

Life cycle assessment analysis of supercritical coal power units

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Abstract This paper presents the Life Cycle Assessment (LCA) analysis concerning the selected options of supercritical coal power units. The investigation covers a pulverized power unit without a CCS (Carbon Capture and Storage) installation, a pulverized unit with a “post-combustion” installation (MEA type) and a pulverized power unit working in the “oxy-combustion” mode. For each variant the net electric power amounts to 600 MW. The energy component of the LCA analysis has been determined. It describes the depletion of non-renewable natural resources. The energy component is determined by the coefficient of cumulative energy consumption in the life cycle. For the calculation of the ecological component of the LCA analysis the cumulative CO₂ emission has been applied. At present it is the basic emission factor for the LCA analysis of power plants. The work also presents the sensitivity analysis of calculated energy and ecological factors.

Keywords: LCA; CCS; Ecological analysis; Post-combustion; Oxy-combustion; Cumulative energy consumption

1 Introduction

The Life Cycle Assessment analysis (LCA) of energy systems deals with the full range of environmental hazards in the interconnected energy and technological processes through all stages of the life cycle. The term “life cycle”

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means that the analysis covers raw material production, manufacturing, distribution, usage and disposal.

Three groups of environmental impacts can be distinguished [2,4]:

- the influence exerted on the quality of the ecosystem (for example air pollution, water and soil pollution, wastes storage),
- the influence exerted on the human health (for example occupational diseases and industrial safety),
- depletion of natural resources, the resulting degradation of the terrain and the structure of underground waters.

The production of energy carriers (for example electricity) involves the following LCA components:

- exploitation of natural energy resources (for example coal) and non-energy raw materials (for example limestone),
- construction of the power plant,
- exploitation of the power plant – electricity production,
- decommissioning of the power plant – wastes utilization (for example scrap) and recultivation of the terrain.

The paper provides algorithms and results of calculations concerning two components of LCA analysis: cumulative energy consumption and the ecological component dealing with CO₂ emissions. CO₂ emission has been chosen mainly in order to compare various ways of CO₂ capture.

2 Energy analysis of the integrated power unit in the life cycle

Figure 1 presents the calculation diagram of the energy analysis of the integrated coal power unit in the life cycle.

In the case of hard coal five components can be distinguished:

- deposit preparation – energy consumption E_{PZ} ,
- coal mining – energy consumption E_{WW} ,
- coal processing – energy consumption E_{PW} ,
- transport of the coal – energy consumption E_{TW} ,
- decommissioning of the mine – energy consumption E_{LP} .

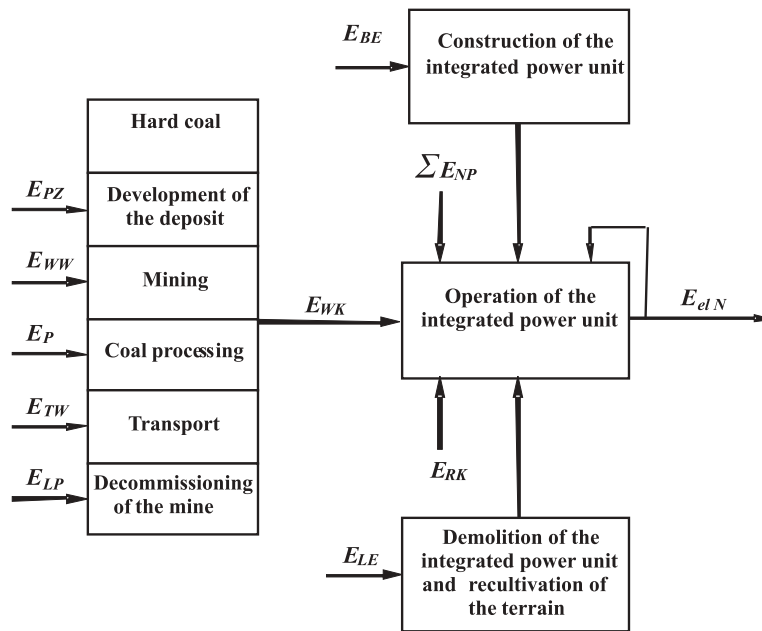


Figure 1. Calculation diagram for the energy analysis of an integrated coal power unit in the life cycle.

The total cumulative energy consumption related with the hard coal cycle yields:

$$E_{WK} = E_{PZ} + E_{WW} + E_{PW} + E_{TW} + E_{LP} . \quad (1)$$

The other symbols in Fig. 1 denote:

- ΣE_{NP} – cumulative energy consumption assigned to raw materials (except fuels) supplied to the power unit,
- E_{elN} – net electricity production during operation of the power unit,
- E_{RK} – cumulative energy consumption connected with the maintenance and overhauls of the power unit,
- E_{BE} – cumulative energy consumption imposed by the construction of the power unit,
- E_{LE} – cumulative energy consumption due to the decommissioning of the power unit.

If the energy balance boundary of the LCA analysis includes only the fuel cycle and integrated power unit, the cumulative energy consumption is

calculated from the relation:

$$E_{LCA} = E_{WK} + \sum E_{NP} + E_{RK} + E_{BE} + E_{LE} , \quad (2)$$

where E_{LCA} denotes the cumulative energy consumption in the life cycle.

The first two items in equation (2) are calculated from the relation:

$$E_{WK} + \sum E_{NP} = E_{elNR} \cdot e_{el}^* \cdot n_{LCA} , \quad (3)$$

where:

- E_{elNR} – annual net electricity production by the integrated power unit with the nominal load,
- e_{el}^* – coefficient of the cumulative energy consumption charging the electricity production in the integrated power unit,
- n_{LCA} – number of the working years of the integrated power unit.

The coefficients of the cumulative energy consumption for the considered two options of the integrated power unit are calculated from the relations:

- pulverized power unit in the „post combustion” mode

$$e_{elpp}^* = \frac{1}{E_{elN}} \cdot (P_W \cdot e_W^* + P_r \cdot e_r^* + EA \cdot e_{EA}^* + KW \cdot e_{KW}^* + WA \cdot e_{WA}^* + WS \cdot e_{WS}^* - G \cdot e_G^* - O \cdot e_O^*) , \quad (4)$$

- pulverized power unit in the „oxy-combustion” mode

$$e_{elpo}^* = \frac{1}{E_{elN}} \cdot (P_W \cdot e_W^* + P_r \cdot e_r^* + WS \cdot e_{WS}^* - N \cdot e_N^* - \sum GS_k \cdot e_{GSk}^* - O \cdot e_O^*) , \quad (5)$$

where:

- P_w – consumption of coal,
- e_w^* – coefficient of the cumulative energy consumption for coal,
- P_r – consumption of the fire up fuel,
- e_r^* – coefficient of the cumulative energy consumption for the fire up fuel,
- EA – consumption of the ethanoloamine,

e_{EA}^*	–	coefficient of the cumulative energy consumption for the ethanoloamine,
KW	–	consumption of limestone,
e_{KW}^*	–	coefficient of the cumulative energy consumption for the limestone,
WA	–	consumption of the ammonia water,
e_{WA}^*	–	coefficient of the cumulative energy consumption for the ammonia water,
WS	–	consumption of raw water,
e_{WS}^*	–	coefficient of the cumulative energy consumption for the raw water,
E_{elN}	–	net electricity production,
e_{el}^*	–	coefficient of the cumulative energy consumption charging the electricity production (loco power plant); indices: <i>pp</i> – pulverized power unit in the „post-combustion” mode, <i>po</i> – power unit in the „oxy-combustion” mode,
G	–	production of gypsum,
e_G^*	–	coefficient of the cumulative energy consumption for the gypsum,
O	–	production of useful wastes,
e_O^*	–	coefficient of the cumulative energy consumption for the useful wastes,
N	–	by-production of nitrogen,
e_N^*	–	coefficient of the cumulative energy consumption for the nitrogen,
GS_k	–	chemically inactive gas (for example argon),
e_{GSk}^*	–	coefficient of the cumulative energy consumption of chemically inactive gas.

For the calculation of the energy consumption related to the construction of the power station the consumption of the basic building materials has been taken into consideration. According to the data presented in [6] the consumption of building materials during the construction phase amounts to:

- concrete – about 160 t/MW, coefficient of the cumulative energy consumption: 1.4 GJ/t;
- steel products – about 51 t/MW, coefficient of the cumulative energy consumption: 32 GJ/t;

- iron products – about 0.62 t/MW, coefficient of the cumulative energy consumption: 23.5 GJ/t;
- aluminium – about 0.42 t/MW, coefficient of the cumulative energy consumption: 224.5 GJ/t.

The total coefficient assigned to the construction of the power unit amounts to:

$$e_{BE}^* = e_{BEb}^* + e_{BEs}^* + e_{BE}^* + e_{BEa}^* = 1.965 \frac{\text{TJ}}{\text{MW}} .$$

According to [5] the cumulative energy consumption assigned to the maintenance and overhauling of the power unit with reference to the installed capacity is:

$$e_{RK}^* = 9.7 \frac{\text{TJ}}{\text{MW}} ,$$

where e_{RK}^* denotes the coefficient of the cumulative energy consumption assigned to the maintenance and overhauling of the power unit. The data quoted in [5] show that the cumulative energy consumption assigned for the demolition of the power unit and the recultivation of the terrain amounts to:

$$e_{LE}' = 0.095 \frac{\text{TJ}}{\text{MW}} ,$$

where e_{LE}' denotes the cumulative energy consumption assigned to the decommissioning of the power unit without taking into account the scrap recycling. Assuming that 75% of the steel scrap is recycled and the coefficient of the cumulative energy consumption of the scrap is equal to 0.295 MJ/kg [7], then:

$$e_{LE}^* = e_{LE}' - e_{LEzs}^* = 0.084 \frac{\text{TJ}}{\text{MW}} .$$

The sum of the energy consumption assigned for the construction, maintenance, overhauls and decommissioning of the power unit in reference to the installed capacity equals:

$$e_{BE}^* + e_{RK}^* + e_{LE}^* = 11.75 \frac{\text{TJ}}{\text{MW}} .$$

Figure 2 presents the calculation diagram of the ecological analysis of the integrated coal power unit in the course of its life cycle. In the case of hard coal six components for LCA can be distinguished, namely:

- direct emission of k -th noxious substance in the process of heat and power generation in the coal mine,
- development of the deposit – emission P_{PZk} of k -th noxious substance,
- mining – emission P_{WWk} of k -th noxious substance,
- coal processing – emission P_{PWk} of k -th noxious substance,
- transport of coal – emission P_{TWk} of k -th noxious substance,
- discarding of the deposit – emission P_{LPk} of k -th noxious substance.

Total cumulative emission related to the hard coal cycle is expressed as:

$$P_{WKk} = P_{bWk} + P_{PZk} + P_{WWk} + P_{PWk} + P_{TWk} + P_{LPk} . \quad (6)$$

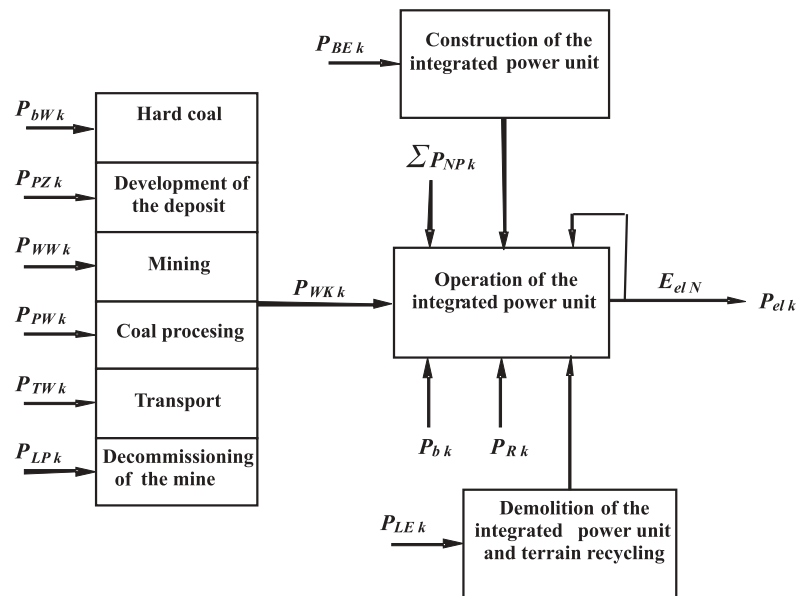


Figure 2. Calculation diagram of the ecological analysis of the integrated coal power unit in the life cycle.

The other symbols in Fig. 2 denote:

ΣP_{NPk}	–	cumulative emission of k -th noxious substance assigned to the raw materials supplied to the power unit,
P_{RKk}	–	cumulative emission of k -th noxious substance assigned to the maintenance and overhauls of the power unit,
P_{bk}	–	direct emission of k -th noxious substance,
P_{BEk}	–	cumulative emission of k -th noxious substance assigned to construction of the power unit,
P_{LEk}	–	cumulative emission of k -th noxious substance assigned to the decommissioning of the power unit,
P_{elk}	–	cumulative emission of k -th noxious substance assigned to the production of electricity (loco power plant).

If the the energy balance boundary of the LCA analysis comprises merely the fuel cycle and integrated power unit, the cumulative emission of the k -th noxious substance is calculated from the relation:

$$P_{elk} = P_{WKk} + \sum P_{NPk} + P_{Rk} + P_{BEk} + P_{LEk} + P_{bk} , \quad (7)$$

where P_{bk} denotes the direct emission of the k -th noxious substance in the process of converting coal into electricity. The other symbols concern cumulative emissions.

The first three items concerning direct emissions in Eq. (7) are calculated from the relation:

$$P_{WKk} + \sum P_{NPk} + P_{bk} = E_{elNR} \cdot p_{kel}^* \cdot n_{LCA} , \quad (8)$$

where p_{kel}^* denotes the operation coefficient of the cumulative emission of the k -th noxious substance assigned for the production of electricity by the integrated power unit. Other symbols at the right-hand side of Eq. (8) are the same as in Eq. (3). The coefficients of the cumulative emission in the considered two options of the integrated power unit are calculated from the relations:

- pulverized power unit in the „post combustion” mode

$$p_{kelpp}^* = \frac{1}{E_{elN}} \left[P_W \cdot (p_{kW}^* + p_{kW}) + P_r \cdot (p_{kr}^* + p_{kr}) + EA \cdot p_{kEA}^* + \right. \\ \left. + KW \cdot (p_{kKW}^* + p_{kKW}) + WA \cdot p_{kWA}^* + WS \cdot p_{kWS}^* - \right. \\ \left. - G \cdot p_{kG}^* - O \cdot p_{kO}^* \right] , \quad (9)$$

- pulverized power unit in the „oxy-combustion” mode

$$p_{kelpo}^* = \frac{1}{E_{elN}} \cdot \left[P_W \cdot (p_{kW}^* + p_{kW}) + P_r \cdot (p_{kr}^* + p_{kr}) + WS \cdot p_{kWS}^* - N \cdot p_{kN}^* - \sum_i GS_i \cdot p_{kGS_i}^* - O \cdot p_{kO}^* \right], \quad (10)$$

where:

- p_{kw}^* – cumulative emission of the k -th noxious substance assigned to extraction and transport of coal,
- p_{kw} – direct emission of the k -th noxious substance assigned to burning of the coal,
- p_{kr}^* – cumulative emission of the k -th noxious substance assigned to production and transport of the lighting fuel,
- p_{kr} – direct emission of the k -th noxious substance assigned to burning of the lighting fuel,
- p_{kEA}^* – cumulative emission of the k -th noxious substance assigned to production and transport of the ethanoloamine,
- p_{kKW}^* – cumulative emission of the k -th noxious substance assigned to extraction and transport of limestone,
- p_{kKW} – direct emission of the k -th noxious substance assigned to use of the limestone,
- p_{kWA}^* – cumulative emission of the k -th noxious substance assigned to production and transport of ammonia water,
- p_{kWS}^* – cumulative emission of the k -th noxious substance assigned to production and transport of raw water,
- p_{kel}^* – cumulative emission of the k -th noxious substance assigned to electricity production (pp – pulverized power unit in the „post-combustion” mode, po – pulverized power unit in the „oxy-combustion” mode),
- p_{kG}^* – cumulative emission of the k -th noxious substance assigned to production of gypsum in the substitute process,
- p_{kO}^* – cumulative emission of the k -th noxious substance assigned to the useful wastes,
- p_{kN}^* – cumulative emission of the k -th noxious substance assigned to by-production of nitrogen,
- $p_{kGS_i}^*$ – cumulative emission of the k -th noxious substance assigned to by-production of chemically inactive gas.

Other symbols are the same as in Section 2.

For calculations of the ecological component of the LCA analysis the cumulative CO₂ emission has been applied. At present it is a basic emission factor in the LCA analysis of power plants. The presented universal methodology may be also adapted for other categories of ecological analysis. For the calculation of emissions assigned to the construction of the power station the consumption of basic building materials has been taken into consideration according to the data presented in Section 2.

Due to small aluminium and iron consumption the emissions assigned to these have been neglected in calculations of cumulative CO₂ emissions related to with the construction of the power unit. In the case of concrete and steel products the cumulative CO₂ emission amounts to [3]:

$$p_{CO_2b}^* = 0.047 \text{kg CO}_2 / \text{kg of concrete,}$$

$$p_{CO_2s}^* = 1.434 \text{kg CO}_2 / \text{kg of steel products,}$$

where:

$p_{CO_2b}^*$ – cumulative CO₂ emission assigned to the production of concrete,

$p_{CO_2s}^*$ – cumulative CO₂ emission assigned to the production of steel products.

Therefore, cumulative CO₂ emissions charging the construction of the power plant in reference to the installed capacity equals:

$$p_{CO_2BE}^* = 160 \cdot 10^3 \cdot 0.047 + 51 \cdot 10^3 \cdot 1.434 = 80.65 \frac{\text{tCO}_2}{\text{MW}},$$

where $p_{CO_2BE}^*$ denotes the cumulative CO₂ emission assigned to the construction of the power plant.

3 Results of the life cycle assessment analysis concerning the integrated power unit

The life cycle assessment analysis has been carried out for four variants of integrated power units, namely:

- pulverized power unit without a CCS (Carbon Capture and Storage) installation - basic variant (PF-no CCS),
- pulverized unit with a “post-combustion” installation (PF-MEA),
- pulverized power unit working in the “oxy-combustion” mode – without using nitrogen (PF-OXY-N₂ waste),

- pulverized power unit working in the “oxy-combustion” mode – nitrogen used as a useful product (PF-OXY-N₂ product).

Table 1 provides a set of data for the LCA analysis of the considered variants of power units [1,7].

Table 1. Data for the LCA analysis of the considered variants of the power units.

	Unit	PF-no CCS	PF-MEA	PF-OXY N ₂ product	PF-OXY N ₂ waste
Coefficient of the power station internal load	%	6	19.2	26.9	26.9
Net coefficient of direct chemical energy consumption of coal	MJ/MWh	8107.2	10 810.8	10 555.2	10 555.2
Net coefficients of direct consumption:					
• limestone	kg/MWh	13.77	18.31	–	–
• ammonia	kg/MWh	1.40	1.86	–	–
• ethanoloamine	kg/MWh	–	1.413	–	–
• raw water	kg/MWh	1085	1931	1727	1727
Net coefficients of by-production:					
• gypsum	kg/MWh	17.80	23.67	–	–
• nitrogen	kmol/MWh	–	–	101.59	–
Coefficients of cumulative energy consumption:					
• hard coal	kJ/kJ	1.064	1.064	1.064	1.064
• limestone	kJ/kg	46	46	–	–
• ammonia	kJ/kg	43 500	43 500	–	–
• ethanoloamine	kJ/kg	–	46 490	–	–
• raw water	kJ/kg	31.22	31.22	31.22	31.22
• gypsum	kJ/kg	890	890	–	–
• nitrogen	MJ/kmol	–	–	46.76	–
CO ₂ emission factors:					
• hard coal	kg CO ₂ /MWh	726	969	946	946
• limestone	kg CO ₂ /MWh	4.55	6.05	–	–
• ammonia	kg CO ₂ /MWh	1.78	2.36	–	–
• ethanoloamine	kg CO ₂ /MWh	–	0.037	–	–
• raw water	kg CO ₂ /MWh	3.39	6.04	5.39	5.39
• gypsum	kg CO ₂ /MWh	0.89	1.18	–	–
• nitrogen	kg CO ₂ /MWh	–	–	475	–

For each variant the net electric power amounts to 600 MW. It has been assumed that the LHV of coal equals 21.09 MJ/kJ, the carbon fraction equals to 51.5% and the sulphur fraction equals 1%. It has been assumed that the efficiency of CO₂ capture is:

- MEA – $\eta_{MEA} = 90\%$,
- OXY – $\eta_{OXY} = 98\%$.

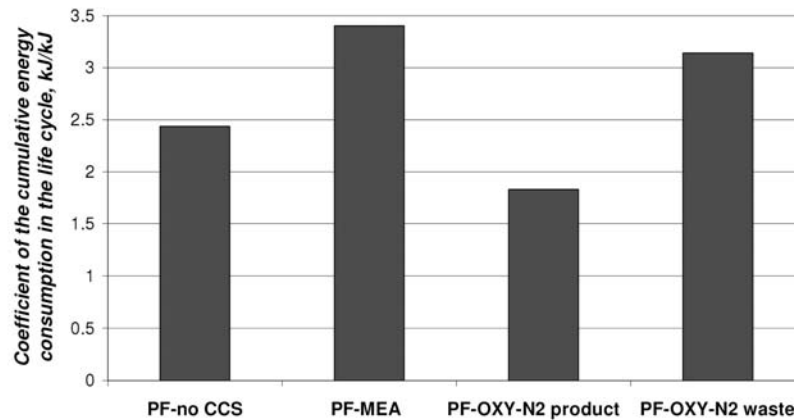


Figure 3. Coefficients of cumulative energy consumption in the life cycle of all the considered variants of integrated power unit.

Figures 3 and 4 present the calculated coefficients of cumulative energy consumption and the coefficients of cumulative CO₂ emission for the considered variants. The analysis of the power plant with “oxy-combustion” provides interesting results. In the case of using nitrogen as a useful product the coefficient of cumulative energy consumption decreases by about 40% if compared with the case of nitrogen treated as waste. Even more spectacular results have been obtained in the case of CO₂ emission. The full use of nitrogen causes a negative CO₂ emission in the case of the “oxy-combustion” technology. It proves that this technology is not only a “zero emission”, but also reduces the CO₂ emission in other branches of the national energy system. But it is rather difficult to achieve a full utilization of nitrogen.

Figures 5 and 6 show the influence of the ratio of using nitrogen (a by-product of the air separation unit) on the cumulative energy consumption

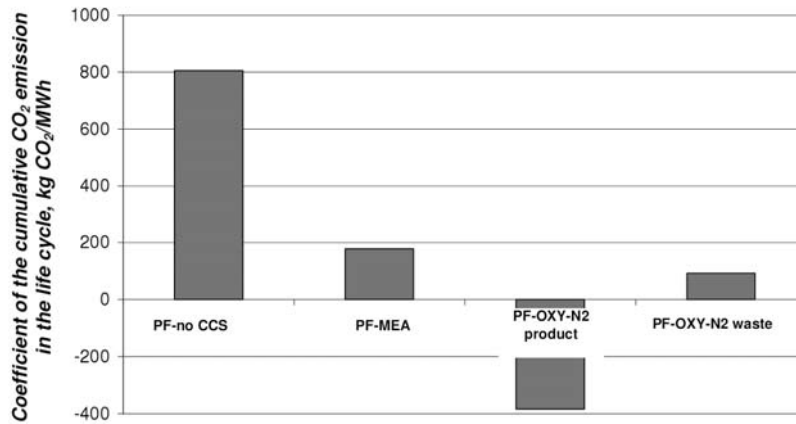


Figure 4. Coefficient of cumulative CO₂ emission in the life cycle of the considered variants of integrated power unit.

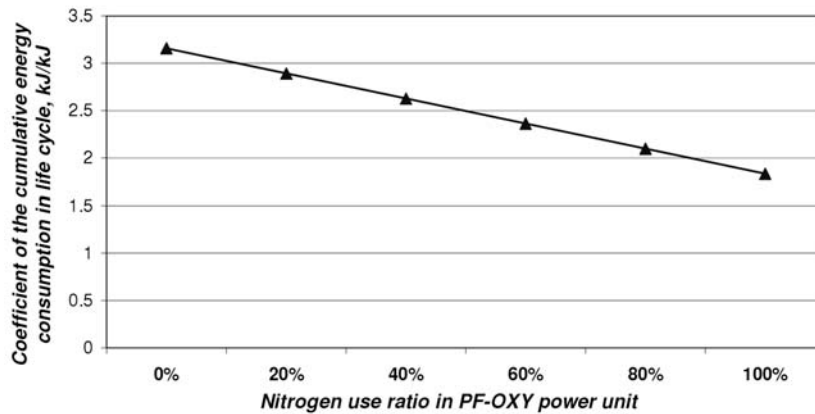


Figure 5. Coefficient of cumulative energy consumption in reference to the nitrogen use ratio in the case of “PF-OXY-N2-product”.

and on the coefficient of cumulative CO₂ emission during the life cycle. It has been noticed that the degree of using nitrogen affects considerably the coefficient of cumulative energy consumption in the life cycle. The rate of the coefficient of cumulative energy consumption changes by 0.131/10% nitrogen use.

Even more interesting results have been obtained in the case of cumulative CO₂ emission. It has turned out that when the degree of nitrogen

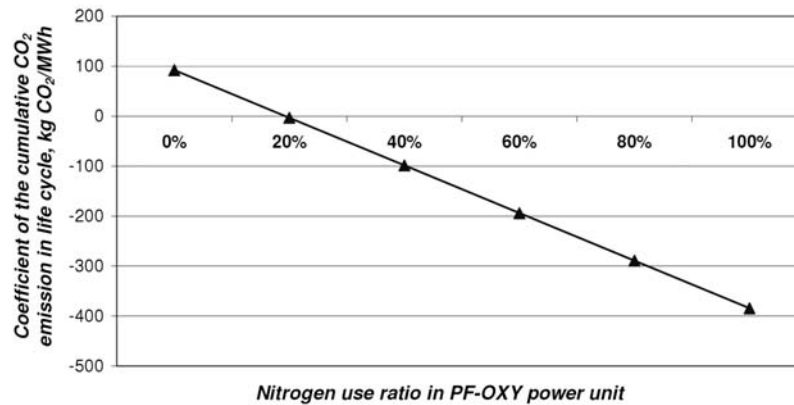


Figure 6. Coefficient of cumulative CO₂ emission in reference to the nitrogen use ratio in the case of “PF-OXY-N₂-product”.

usage reaches 20%, the power unit applying “oxy-combustion” becomes a “zero emission” technology with respect to CO₂ emission. A further increase of the nitrogen use ratio leads to negative CO₂ emissions, which is very favourable for the national energy system. It has been assumed that the by-production of nitrogen substitutes nitrogen produced in advanced air separation units (ASU).

4 Summary

The energy component of the life cycle analysis (LCA) describes the depletion of non-renewable natural resources. It is determined by the coefficient of cumulative energy consumption during the life cycle, which is calculated with reference to the net electricity production. The basic variant of the power unit (PF-no CCS) is characterized by the lowest value of the coefficient of cumulative energy consumption, which equals to 2.437. The application of the “post-combustion” installation increases the coefficient to 3.404 (which is 40% in reference to the base variant). The application of the „oxy-combustion” technology (without using nitrogen as a useful product) renders more profitable results. The coefficient of cumulative energy consumption in this technology equals to 3.141 (an increase of about 30% in reference to the base variant). The full use of nitrogen as a useful product leads to the decrease of the coefficient of cumulative energy consumption by about 40% in reference to the base variant (the nitrogen is treated as waste).

For calculation of the ecological component of the LCA analysis the cumulative CO₂ emission has been applied. At present, it is a basic emission factor for the LCA analysis of power plants. The structure of the coefficient of cumulative energy consumption in the whole life cycle indicates a dominant influence of fuel consumption (98.5% and 99% concerning the variants PF-OXY-N₂ waste, respectively). In the case of PF-MEA this share amounts to 97.9%. Similarly to the coefficient of cumulative energy consumption, the main share in CO₂ emission depends on the fuel consumption (98.7% for the basic variant). This share decreases to about 94% in CCS cases („post-combustion” and „oxy-combustion”).

The nitrogen use ratio influences strongly the coefficient of cumulative energy consumption and CO₂ emission during the life cycle. The full use of nitrogen decreases the coefficient of cumulative energy consumption by about 40%. It has turned out that when the nitrogen use rate reaches 20%, the “oxy-combustion” plant becomes a “zero emission” technology with respect to CO₂ emission. When the nitrogen use rate exceeds the value of 20%, the „oxy-combustion” plant changes over to a technology with negative CO₂ emissions. It means that this technology leads to a reduction of CO₂ emission in other branches of the national energy system. But it should be stressed that a 100% utilization of nitrogen may prove to be impossible.

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