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Absorptive separation of carbon dioxide from flue gas of high capacity power plants

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Abstract

The paper presents a methodology for modeling the processes of absorptive separation of carbon dioxide (CO₂) from the power plant flue gases. The absorption systems of two supercritical power plants with the capacity of 460 MW and 600 MW were selected for the study. The process of CO₂ separation from flue gases by means of chemical absorption with the use of monoethanolamine and NH₃ aqueous solutions was analysed. The power plant demands for power needed for the separation, compression and transport of CO₂ to the disposal site was determined. The effects of absorptive separation of CO₂ for the power plant were determined, and an economic analysis of such an undertaking was conducted.

Keywords: CO₂ capture, economic and technical analysis

1 Introduction

As technological progress advances, the tremendous impact of human activity on the environment can be seen. There is no human activity that does not have any effect on the atmosphere, hydrosphere, the world of plants and animals or any other part of the surrounding world. This world, however, is unable to keep pace with the changes, and for this reason, together with new technologies which are introduced, measures have to be taken to protect the environment from their harmful effect.

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The problem of the carbon dioxide (CO_2) impact on the environment is an ongoing and controversial issue – in the world of science there are both supporters and opponents of the theory that CO_2 greatly contributes to the greenhouse effect. Regardless of which side we take, the decisions related to the reduction in CO_2 emissions have already been made, and thereby our state is obliged to take action to this end.

Many organisations and research projects have been established in the world to promote action leading to the reduction in the emissions of greenhouse gases. The reduction in carbon dioxide emissions is one of the more important goals of the European Union energy policy, and the quantitative commitments related to the reduction in the greenhouse gas emissions were included in the Kyoto Protocol [17].

The activities connected with the separation of CO_2 from a gaseous mixture have been studied carefully, especially in the chemical industry. Therefore, cooperation between power engineers and chemists should be initiated with a view to adjusting the solutions known from the chemical industry to the needs of power engineering. There are several problems that have to be faced in this field: firstly – the energy consumption of processes; secondly – the demand for the location of CO_2 separation systems, especially in power plants which are already in use; next – the problem of the separated gas storage and disposal.

Extensive research work is now being done in various scientific and industrial centres to find the optimum solutions in this area. In the case of the separation of CO_2 from flue gases, it is mainly focused on the following issues:

- the search for reliable methods of the analysis of physiochemical processes in the separation of CO_2 from flue gases in coal and gas technologies,
- the search for a new generation of sorbents with proper operating characteristics both in the absorption and desorption processes,
- integration of the CO_2 separation processes with the systems of electricity and heat regeneration.

2 Technologies of separation of CO_2 from flue gases

The best way to protect the air is to eliminate or reduce emissions at their source. In practice, however, there is no possibility of total elimination of pollutants emitted into the atmosphere, and consequently there is no way to avoid the purification of gases as they advance from the emission source to the emitter that releases them into the atmosphere. As far as CO_2 is concerned, there are three basic groups of its separation (Fig. 1).

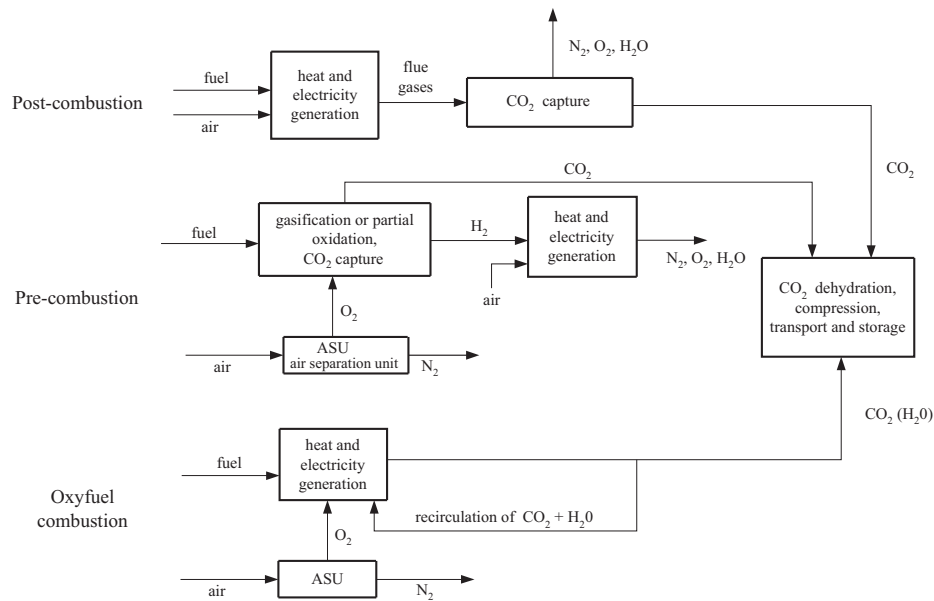


Figure 1: Division of carbon dioxide separation methods: ASU – air separation unit.

The methods of CO_2 separation from flue gases presented in Fig. 1 can be characterised as follows [2,3,5,9,12,21]:

- **Post-combustion** – separation of CO_2 from flue gases after the combustion process by means of chemical absorption, the use of membrane processes, cryogenic methods or adsorption processes. Next, CO_2 is compressed and transported to the disposal site.
- **Pre-combustion** – CO_2 separation techniques before the combustion process. In the case of coal, the gas obtained in the process of gasification is decarbonised. Carbon dioxide which is separated in the physical absorption process is removed in greater concentration than in the post-combustion methods and under high pressure. The result of this action is fuel rich in hydrogen. A similar process can be applied for gas fuel, thus replacing gasification with the process of reforming (synthesis gas production).
- **Oxyfuel combustion** – combustion in a high concentration of O_2 with CO_2 recirculation. In this method nitrogen is removed from the air needed for combustion, and the fuel is burnt in the oxygen atmosphere, whereas CO_2 is recirculated to control the combustion temperature. The flue gases practically contain only CO_2 and steam. After steam is condensed, a flow of CO_2 is obtained, ready for transport and storage or disposal.

3 Absorptive methods of CO₂ separation

Absorptive CO₂ separation belongs to the group of post-combustion methods. The focus of this paper is chemical absorption. The sorbents are aqueous solutions of compounds such as: amines (for example MEA – monoethanolamine, DEA – diethanolamine), ammonia, potassium or sodium hydroxide. The reactions that take place between the compounds and CO₂ are most often reversed with the use of outside heat. The outcome is a mixture of CO₂ and steam plus regenerated sorbent. Monoethanolamine is considered to be one of the better sorbents of the ones mentioned above due to its high CO₂-related sorptive properties, and the capability of absorbing CO₂ at low pressure.

Absorption is the phenomenon during which gas is taken in by a liquid in which it dissolves to a small or large degree. Absorption processes have two basic goals: one – to separate one or more components from the gas phase (which often involves the component recovery); the other – to obtain a particular component in the liquid phase [13,15]. At present absorption is the method most often used to separate CO₂ from flue gases because the process is highly efficient and the result is a product of high purity. Carbon dioxide separation is based here on one or several reversible reactions between CO₂ and other substances. The absorption process is carried out in the absorber-stripper system. Figure 2 presents a simplified diagram of such a system.

4 Model of a supercritical power plant

Two supercritical power plants with the capacity of 460 MW and 600 MW were selected for the analysis. Their models were created with the commercial Gate-Cycle software [18]. Different fuel composition was assumed for the power plants to obtain flue gases with a different content of CO₂. Tables 1 and 2 present the obtained parameters of the flue gases.

5 Model of the chemical absorption/desorption process for a power plant

The scope of modeling included the following steps:

- creation of the model of the absorption column in the commercial package software Aspen Plus [19],
- determination of the number of columns needed to separate carbon dioxide from the flue gases under analysis,

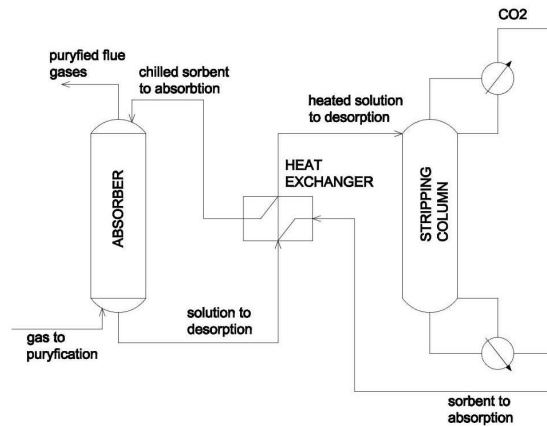


Figure 2: Scheme of the absorber-stripper system [15].

Table 1: Flue gas parameters from 460 MW power plant.

Temperature	80 °C
Pressure	102.24 kPa
Mass flow	425.6 kg/s
Composition (mole fraction)	
N ₂	0.7168
CO ₂	0.1407
H ₂ O	0.1148
O ₂	0.01734
SO ₂	0.00178
Ar	0.00858

Table 2: Flue gas parameters from 600 MW power plant.

Temperature	117.36 °C
Pressure	101.24 kPa
Mass flow	544 kg/s
Composition (mole fraction)	
N ₂	0.7135
CO ₂	0.1538
H ₂ O	0.0835
O ₂	0.0179
SO ₂	0.0009
Ar	0.0088

- selection and analysis of the impact of selected parameters on the absorption process effectiveness.

Figure 3 presents the absorber model created in the applied software Aspen Plus. The flue gas mass flow which is fed into the absorption column was divided into a few smaller ones on account of the permissible size of absorption columns [11]. The divided flue gases were fed into several absorbers. In each of them, an identical process takes place.

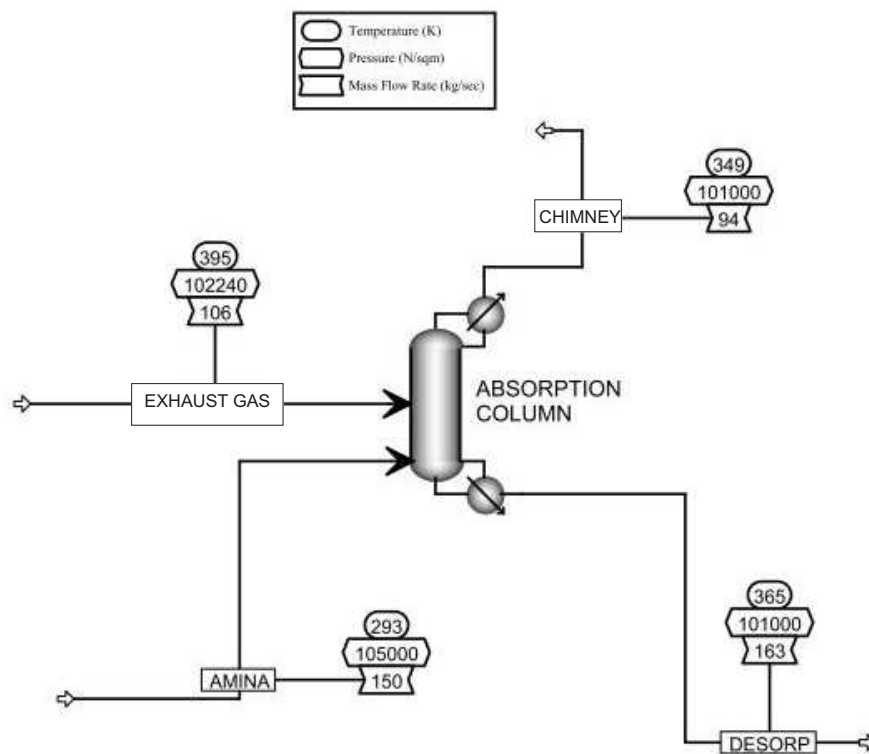


Figure 3: Flowsheet of the absorber model with flows from the software Aspen Plus.

Two variants were considered due to the possible way of modeling absorption/desorption processes. The distinctive feature is how heat is brought into the stripper. In Variant I, direct input of the heat flux (Q) into the stripper was modeled. In Variant II, the heat was brought to the stripper through a steam – desorption agent heat exchanger. Variant II is closer to the real process. The modeling

conducted according to the two variants gave the same results. Therefore, it was Variant I which was adopted for the analysis, as its analysis is less complicated. Figures 4 and 5 present detailed diagrams of CO₂ separation for one absorber/stripper system according to the described variants. For 460 MW power plant CO₂ separation will proceed in four such technological cycles.

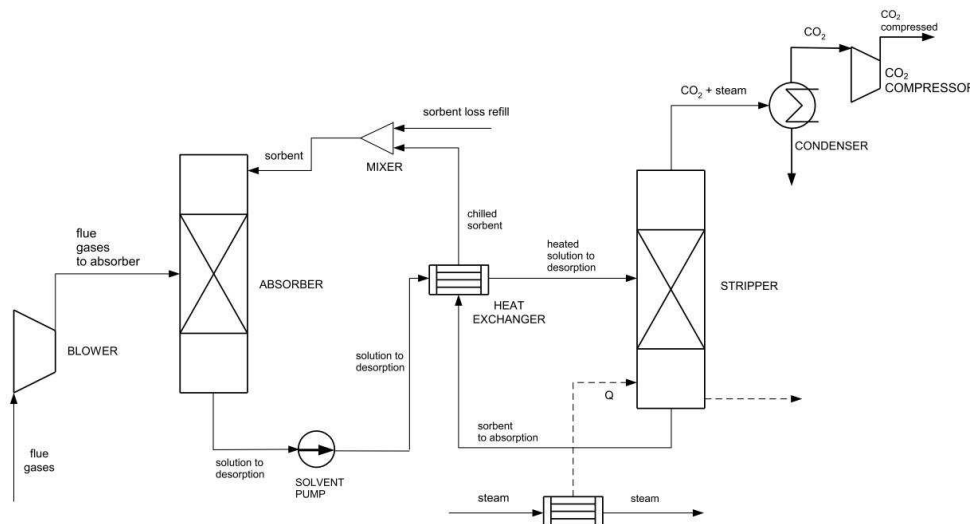


Figure 4: Flowsheet of CO₂ capture by means of chemical absorption method – Variant I.

6 Results of the analysis of CO₂ absorption process by means of the amine method for 460 MW power plant

Considering the system of the amine absorption process, presented before in Fig. 4, the impact of the sorbent temperature, flue gas temperature, and MEA concentration on the process of CO₂ separation from flue gases was analysed.

6.1 Sorbent temperature

The temperature was changed within the range of 20–60 °C. The rise in the sorbent temperature involves losses of the MEA solution (the share of amine and water, i.e., of the ballast substances, in the purified flue gases increases – Fig. 6). A rise in the sorbent temperature in the range specified above involves a rise in

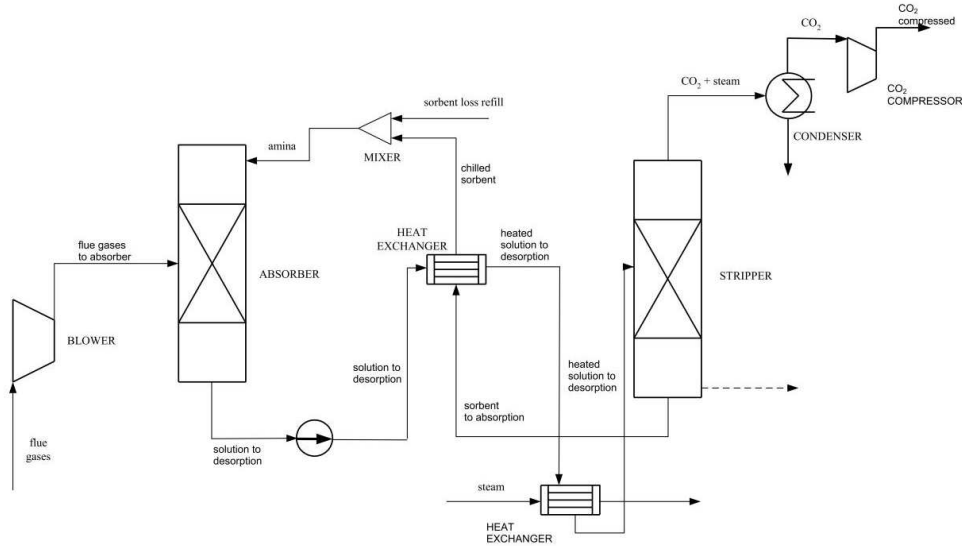


Figure 5: Flowsheet of CO₂ capture by means of chemical absorption method – Variant II.

the purified flue gas temperature by 11 °C. It can be concluded from the presented calculation results that the lower the temperature of the absorption process, the better. There are fewer ballast substances in the obtained flue gases, and more carbon dioxide is absorbed by the sorbent.

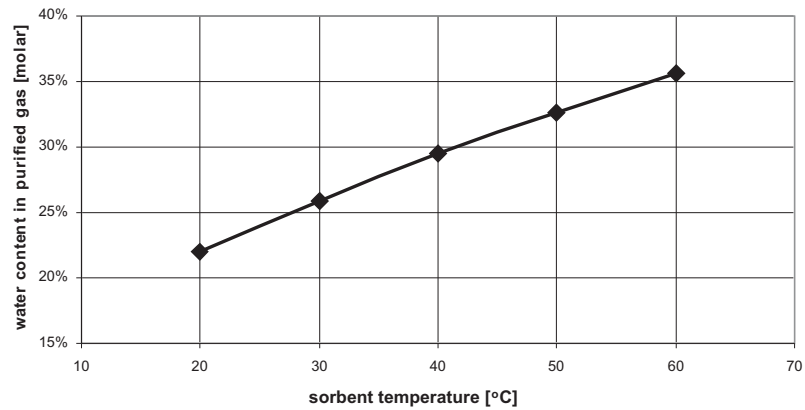


Figure 6: The impact of the sorbent temperature on the content of H₂O in the purified flue gases.

6.2 Flue gas temperature

The impact of the flue gas temperature on the absorption process is similar to the effect of the temperature of the sorbent. In this case, the change in the flue gas temperature was studied within the range of 80–110 °C with a constant sorbent temperature. In this situation, there is a rise in the temperature of the purified gas by 1 °C, i.e., a change in the flue gas temperature has a smaller impact on the process than a change in the temperature of the sorbent (Fig. 7). The effect on the composition of the purified gas is similar to that of the changes in the MEA temperature. Consequently, the lower the flue gas temperature, the fewer ballast substances are contained in the gas leaving the absorber.

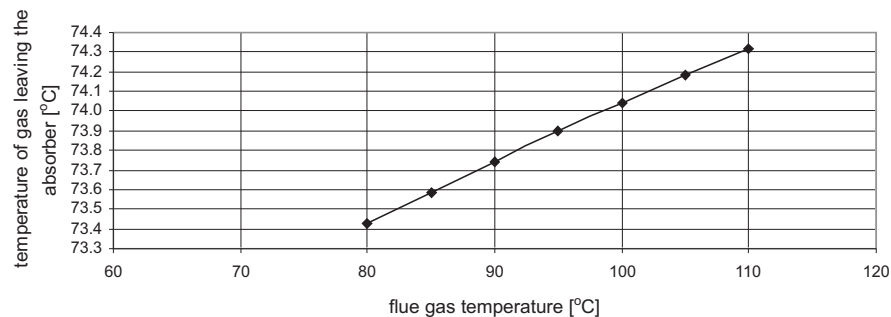


Figure 7: The impact of the flue gas temperature on the temperature of the purified gas.

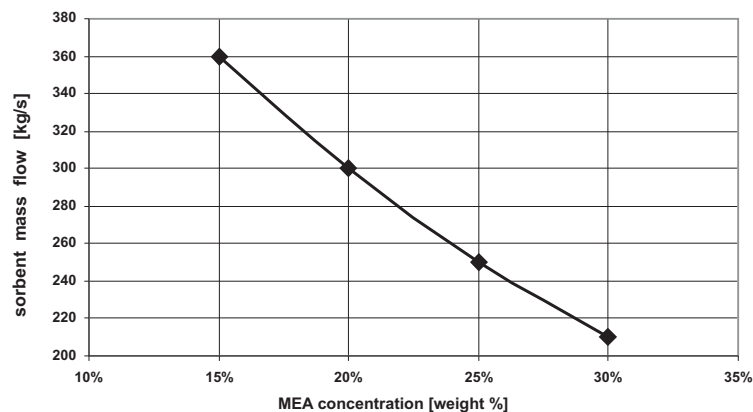


Figure 8: Change in the sorbent flow as a function of MEA concentration (the same degree of CO₂ absorption).

6.3 Monoethanolamine concentration

The impact of the monoethanolamine (MEA) concentration in the aqueous solution of the sorbent on CO₂ absorption is presented in Fig. 8. According to the reference literature data [6], the concentrations from 15% to 30% can be used, and such concentrations were analysed in this paper. The modeled absorptive column is an equilibrium column (reactions proceed according to chemical equations). Therefore, in order to achieve a similar degree of CO₂ absorption (trace amount in the purified gas), the sorbent flow had to be increased.

7 Results of the analysis of CO₂ chemical absorption process with the use of ammonia water as sorbent for 460 MW power plant

For the process of ammonia absorption, the impact of the following factors was examined: the sorbent temperature, the pressure in the column, and the concentration of ammonia water. Example results are presented in Figs. 9 and 10.

7.1 Sorbent temperature

The Fig. 9 shows ammonia content in flue gases). The temperature was changed within the range of 2–20 °C (following the CAP – chilled ammonia process [20]). It noticed that the higher the temperature was, the more ballast substances were present in the purified flue gases.

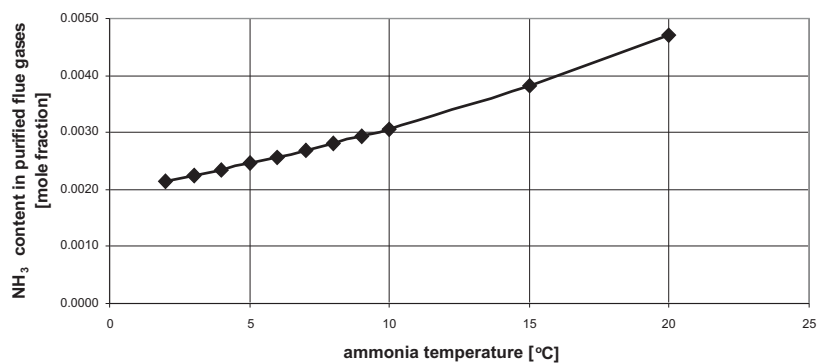


Figure 9: The impact of ammonia temperature on the CO₂ absorption process.

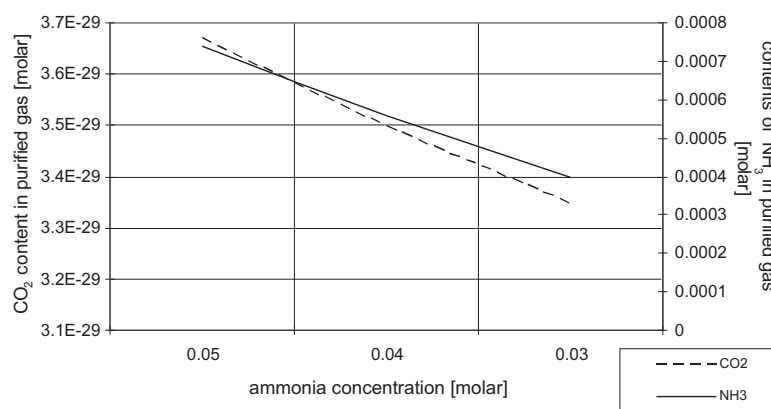


Figure 10: The impact of ammonia water concentration on purified flue gas composition.

7.2 Ammonia water concentration

The impact of the ammonia water concentration was analysed (Fig. 10). It can be noticed that a concentration of as little as 3 %mol. of the ammonia solution leaves only trace amounts of CO₂. Moreover, the lower the ammonia concentration, the fewer ballast substances in the purified flue gases.

8 Results of the analysis of CO₂ chemical absorption process with the use of K₂CO₃ aqueous solution as sorbent for 460 MW power plant

In the case under analysis, the use of the K₂CO₃ aqueous solution gives worse results than those obtained with amine solutions. Example results are presented in Fig. 11.

In the case under examination, the flue gas and sorbent pressure was 2.1 MPa. Better results can be obtained by raising the pressure, but this is unjustified in terms of both economy and energy. Moreover, even a 30% K₂CO₃ concentration does not remove CO₂ to trace amounts.

Considering the results mentioned above, absorption by means of the K₂CO₃ solution was rejected, and two other sorbents – amine and ammonia – were selected for further analysis.

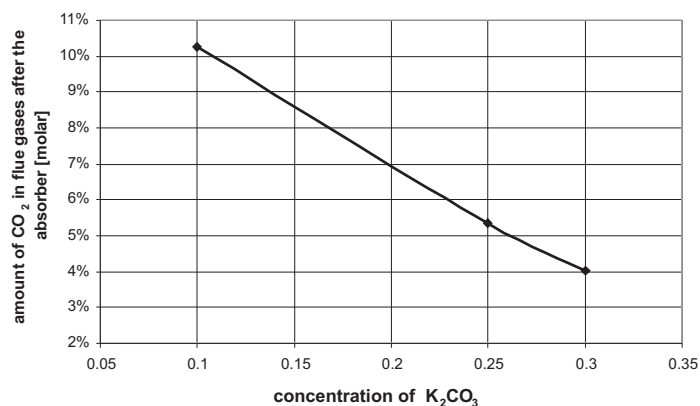


Figure 11: The impact of K_2CO_3 concentration on CO_2 content in flue gases leaving the absorber.

9 Desorption process for 460 MW power plant

The desorption system is composed of the following facilities (Fig. 12): a pump which increases the pressure before the stripper, a heat exchanger which heats up the gas mass flow to be desorbed, a stripping column, a system which feeds heat into the stripper, and a cooling system of the steam – CO_2 mixture (to separate CO_2 from it). Desorption consists in reversing the reaction in the absorber by feeding heat into the system (in Fig. 12 the heat flux is marked with a broken line). The heat was delivered from the system of a 460 MW power plant (bleeds from the low-pressure turbine, steam parameters: pressure – 250 kPa, temperature – 198.4 °C). The pressure in the stripper is about 200 kPa, and the temperature should not exceed 122 °C, due to the thermal degradation of the sorbent.

After the desorption process for a given power plant was modeled, and the following parameters were analysed:

- the connection of columns – the following configurations were examined: one absorber – one stripper, and two absorbers – one stripper;
- the amount of heat brought to the column – the amount of heat needed to reverse the reactions proceeding in the absorber was looked for;
- the division of the heat fluxes – feeding heat into the stripper at several points;
- the pressure in the stripper.

After the calculations were completed, it was concluded that the best configuration is the system made of two absorbers and one stripper as shown in Fig. 13. In this configuration, the system occupies less space, and features more advantageous

power characteristics. Additionally, it was found that it was more beneficial to feed heat at two points of the stripping column (Fig. 14). Example results are presented in Fig. 15. The chart shows the results of the study of the effect of the heat flux division on the desorption process. It can be noticed that dividing the heat flux and feeding it into the stripping column at two points lead to a smaller consumption of thermal energy necessary to separate 1 kg of CO₂.

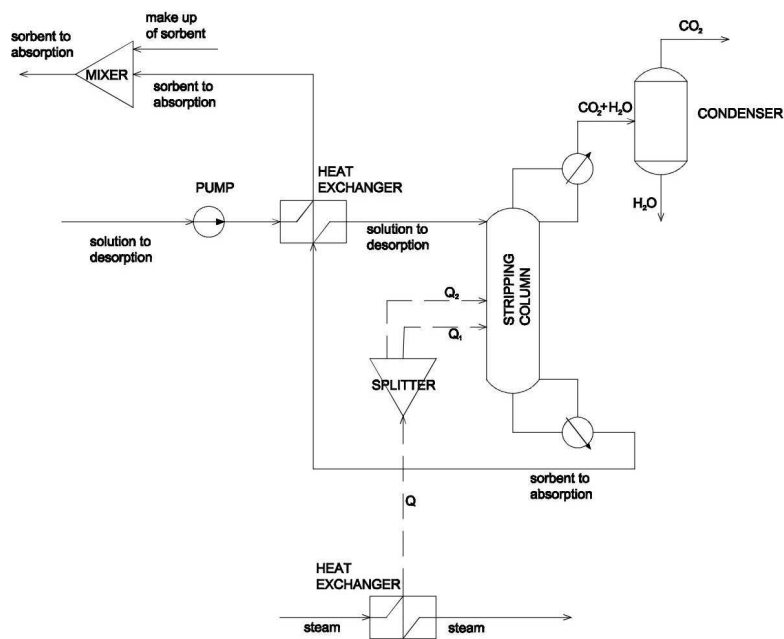


Figure 12: Flowsheet of a desorption system (desorption after the process of amine absorption), Q , Q_1 , Q_2 – heat flux.

A similar analysis was conducted for the ammonia process. The effect of the heat flux division was examined for various heat amounts fed into the stripping column (80, 75, 70, and 65 MW). The heat share in mass flow Q_2 was increased within the range of 0.5–0.9 (cf. Fig. 14). Example results for the system composed of one absorber and one stripper are presented in Fig. 16.

The most important thing from the point of view of power engineering is the amount of heat needed to separate 1 kg of CO₂. For the amine process, the values are 4.7–5.4 MJ/kg of the separated CO₂, whereas for the ammonia process, the values are 2.45–4.33 MJ/kg of the separated CO₂. The values can also be described in the following form:

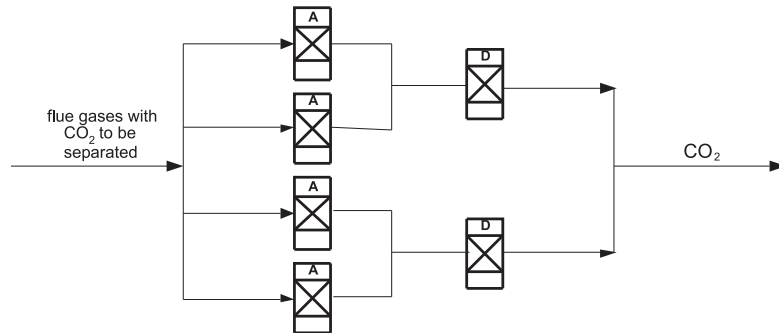


Figure 13: System composed of two absorbers (A) and one stripper (D).

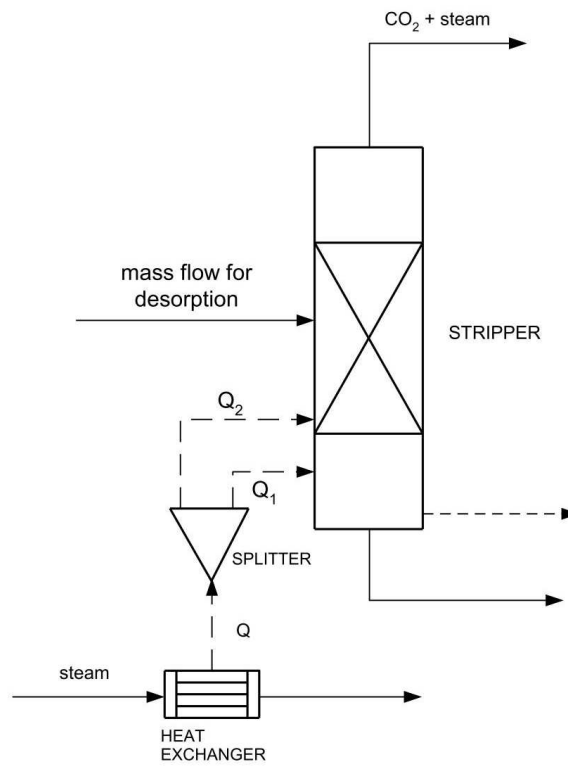


Figure 14: Heat fed into the stripper with heat flux division: Q , Q_1 , Q_2 – heat flux.

- 422 MW_t are needed for the amine process with a full load of the power plant to separate the entire amount of CO₂;
- 220 MW_t are needed for the ammonia process.

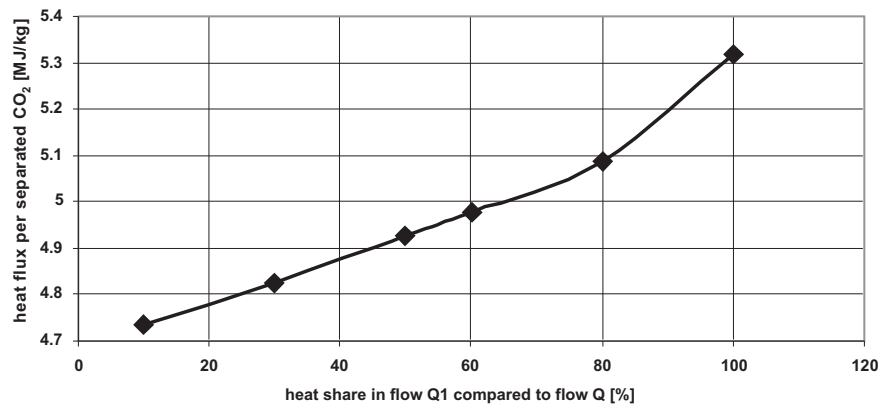


Figure 15: The effect of heat flux division on the amount of separated CO₂ (amine process).

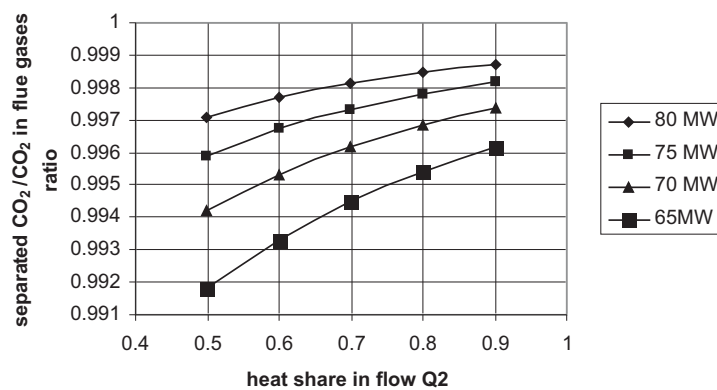


Figure 16: The effect of heat flux division on the amount of separated CO₂.

10 The process of CO₂ separation from flue gases for 600 MW power plant

An analysis of CO₂ separation for 600 MW plant was carried out on the basis of the study made for the power plant capacity of 460 MW. In this case, the study

was limited to technological structures which give good results for 460 MW power plant. Here, the flue gases were fed into six absorbers because the mass flow of the flue gases leaving the power plant is greater. The CO₂ separation system can therefore be presented schematically as in Fig. 17.

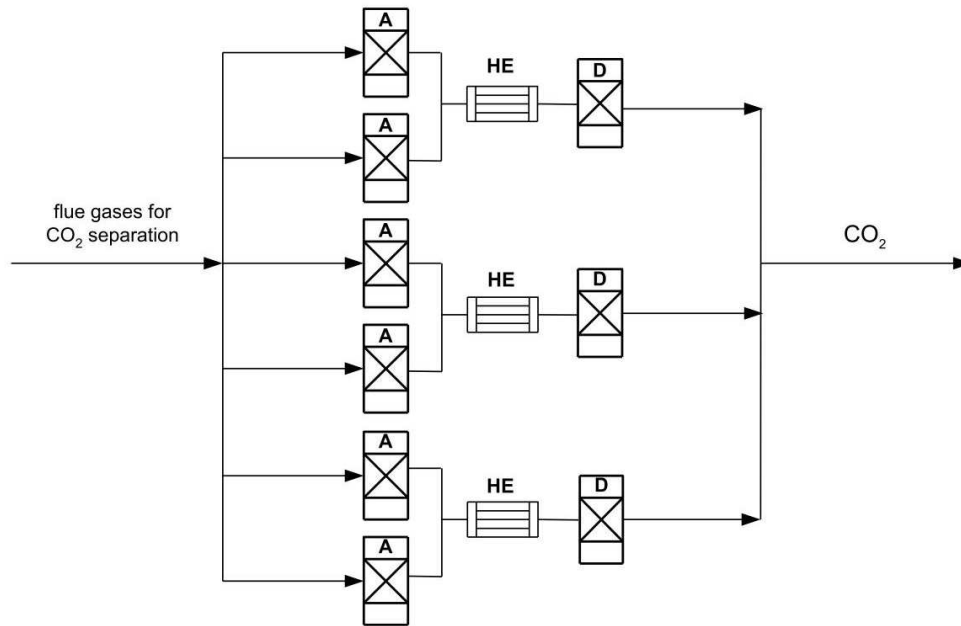


Figure 17: Scheme of the heat flux for CO₂ separation system: A – absorber, D – stripper, HE – heat exchanger.

Considering previous studies, an analysis of the process of CO₂ separation was carried out. It confirmed the demand of heat needed for desorption which had been determined earlier (to separate 99% of CO₂, heat is necessary in the amount of 4.7 MJ/kg of CO₂). This gives 580 MW_t for the power plant under analysis operating at full load, and at the entire amount of CO₂ separated by means of the amine method. For the ammonia method, the amount of heat needed for desorption which had been determined earlier for the power plant with a smaller power capacity was confirmed (to separate 99% of CO₂, heat is necessary in the amount of 2.45 MJ/kg of CO₂). This gives 302 MW_t for the power plant under analysis operating at full load, and at the entire amount of CO₂ separated.

11 Compression and transport of separated CO₂

The CO₂ separated from flue gases should be disposed of. This involves the CO₂ compression and transport for further use or storage. To complete the analysis of energy consumption of the processes of carbon dioxide capture, the problems of compression and transport of the captured CO₂ were also considered. The basic assumptions for the calculations related to the compression and transport of CO₂ were made on the basis of the reference data [1,9]:

- The CO₂ pressure – 10.5 MPa; CO₂ compression to this value (above critical pressure) makes transport more effective. Moreover, it guarantees that the mass flow pressure along the entire section of the pipeline will not fall below the critical value, and no change in phase will occur.
- The CO₂ temperature – 15 °C; at the temperature below 20 °C and pressure above the critical value, the CO₂ density varies from 800–1200 kg/m³, which creates good conditions for transport.
- The pipeline length – 150 km, pipeline sections with the length from 100–150 km are assumed for the transport of CO₂ in the supercritical state, for longer distances compression stations should be used to remedy the pressure losses in transit.

The following factors were modeled: the compression of CO₂ to the state ready for transport, a 150 km long pipeline, a compression station, and another pipeline with the length of 150 km (Fig. 18). The aim of the analysis in these process modules was the determination of energy consumption. The results of the calculations are presented in Fig. 19.

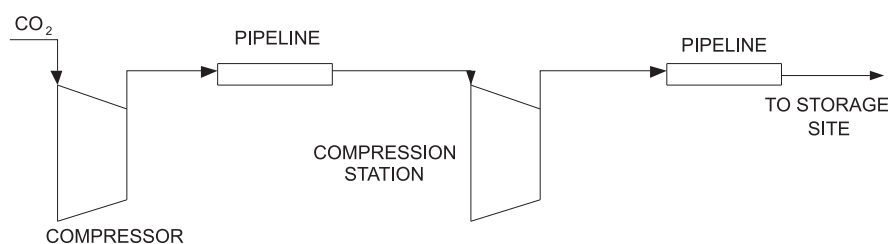


Figure 18: Diagram for modelling CO₂ compression and transport.

The analysis of the processes of the compression and transport of the captured CO₂ showed that these operations were much less energy-consuming than CO₂ separation itself. Similarly to the processes of the gas mixture division, the transport of CO₂ separated by means of the amine method required greater energy expenditures than the ammonia process. For 460 MW power plant, CO₂ com-

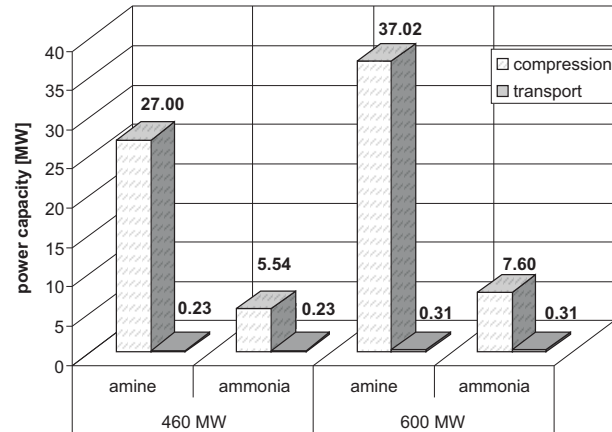


Figure 19: Demand for energy needed for the processes of compression and transport.

pression for transport takes 27.0 MW in the case of the amine process, and 5.56 MW in the case of the ammonia process. For 600 MW power plant, the power values needed to drive the compressors compressing separated CO₂ are 37.02 MW and 7.02 MW, respectively. The differences are due to the fact that after the amine process, a gas with a lower pressure (192 kPa) is obtained than after the ammonia process (2.5 MPa). Consequently, more energy expenditures are necessary to compress the gas to the same pressure value. It should also be noticed that the transport process is much less energy-consuming than the compression process – in the case of transport, the only thing that has to be made up for are the pressure losses arising in the pipeline while transporting the gas at a set distance.

12 Integration of the carbon dioxide capture system with the power plant

For the power plants under consideration, it was proposed that the integration of the carbon dioxide capture (CCS) system with the power plant should be executed through the bleed of low-pressure steam from the gas turbine – a schematic diagram of this system is presented in Fig. 20. Integration occurs through a heat exchanger which feeds heat for the desorption process. The calculations resulted in the parameters of the factors in the exchanger, for each of the variants under analysis. Selected parameters are shown in Fig. 21.

Tables 3 and 4 present a comparison of the cycle net efficiency and of the power

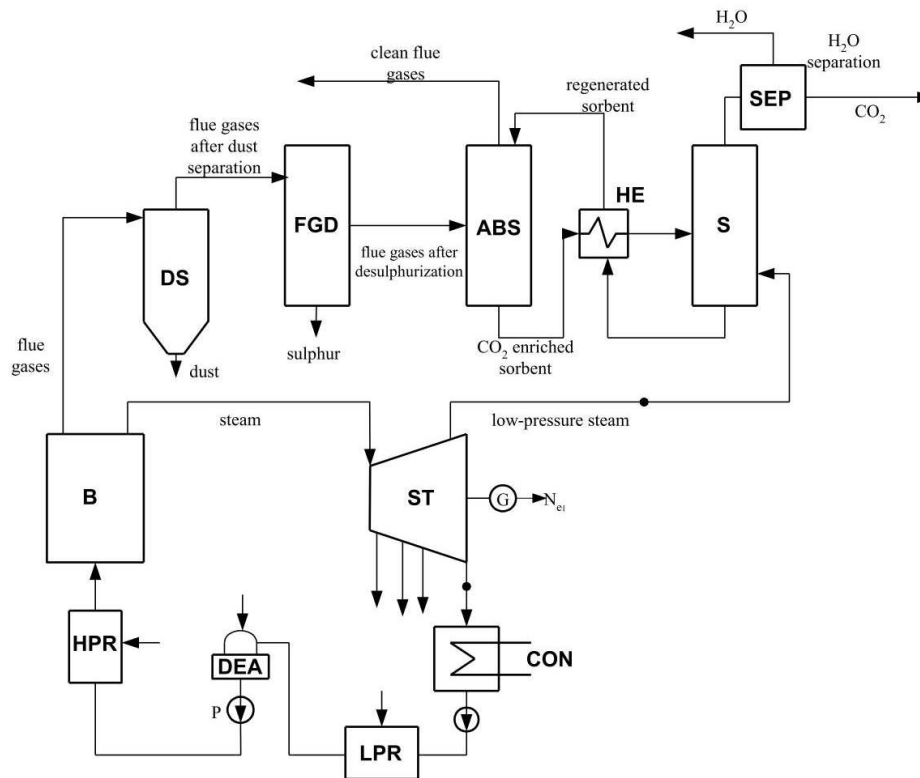


Figure 20: Diagram of the integration of the power unit with the CO₂ capture system: (B – boiler, ST – steam turbine, LPR, HPR – low-pressure- and high-pressure regeneration system, DEA – deaerator, CON – condenser, DS – dust separator, FGD – flue gas desulphurization, ABS – absorber, S – stripper, P – pump, HE – heat exchanger, G – generator, SEP – water separator).

capacity for both power plants (460 MW and 600 MW) without carbon dioxide separation with the power plants for which CO₂ was separated by means of the amine and ammonia methods. They also show the power and cycle efficiency degradation related to the carbon dioxide separation in comparison to the power plant with no CO₂ capture system. The determined value only for the process of carbon dioxide separation were shown, together with those which account for the demand for energy needed to drive auxiliary equipment, e.g., the ‘rich’ solution pump, the compression and transport facilities (marked as ad. eq.– added equipment). The differences in percentage points between 460 MW and 600 MW

power plant result from the fact that the flue gases contained different amounts of CO₂; had the amounts been equal, the percentage of the fall in efficiency and in generated power would have been the same. These data will be used in an economic analysis.

Summing up the conducted analyses, it can be stated that CO₂ separation by means of chemical absorption is an energy-consuming process. The aqueous solution of ammonia seems to be a better sorbent than the solution of amines.

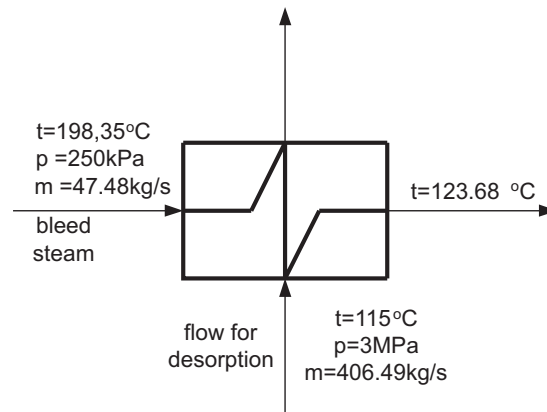


Figure 21: Parameters of the heat exchanger connecting the power plant to the carbon dioxide capture system – ammonia process, 460 MW power plant: m – mass flow, p – pressure, t – temperature.

Table 3: Comparison of 460 MW plant without and with carbon dioxide capture system.

Parameter	Powewr plant without CCS	NH ₃	MEA	NH ₃ + ad. eq.*	MEA+ ad. eq.*
Power capacity [MW]	460.68	402.35	349.48	391.64	322.53
Efficiency [%]	48.09	39.14	36.56	40.97	33.74
Power degradation [%]	–	12.66	24.14	14.99	29.99
Efficiency degradation [%]	–	18.61	23.98	14.81	29.84
Efficiency degradation p.p.	–	8.95	11.53	7.12	14.35

* ad.eq. – added equipment

Table 4: Comparison of 600 MW power plant without and with carbon dioxide capture system.

	Power plant without CCS	NH ₃	MEA	NH ₃ + ad. eq.	MEA+ ad. eq.
Power capacity [MW]	613.35	513.57	421.91	503.24	384.46
Efficiency [%]	50.3	42.12	34.60	41.27	31.53
Power degradation [%]	–	16.27	31.21	17.95	37.32
Efficiency degradation [%]	–	16.26	31.21	17.951	37.32
Efficiency degradation p.p.	–	8.18	15.70	9.03	18.77

13 Integration of the power plant, the carbon dioxide capture system and the biomass-fired boiler

The application of a biomass-fired boiler feeding the desorption system with heat (water boiler) was analysed for the system of CO₂ separation from both power plants under consideration. Thanks to that, the power plant capacity is not reduced as much as in the case of a direct integration of the power plant with the carbon dioxide separation system. The analysed case is one of many possibilities of heat generation outside the power plant system. It should be emphasised, however, that the analysed operation variant is merely hypothetical, considering the present stage of development of power technologies.

Basket willow (*salix viminalis*) was the fuel selected for the study. The decision to use this particular type of biomass resulted from its popularity and market availability, as well as from the possibility to establish a plantation of this kind of crop. At the moment, there are many companies on the market which specialise in comprehensive services for this type of plantations – from the preparation of the necessary documentation, preplanting activities, to the assistance related to agricultural technologies used in the plantation [7,8].

The effect of the integration of the power plant, the carbon dioxide capture system and the biomass-fired system was determined by the calculations. Selected results are shown in Figs. 22–25. The proposed application of a separate source to feed the CO₂ capture system improves the power plant parameters in comparison to a configuration where the heat comes from the power plant.

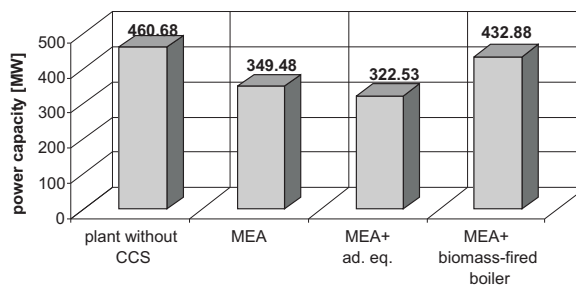


Figure 22: Comparison of variants of 460 MW power plant including CO₂ separation – the amine process.

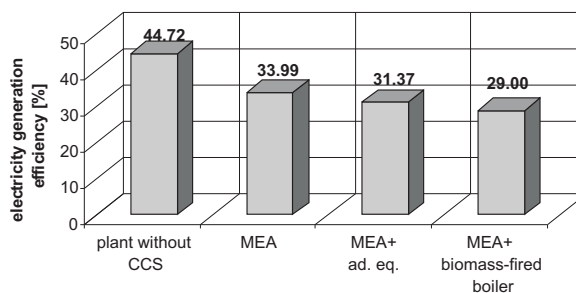


Figure 23: Comparison of electricity generation efficiency of variants of 460 MW power plant including CO₂ separation – the amine process.

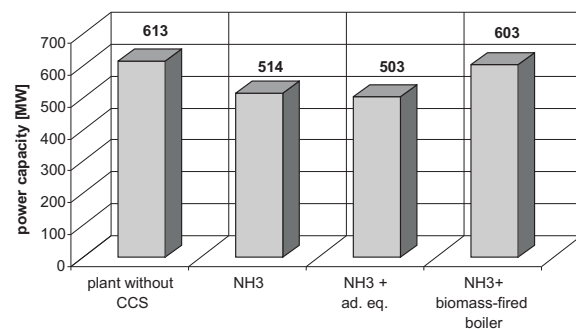


Figure 24: Comparison of power capacity of variants of 600 MW power plant including CO₂ separation – the ammonia process.

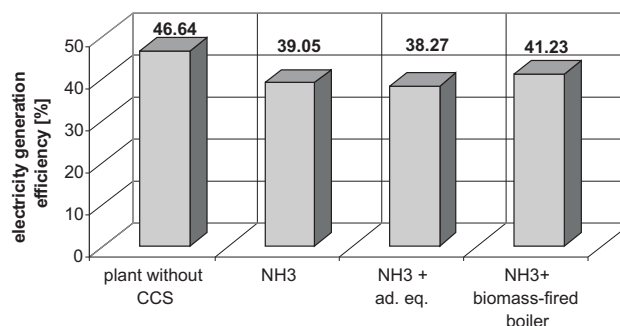


Figure 25: Comparison of electricity generation efficiency of variants of 600 MW power plant including CO₂ separation – the ammonia process.

14 Economic analysis

An economic analysis was carried out for each of the considered technological variants. Its aim was to select a beneficial variant for the cooperation of the power plant with the carbon dioxide capture system, with the economic criterion taken into consideration. The following indices were determined in the conducted economic analysis [10,14]: cash flows – CF, net present value – NPV, internal rate of return – IRR, simple payback period – SPB, and break-even point – BEP.

The assumptions related to the power plant operation which were adopted for the economic analysis (e.g., generated power, fuel composition, fuel mass flow, etc.) were the ones obtained from previously conducted technical analyses. Trading in CO₂ emissions permits was not considered. It was assumed that the waste resulting from gas purification, such as gypsum and artificial fertilisers are a commercial product.

The economic analyses complement the previously performed technical analyses of power plant systems of carbon dioxide capture. They confirm the results of earlier studies, finding the aqueous solution of ammonia to be a better sorbent for CO₂ than amines. Moreover, due to the use of instruments supporting electricity generation from biomass (sale of certificates of renewable energy origin), it is possible to significantly improve the economic performance of such an undertaking if biomass is recycled further.

Table 5 presents the main economic analysis indices determined for 460 MW power plant; the data for 600 MW power plant are shown in Fig. 26. The comparison of results was made as a function of the selling price of electricity. The first value (marked as the minimum price) is the price that determines the break-

even point for a given venture; the next two were selected to compare operation variants of the power plants under analysis. It appears from the presented results that biomass-fired boilers are much more effective than others. It can also be stated that better economic performance is obtained with CO₂ separation with ammonia than with amine. In the calculations it was assumed that it was possible to generate a sufficient amount of heat in biomass-fired boilers. In practice, however, this is still very unlikely for big power plants at the present stage of development of biomass-fired boilers.

To sum up the conducted analysis, it can be stated that carbon dioxide separation from flue gases by means of chemical absorption is expensive, which substantially increases the costs of electricity generation (usually the price is higher than the one on the energy exchange).

Table 5: Comparison of the NPV, IRR and SPB indices for 460 MW power plant.

Net present value, NPV					
	without CCS	MEA	MEA+ biomass	NH ₃	NH ₃ biomass
Minimum price	12 250 676	1 558 511	21 489 574	15 098 026	5 067 483.15
200.00 PLN	140 789 498	-5 307 586 079	-1 822 875 559	-1 782 101 780	201 785 867.36
250 PLN	2 110 581 532	-3 619 395 518	253 779 066	105 492 481	2 095 255 907.11
Internal rate of return, IRR					
	without CCS	MEA	MEA+ biomass	NH ₃	NH ₃ biomass
Minimum price	2.56%	2.51%	2.60%	2.57%	2.52%
200.00 PLN	3.13%	–	–	–	3.43%
250 PLN	2 10.09%	–	3.66%	3.00%	10.35%1
Simple payback, SPB					
	without CCS	MEA	MEA+ biomass	NH ₃	NH ₃ biomass
Minimum price	15	15	15	15	15
200.00 PLN	14	–	–	–	14
250 PLN	2 8	–	14	15	18

15 Conclusions

The reduction in CO₂ emissions in the processes of energy generation is an important object of current research. Due to the binding legal regulations, and bearing in mind those which are now being prepared, many actions are taken to reduce

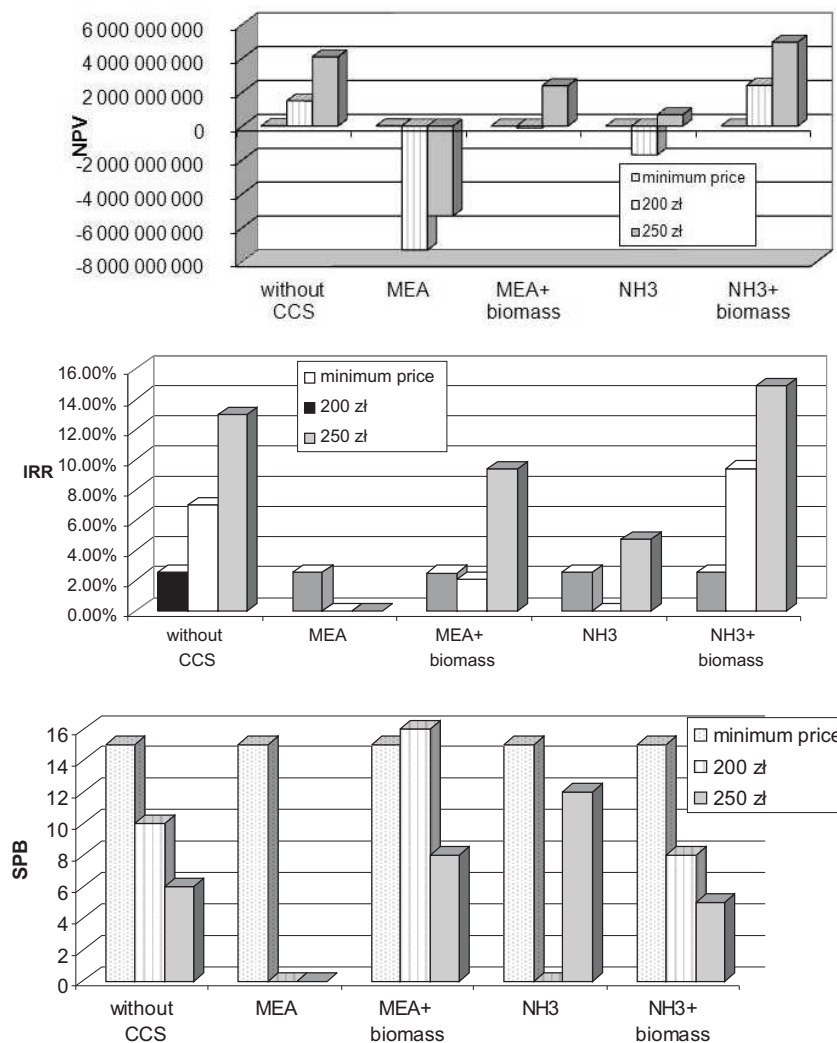


Figure 26: NPV, IRR and SPB indices for 600 MW power plant.

CO₂ emissions. The issue is urgent especially for coal-fired technologies, where CO₂ content in flue gases is considerable. Absorptive carbon dioxide separation from gas mixtures is a common process in the chemical industry.

The unit amounts of heat necessary to separate 1 kg of CO₂ (the amount of heat intended only for desorption processes) were determined. For the amine process the value is 4.7–5.4 J/kg, and for the ammonia process – 2.45–4.33 MJ/kg of

separated CO₂. Smaller values were obtained for the heat flux fed into the stripping column at two points. To close the balance of energy demand, the driving energy needed for CO₂ compression and transport was determined. The following results were obtained for 460 MW power plant:

- CO₂ compression and transport for the amine process requires 27.23 MW,
- CO₂ compression and transport for the ammonia process requires 5.77 MW.

The demand for energy needed for compression and transport for 600 MW power plant is as follows:

- the amine process – 37.33 W,
- the ammonia process – 7.91 MW.

Comparing carbon dioxide capture systems with the use of both sorbents for the analysed 460 MW and 600 MW power plants, it was found that CO₂ separation by means of the ammonia method was more advantageous than the amine method because of smaller energy consumption. However, both processes significantly increase the load of the power plant, which adversely affects its generated power and efficiency, for example:

- the power capacity of 460 MW power plant after the application of amine CO₂ separation falls to 322 MW, and the cycle efficiency decreases from 48.09% to 33.74%;
- the power capacity of 460 MW power plant after the application of ammonia CO₂ separation falls to 391 MW, and the cycle efficiency decreases from 48.09% to 40.97%.

The cooperation of a condensing power plant with a biomass-fired boiler whose task was to generate amounts of heat sufficient for desorption processes was analysed. It was assumed that the CO₂ balance for biomass was zero (during biomass combustion the amount of CO₂ released into the atmosphere is equal to the amount the plants absorbed earlier from their surroundings). For such a solution, 460 MW power plant mentioned above reaches the capacity of 432 MW after the application of amine carbon dioxide separation. The application of this solution, especially with an additional use of a backpressure turbine, is an energy-saving measure at the same level of CO₂ emissions.

Economic analyses of the considered variants of a condensing power plant integration with a CO₂ capture system were also presented. They confirmed the results of previously conducted technical analyses. They found the aqueous solution of ammonia to be a better sorbent than the amine aqueous solution. The variant of the power plant cooperating with a biomass-fired boiler is valuable economically. The effect is a consequence of the possibility of the sale of certificates of renewable energy origin.

It appears from the conducted study that the process of CO₂ separation is energy-consuming and expensive. The results of the calculations and analyses presented in the paper necessitate the search for new and better solutions to the carbon dioxide separation processes which will be cheaper, less energy-consuming, and which will require less space for their placement.

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