{3a}\left(Mc_p\right)_{VP}X_{CO_2}\frac{R}{\left(Y_{CO_2}\right)_P}\left\{\left[1+\frac{\left(\frac{p_{6a}}{p_{5a}}\right)^{\frac{\kappa_{VP}}{z_{VP}}}-1}{\eta_{i,VP}}\right]^{z_{VP}}-1\right\}\right\}, \tag{2}$$

where:
LHV - Lower Heating Value, kJ/kg, (Mc_p) - specific molar heat capacity, kJ/kmol·K, p- pressure, bar, T - temperature, K, z - number of stages in the compressor or vacuum pump, κ - isentropic process exponent, η - efficiency, %, δ - power station internal load rate.
Index: 1a, 2a - characteristic points in the system of membrane separation (fig.2), C - compressor, VP - vacuum pump, f - fuel, el - electrical, em - electromechanical, REF - reference system

The equation (2) permits to determine what part of the power rating of the power plant is consumed during the membrane separation of CO_2 from the flue gases in relation to the assessment indices of this process e.g. carbon dioxide recovery ratio R and purity of permeate

$(Y_{CO2})_P$. The first part in the curly bracket is connected to the flue gases compression process, the second is connected to the vacuum pump.

The results of the calculations from the Aspen software are presented in figure 2. The figure presents the line of constant values of the mole fraction of CO_2 in the permeate and the line of constant values of the recovery ratio in the plane p_{2a}-p_{5a} (fig.3). This plot includes the line of constant values of the rate δ_1 which is calculated from the equation (2). For the calculation all of these isolines the algorithm of artificial networks was applied.

This figure allows to sort and to select such conditions of the process, for which value reaches δ_1 minimum and in the same time the mole fraction of CO_2 in the permeate and the carbon dioxide recovery ratio are very high.

The area in which the mole fraction of CO_2 in the permeate is greater than or equal to 0.8 and in the same time the recovery ratio is greater than or equal to 0.9 is marked in the figure.

It can be found in the literature [3,5], that for the sake of the costs of compression, transport and deposition of carbon dioxide its permeate purity $[(Y_{CO2})_P]_{limited}$ should to be contained within the range from 0.8 to 0.95, and the carbon dioxide recovery ratio (marked as $R_{limited}$) ought to be larger than 0.8 or even 0.9.

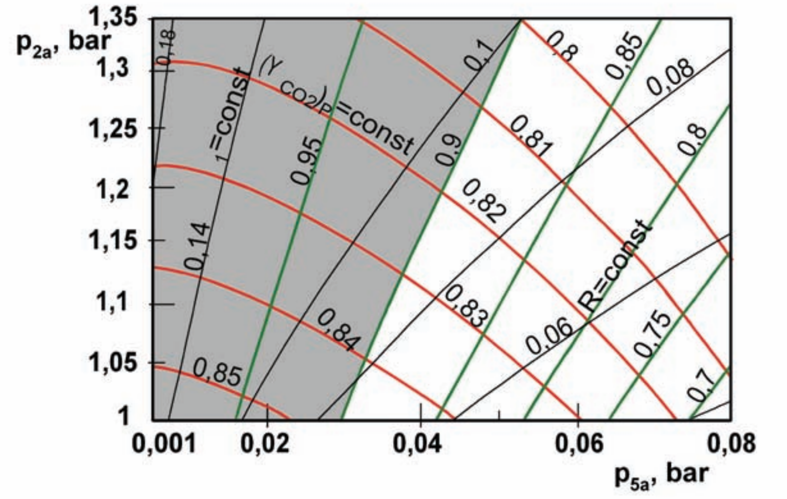

Fig.3 The line of constant values of the mole fraction CO_2 in the permeate $(Y_{CO2})_P$ = const, the recovery ratio CO_2 R = const, and the power station internal load rate δ_1 = const in the plane p_F - p_P for α^* =200 with area mark $(Y_{CO2})_P \geq 0.8$ i $R \geq 0.9$

In this area the minimum power station internal load rate δ_1 is searched for the range of value $R \geq R_{limited}$ and $(Y_{CO2})_P \geq [(Y_{CO2})_P]_{limited}$.

If assume that $(Y_{CO2})_P \geq 0.8$ and $R \geq 0.9$ and use the characteristic from fig.3 we obtain values: $(Y_{CO2})_P = 0.848$, $R = 0.9$, $p_F = 1$bar and $p_P = 0.028$bar. For such parameters the process power station internal load rate amounts to 7.51%.

It was assumed that separated carbon dioxide was subjected to atmospheric pressure and it had a high temperature. In order to transport separated CO_2, first it has to be cooled and next compressed to high pressure. Scheme of these processes is presented in fig.2. Power station internal load rate δ_2 already includes the power needed for carbon dioxide compression process.

According to the literature [4,10,12] liquefaction of CO_2 for transport needs the compression of CO_2 to pressure around 100 – 120 bar. It depends on the permeate purity. In this analysis carbon dioxide was compressed to 100 bar.

The electric power needed for the driving motor of the CO_2 compression equals to:

$$N_{elC1} = \frac{T_{7a}\left(Mc_p\right)_{C1} X_{CO_2}}{\eta_{em}} \frac{R}{\left(Y_{CO_2}\right)_P} \left\{ \left[1 + \frac{\left(\frac{p_{8a}}{p_{7a}}\right)^{\frac{\kappa_{C1}}{z_{C1}}} - 1}{\eta_{i,C1}} \right]^{z_{C1}} - 1 \right\}, \qquad (3)$$

where: N - power, MW

The efficiency of electricity production in the power plant with the electric power of the motor compressors driving and vacuum pump taken into consideration cab be written as

$$\eta_{el,CCS} = \frac{N_{el,REF} - (N_{el,C} + N_{el,VP} + N_{el,C1})}{m_f \cdot LHV} = \eta_{el,REF}(1-\delta_2), \qquad (4)$$

where:

$$\delta_2 = \frac{N_{el,C} + N_{el,VP} + N_{el,C1}}{N_{el,REF}}, \qquad (5)$$

and it make up power station internal load rate CCS installation.

The results of thermodynamic analysis of the influence of the CCS installation for the supercritical coal fired power plant are presented in table 1.

Tab. 1 The parameters of the devices connected to the CCS installation

Characteristic parameters	Unit	Power Plant with CO_2 capture
$N_{el,C}$	MW	0
$N_{el,VP}$	MW	45,07
$N_{el,C1}$	MW	74,07
δ_1	-	0,0751
δ_2	-	0,1981
$\eta_{el,REF}$	-	0,4878
$\eta_{el,CCS}$	-	0,3912

3. Economical analysis and the results of the calculations

In the conducted analysis of the economical effectiveness the net present value (NPV) method was used. NPV is one of the fundamental and most frequently applied economic coefficients for the assessment of the economical effectiveness of the investments. It can be described by the equation:

$$NPV = \sum_{\tau=1}^{N} \frac{CF_\tau}{\left(1+r\right)^\tau}, \qquad (6)$$

The value of the discount rate was assumed at 6,2%. In order to determine the cash flow CF_τ the total investment costs (J), profits from sales (S_{el}), overall costs of production (K_{PR}), the income tax (P_d), changes of the working capital (K_{obr}), amortization charges (A), interest (F) and clearance value of the designed installation (L) $\left(L,\ L_\tau = 0\ when\ 0 \le \tau \le N-1\right)$ had to be known.

Thus, the equation describing the cash flow CF_τ can be written as:

$$CF_\tau = \left[-J + S_{el} - \left(K_{PR} + P_d + K_{obr}\right) + A + F + L\right]_\tau, \qquad (7)$$

The investment costs in signified analysis are given by equation:

$$J = i_N \cdot N_{el} + i_{CCS} \cdot N_{el}, \qquad (8)$$

where: i_N – unit investment cost for the power installation, €/kW, i_{CCS} – unit investment costs for the CCS installation, €/kW.

The essential component of the equation (7) is the profit from sales, expressed as:

$$S_{el} = \int_0^{\tau_{el}} N_{el} \cdot C_{el} \cdot d\tau_{el} \ , \tag{9}$$

where: C_{el} – average price of electricity, € /MWh, τ_{el} – the annual time of operation, h.

Total costs of production were determined as a sum of the following costs:

$$K_{PR} = K_F + K_o + K_{ps} + K_E + K_{sr} + K_r + A_k + A + F \ , \tag{10}$$

where: K_F – cost of fuel, K_o – cost of services, K_{ps} – cost of other raw materials, K_E – other operating costs, K_{sr} – environmental costs, K_r – costs of maintenance and exploitation, A_k – excise duty, A – amortization costs, F –interest.

The economic analysis were made for the reference system and also for similar power unit, taking into account the investments and costs connected to the CO_2 capture installation. For the system with CO_2 separation previously calculated values permeate purity $(Y_{CO2})_P = 0.848$ and carbon dioxide recovery ratio R = 0.9 were assumed.

Exemplary literature data [1,4,5,9,11] for different supercritical power stations taking into account the cost for CO_2 separation were served to determine the investment costs.

For the economic analysis the investment costs were assumed at 1100 €/kW for the reference system and at 1450 €/kW for the power plant with CO_2 capture. In the calculations, operating costs of capture installation were assumed at 3 €/MWh. The annual time of operation was 8000 hours. Amortization rate was given at 6.67 %. The constant of repairs was determined at the level of 0.5% of the capital costs for the first ten years of operation and 1% for the following ten years. It has been assumed that the investment cost are spread into three years of the construction: 15% in the first year, 30% in the second year and 55% in the third year. It has been also assumed that the conduction of the power generating plant is financed in 15% by own means and in 75% by the commercial credit at the interest of 6%. The credit is assumed to be repaid in equal payments in the course of ten years. The income tax rate was assumed at 19%. Excise duty was assumed at 5 €/MWh and the average cost of fuel was 55 €/Mg. The residual clearance value of the designed system is assumed at $20\% \cdot J$, and the working capital as equal to zero.

In the economic analysis the limit sale price of electricity C^{gr} was calculated. For the reference systems without CO_2 capture it was described by the index REF and for the power plant with carbon capture installation it was described by the index CCS.

For both systems the limit sale price of electricity is a quantity determined by the condition

$$NPV(C^{gr}) = 0 \ , \tag{11}$$

An important economic rate for the power system with CO_2 capture is also the CO_2 emission avoided (E_{AV}) and its cost. The cost of CO_2 emission avoidance (C_{AV}) is calculated according the equation:

$$C_{AV} = \frac{C^{gr}_{CCS} - C^{gr}_{REF}}{E_{AV}} \ , \tag{12}$$

where:

$$E_{AV} = E_{REF} - E_{CCS} \ , \tag{13}$$

E –CO_2 emission, index: REF – reference system, CCS – plant with CO_2 capture.

The results of the economic analysis are presented in table 2. The analysis of susceptibility were also performed. The influence of the investment costs and the fuel cost were tested. The results of the susceptibility analysis are presented in figures (fig.4 i fig.5).

Tab. 2 Results of the economic analysis calculation

	Unit	**Value**
Annual operating time	h	8000
Unit sale price of electricity C^{gr}_{REF}	€/MWh	37.86

Emission CO_2 (E_{REF})	kg/MWh	726
Unit sale price of electricity after CO_2 separation C_{CCS}^{gr}	€/MWh	56.91
CO_2 emission after separation (E_{CCS})	kg/MWh	73
CO_2 emission avoided (E_{AV})	kg/MWh	653
Costs of CO_2 avoiding emission C_{AV}	€/$MgCO_2$	29.18

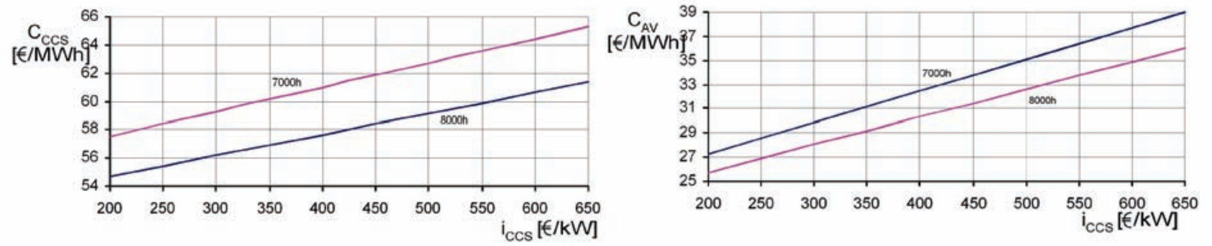

Fig.4 The influence of the investment costs of the CCS installation on the limit sale price of the electricity and on the cost of CO_2 avoided emission

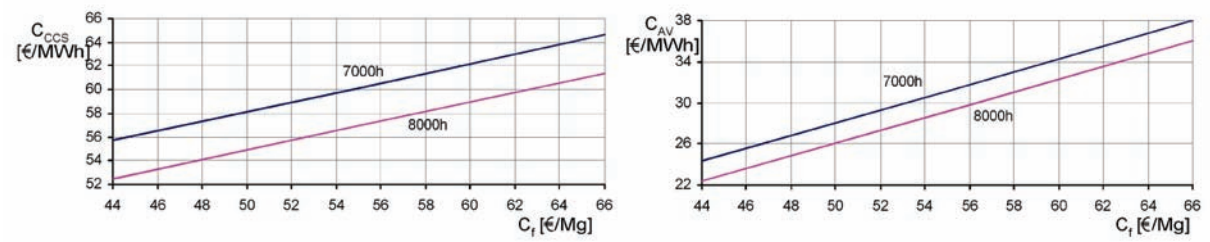

Fig.5 The influence of the fuel costs of the limit sale price of electricity and on the cost of CO_2 avoided emission for the investment costs at 1450 €/kW

The susceptibility analysis ware carried out. The analysis showed that the costs of CO_2 avoiding emissions decrease with decreasing the investment cost. The cost of fuel has an important influence on the price of electricity.

In the susceptibility analysis costs of fuel ware tested. The price of fuel was changed by 20% from considered value. A change of fuel price has an influence the change of the limit sale price of electricity by around 4 € for and above 6 € on the costs of CO_2 avoided emissions.

4. Conclusions

The paper presents the relations between the energy consumption of the membrane separation of CO_2 from the flue gases and the recovery ratio and mole fraction of CO_2 in the permeate as well as the pressure of the flue gases and the pressure of the permeate. The power rating losses and the efficiency of the power plant were determined for both processes – CO_2 separation and compression. In order to decreases power and efficiency of electricity we integrated CCS installation with supercritical coal power plant.

The power rating of installations connected to the CO_2 separation equals to 7.51% of the power station power. As a result the efficiency of the power plant decreases from 48.78% to 45.02%. Take into consideration the influence of CO_2 compression the power station internal load rate is equal to 19.81 % and the efficiency of electricity production decreases to 39.12 %.

In order to decrease heat losses the heat coming from the flue gases and the permeate cooling may be used in the reference system of the steam-water system steam turbine. It makes possible to partly eliminate the steam bleeding. Elimination of the steam bleeding causes an increase of the steam flow to the steam turbine and increases the power. The efficiency of the electricity production is growing in the reference system.

The economic analysis was calculated for the reference system and also for power unit, taking into account the investments and the costs connected to the CO_2 capture installation. In this analysis the limit sale price of electricity and costs of CO_2 avoided emissions was calculated. This investment is profitable when the limit sale price of electricity equals to 56.91 €/MWh or purchase price of CO_2 permission exceed value of 29.18 €/MgCO_2.

In the susceptibility analysis of the investment costs, price of fuel and annual operating time was tested. The cost of electricity generation decreases with longer annual operating time and also when the investment costs decrease. When the CCS installation investment costs increase to 650 €/kW the price of electricity increase about 4,5 – 5 €. However, the costs of CO_2 avoided emissions increase about 7 – 8 €. The fuel price has an influence of about 4 € on the price of electricity and of above 6 € on costs of CO_2 avoided emissions.

Acknowledgements

The investigations presented in this paper have been carried out within the frame of the research project No. PBZ-MEiN-4/2/2006.

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