Environmental costs resulting from the use of hard coal to electricity generation in Poland

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Abstract. In the world's fuel mix used for generating electricity, the most common fossil fuel is coal. In the EU, coal combustion and electricity generation entail the need to purchase emission allowances (EUA) whose purchase costs affect the costs of electricity generation significantly. The research described in the article shows how current market conditions shape the profitability of generating electricity from coal and how Clean Dark Spread (CDS) changes as a function of changes in energy and coal prices at the assumed levels of emission and prices of EUA allowances. The article compares the results of CDS calculations in two variants. Areas have been highlighted where prices of both coal and EUA allowances cause CDS to assume values at which the prices of generated electricity do not cover the costs of fuel (i) and CO_2 emission allowances, cover all costs (ii), or constitute positive prices (iii), but still do not cover all fixed costs. With higher power plant efficiency, CO_2 emissions are lower (0.722 t/MWh). The costs of purchasing fuel required to generate 1 MWh of electricity are also lower. In such case—even with relatively high prices of coal—a power plant can achieve profitability of electricity generation.

1 Introduction

In the world's fuel mix, for years, coal has had the biggest share among fuels used for generating electricity. According to [1], in 2015, the share of coal was 40%, and coal was used to generate 9,639 TWh of electricity (Fig. 1). The second place is occupied by natural gas (22%) and the third one—by water (16%). To compare, in the 6,131 TWh of electricity produced in 1973 [2], the share of coal was lower by 3 percentage points, the second place went to petroleum and petroleum products (25%), and the third one—also to water (21%). Fig. 2 shows the share of coal power industry (both hard coal and brown coal) in the energy mix of selected countries in 2015.

The following countries (Fig. 2) have the highest share of coal power generation in the world: Kosovo (97% in 2014), South Africa (90%), and Poland (79%). On a global scale, coal power generation (including both hard coal and brown coal) amounted to 40% of total electricity production.

In the Polish power system, coal (both hard and brown) is the primary solid fuel used to generate electricity. Between 2010 and 2015, electricity generation in Poland increased by 5% (from 157.7 to 164.9 TWh [3]). In coal-fired power plants (including both hard coal and brown coal), there has been a 4% drop (from 136.5 to 130.5 TWh). In the case of hard coal-fired power plants, the share decreased by 8.6 percentage points; production dropped by 10.1 TWh and

amounted to 77.7 TWh in 2015. Brown coal-fired power plants achieved a growth (by 1.2 percentage points). Their electricity generation increased to 52.8 TWh.
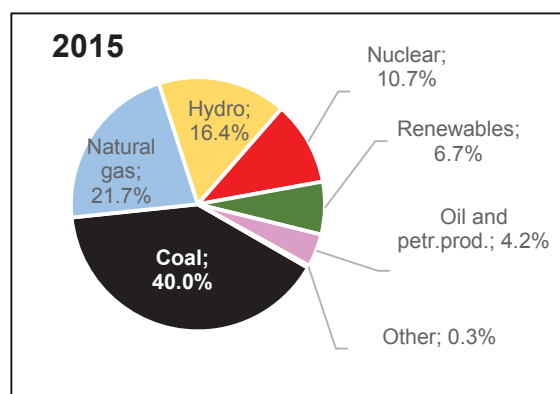

Fig. 1. Worldwide breakdown of electricity generation by fuel in 2015 [1].

However, coal combustion is often associated with the emission of various pollutants: e.g. CO_2, SOx, NOx, particular matter (PM), and fly ash [4, 5, 6]). In the case of electricity generation, it is often necessary to carry out many simulations to calculate fuel and environmental costs [7, 8].

The article aims is to present simulation calculations that will show changes in the theoretical producer's margin (CDS—Clean Dark Spread) at the assumed prices of coal and electric energy.

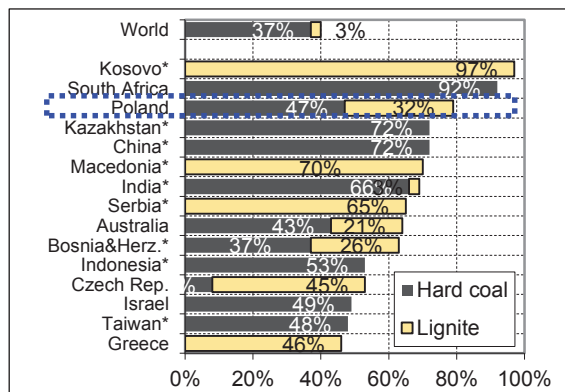* Corresponding author: kszlugaj@min-pan.krakow.pl

Fig. 2. Share of coal in the energy mix of selected countries of the world in 2015 (* in 2014) [1].

2 CO₂ emissions in the world

In 2015, worldwide emissions of CO_2 amounted to 36.2 billion t (Fig. 3). Even though this number is higher than in 1990 by 59% (or 13.5 billion tCO_2), it was the first time when a decline in comparison with the previous year occurred (by -0.3%, i.e. 0.1 billion tCO_2). A slowdown in the growth of emissions has been observed since 2013.
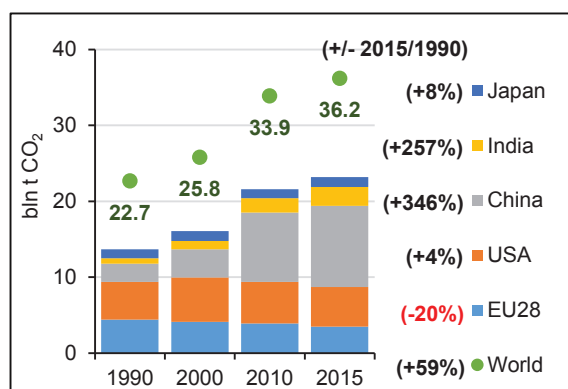

Fig. 3. CO_2 emissions by selected country, 1990-2015 (own work based on [9]).

In the case of EU28 countries, emissions decreased by 20% (0.9 billion tCO_2) compared to 1990 and amounted to 3.5 billion tCO_2 in 2015 (Fig. 4).

Asia's strong industrial growth and transferring energy-intensive industry to this part of the world by global corporations contribute to a large increase in CO_2 emissions. For example, in China, it increased by as much as 346% (by 8.3 billion tCO_2), and in India—by 257% (1.8 billion tCO_2).

Worldwide CO_2 emissions per capita amounted to 4.9 t in 2015, which constitutes an increase by 14% compared to 1990. The highest increase of emissions was observed in: China (285%, 7.7 tCO_2/capita in 2015) and Malaysia (170%, 8.1 tCO_2/capita in 2015). In the EU28 countries, it decreased by 25% compared to 1990 and amounted to 6.9 tCO_2/capita. In Poland, this emission is lower than in the Netherlands and Germany. In 2015, it amounted to 7.6 tCO_2/capita, which constitutes a decrease by 20% compared to 1990 and by 10% compared to 2010.

One of the major sources of CO_2 emissions is heat and electricity generation (Fig. 5). This industry contributed to 42% of the global CO_2 emissions (13.6 billion t) in 2014.
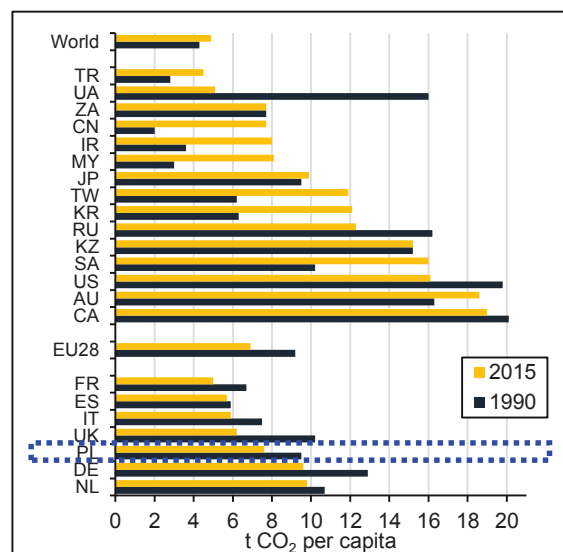

Fig. 4. CO_2 emissions by selected country, tCO_2/capita (own work based on [9]).
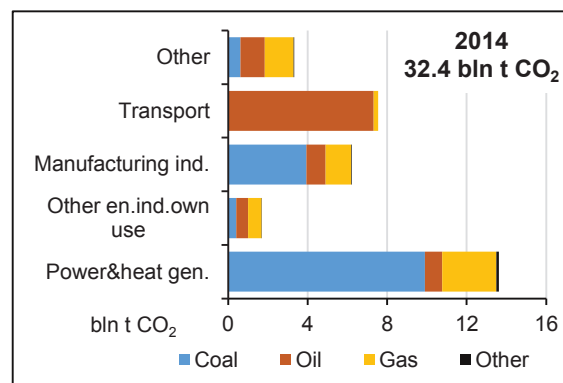

Fig. 5. World — CO_2 emissions by sectors, 2014 [10].

Coal is one of the fuels that are used to generate electricity and have the largest impact on CO_2 emissions. In 2014, coal-fired power plants accounted for 31% of worldwide CO_2 emissions (9.9 billion tCO_2).

3 Assessment of the influence of the prices of CO₂ emission allowances on the prices of electricity

The costs related to CO_2 emissions are an important factor influencing electricity prices. The costs of purchasing CO_2 emission allowances will have an increasing share in the costs of electricity generation. This is caused by the high CO_2 emissions associated with generating electricity from coal compared to other energy carriers. For the EU, reducing CO_2 emissions is the main priority of the climate policy [11,12,13,14]. This makes the events related to the CO_2 emission allowances trading market extraordinarily important for the power industry in Poland. These events affect the

assessment of the competitiveness of coal compared to other fuels.

In Europe, an emissions trading system has been introduced following the implementation of Directive 2003/87/EC (the so-called ETS Directive) and Directive 2009/29/EC that improves the EU ETS system. This market has been functioning since January 2005, currently within the so-called third trading period (2013–2020). The participation in the system is mandatory for the types of business activities specified in the directive. Emission allowances are tradable both on exchanges and on the over-the-counter market. They can also be sold or purchased on the basis of commercial agreements with any company [15].

The most liquid market of derivatives for CO_2 emission allowances is the European Climate Exchange (ICE-ECX) based in London. Fig. 6 presents monthly average (spot) price changes of EUA emission allowances (ICE-ECX exchange) in EUR/tCO_2 in the years 2006–2017. The diagram also shows the dates of individual emission allowance trading periods (2005–2007, 2008–2012, 2013–2020). Companies subject to the emissions trading system must acquire allowances that decrease in number in each trading period. The price level of emission allowances in the third trading period is approx. 4.3–8.5 EUR/t.
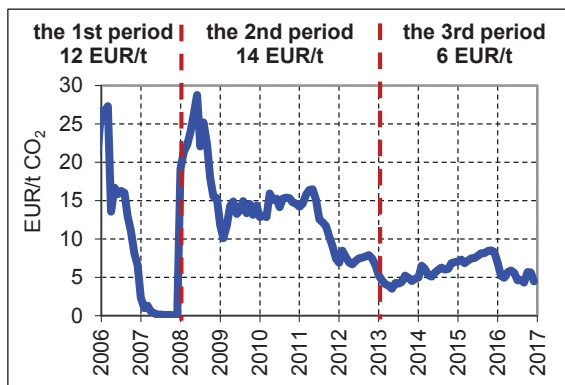

Fig. 6. Average monthly prices of EUA emission allowances (ICE-ECX), EUR/tCO_2—futures contracts as of December of each year [16]).

In January 2017, Thomson Reuters (TR) analysts presented forecasts for the pricing of EUA allowances in the years 2017–2030, at nominal and real prices. Real (using 2015 as the base year) and nominal prices (Tab.1) [16].

According to the data presented, the prices of the allowances will increase. By 2020, there will be an increase of approx. 50%. This will mainly be an effect of the Market Stability Reserve (MSR). The extent of its influence will depend on the allowance transfer ratio from auctions to the MSR reserve. The planned level of this indicator will be either 12% or 24%.

As a result, the level of CO_2 emission allowance prices will increasingly affect the level of electricity prices. This cost element can also significantly affect the price competitiveness between individual energy carriers. It may occur especially after it becomes

necessary to acquire all (100%) of the required CO_2 emission allowances at market prices.

In order to investigate the impact of CO_2 emission allowance prices on electricity generation costs, an analysis of the theoretical energy producer's margin (spread) has been carried out.

Table 1. Forecast for the pricing of EUA allowances in the years 2017–2030 by Thomson Reuters (* using 2015 as the base year) [16].

Kind of Prices	2017	2020	2025	2030
Nominal prices, EUA	5.9	9.0	14.3	23.8
Real prices*, EUA	5.8	8.3	12.1	18.7

Spread is defined as the difference between the market price of electricity and the price of fuel used to generate it, with due regard for the efficiency of the process (both figures must be expressed in the same units, e.g.: EUR/MWh, USD/GJ, PLN/MWh, etc.).

For coal, the term used is "Dark Spread"; for gas, it's "Spark Spread". If, when calculating the spread, the cost of CO_2 emissions (related to a given fuel's combustion) is taken into account additionally, the word "Clean" is added to the spread name.

Therefore, "Clean Dark Spread" (CDS) is the theoretical producer's margin for generating energy from coal at market prices for energy, fuel, and emission allowances, calculated as a simple relation [11, 18]:

$$CDS = C_{EE} - C_W - C_{CO2} \quad [PLN/MWh] \quad (1)$$

where:
- C_{EE} – electricity energy price,
- C_W – fuel purchase price,
- C_{CO2} – emission allowances price.

It can be assumed that the theoretical producer's margin should cover fixed costs of energy generation. Fig. 7 shows the changes in fixed costs in Polish hard coal-fired power plants in the years 2010–2016 as well as the changes in the PLN/USD exchange rate during this period. On the basis of this data, it can be assumed that the recent level of fixed costs is approx. 12.5 USD/MWh (50 PLN/MWh).
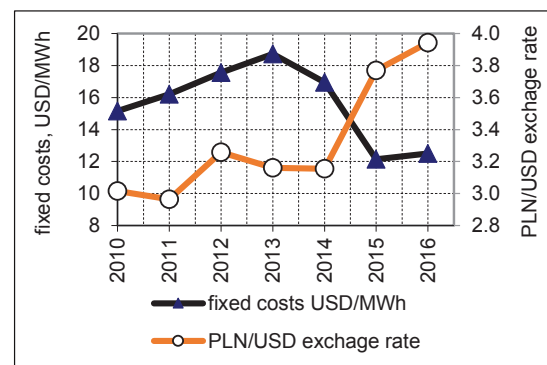

Fig. 7. Comparison of fixed costs in domestic hard and brown coal-fired power plants [19].

Table 2. Input data for CDS calculations—options 1 and 2.

Parameter	Input data for calculation	
Electricity price	35-50 USD/MWh (150-200 PLN/MWh)	
Coal price	1.72-3.50 USD/GJ (7-15 PLN/GJ)	
Calorific value	5 500 kcal/kg (23 GJ/kg)	
Prices of allowances for CO_2 emissions	Calculations were made at two levels: 5 and 10 EUR/ton CO2	
Exchange rates	4.0 PLN/USD and 4.2 PLN/EUR	
Power plant efficiency	36%	46%
CO_2 emission factor (WE) - according to [17]	92.3 kg/GJ= 0.923 tCO₂/MWh	92.3 kg/GJ= 0.722 tCO₂/MWh

Table 2 presents input data used for CDS calculations. The variability of the market prices of electricity in the range of 35–50 USD/MWh (140–200 PLN/MWh) has been assumed. The range of these prices is close to the average monthly spot prices at TGE (Polish Power Exchange) in the last 2 years. Coal prices vary in the range of 2–3.50 USD/GJ (8–15 PLN/GJ). The net as received (NAR) calorific value of this coal is 5,500 kcal/kg (approx. 23 MJ/kg). This number is close to the average parameters of coal combusted by Polish power plants.

Recently, in international trade, a number of price indexes appeared for coal with decreased quality compared to the so-called standard coal (6,000 kcal/kg, NAR). One of them is 5,500 kcal/kg coal traded in such countries as Australia or South Africa [20].

Calculations have been made for two pricing levels of emission allowances: 5 and 10 EUR/tCO₂, assuming that a power plant must buy 100% of required

Table 3. Results of simulation calculations of CDS at EUA price of **5 EUR/tCO₂** and power plant efficiency of 36% and 46%.

Coal Price, USD/GJ	Electricity price USD/MWh						
	35.0	37.5	40.0	42.5	45.0	47.5	50.0
	Power plant efficiency: 36%						
2.00	10.2	**12.7**	**15.2**	**17.7**	**20.2**	**22.7**	**25.2**
2.25	7.7	10.2	**12.7**	**15.2**	**17.7**	**20.2**	**22.7**
2.50	5.2	7.7	10.2	**12.7**	**15.2**	**17.7**	**20.2**
2.75	2.7	5.2	7.7	10.2	**12.7**	**15.2**	**17.7**
3.00	0.2	2.7	5.2	7.7	10.2	**12.7**	**15.2**
3.25	-2.3	0.2	2.7	5.2	7.7	10.2	**12.7**
3.50	-4.8	-2.3	0.2	2.7	5.2	7.7	10.2
	Power plant efficiency: 46%						
2.00	**14.5**	**17.0**	**19.5**	**22.0**	**24.5**	**27.0**	**29.5**
2.25	**12.5**	**15.0**	**17.5**	**20.0**	**22.5**	**25.0**	**27.5**
2.50	10.6	**13.1**	**15.6**	**18.1**	**20.6**	**23.1**	**25.6**
2.75	8.6	11.1	**13.6**	**16.1**	**18.6**	**21.1**	**23.6**
3.00	6.7	9.2	11.7	**14.2**	**16.7**	**19.2**	**21.7**
3.25	4.7	7.2	9.7	12.2	**14.7**	**17.2**	**19.7**
3.50	2.8	5.3	7.8	10.3	**12.8**	**15.3**	**17.8**

allowances. Two levels of power plant efficiency have been assumed: 36% (variant I) and 46% (variant II). The results of the CDS calculations for these variants have been summarized in Tables 3 and 4.

Each of the result tables (Tables 3 and 4) for the two price levels of EUA emission allowances, 5 and 10 EUR/MWh, consists of two parts with different power plant efficiency: 36% in the upper part and 45% in the lower part. Calculation results are given in USD/MWh. The calculations have been carried out for coal prices

emission allowances is approx. 12.5 USD/MWh in the case of hard coal-fired power plants.

In the result tables, the fields containing calculated CDS values of ≥12.5 USD/MWh are highlighted in bold. Such values mean that, at given prices of coal, electricity, and CO_2 emission allowances, the producer will get a margin covering at least the fixed costs.

Negative figures mean that energy generation is completely unprofitable. With such parameters (input data), energy prices will not even cover the costs of fuel

Table 4. Results of simulation calculations of CDS at EUA price of **10 EUR/tCO₂** and power plant efficiency of 36% and 46%.

Coal Price, USD/GJ	Electricity price USD/MWh						
	35.0	37.5	40.0	42.5	45.0	47.5	50.0
	Power plant efficiency: 36%						
2.00	5.3	7.8	10.3	**12.8**	**15.3**	**17.8**	**20.3**
2.25	2.8	5.3	7.8	10.3	**12.8**	**15.3**	**17.8**
2.50	0.3	2.8	5.3	7.8	10.3	**12.8**	**15.3**
2.75	-2.2	0.3	2.8	5.3	7.8	10.3	**12.8**
3.00	-4.7	-2.2	0.3	2.8	5.3	7.8	10.3
3.25	-7.2	-4.7	-2.2	0.3	2.8	5.3	7.8
3.50	-9.7	-7.2	-4.7	-2.2	0.3	2.8	5.3
	Power plant efficiency: 46%						
2.00	9.7	12.2	**14.7**	**17.2**	**19.7**	**22.2**	**24.7**
2.25	7.7	10.2	**12.7**	**15.2**	**17.7**	**20.2**	**22.7**
2.50	5.7	8.2	10.7	**13.2**	**15.7**	**18.2**	**20.7**
2.75	3.8	6.3	8.8	11.3	**13.8**	**16.3**	**18.8**
3.00	1.8	4.3	6.8	9.3	11.8	**14.3**	**16.8**
3.25	-0.1	2.4	4.9	7.4	9.9	12.4	**14.9**
3.50	-2.1	0.4	2.9	5.4	7.9	10.4	**12.9**

given in USD/GJ.

The figures in the individual table fields express the calculated CDS values in USD/MWh. The highlighted coal price level in the range of 2.25–3.0 USD/GJ (9–12 PLN/GJ) is the estimated range of prices of steam coal delivered for the commercial power industry in the coming years.

It can be assumed that the minimum theoretical producer's margin that will cover the costs of electricity generation at the assumed prices of fuel and CO_2

and emission allowances.

A comparison of the results of CDS calculations in variants I and II shows how big an impact has power plant efficiency on the achieved result: with higher efficiency, CO_2 emissions are lower (emission factor: 0.7680 t/MWh). The costs of purchasing fuel required to generate 1 MWh of electricity are also lower with higher power plant efficiency. It is also noteworthy that a change in the price of coal by only 1 USD/GJ causes a change in CDS in the range of 2–2.5 USD/MWh.

4 Conclusions

Despite the considerable increase in CO_2 emissions since 1990 (59%), in recent years (since 2012), the dynamics of this increase has weakened significantly. In 2015, for the first time, worldwide CO_2 emissions decreased slightly compared to the previous year. Three large areas: the U.S., China, and the EU (EU28) are responsible for 52–55% of global emissions. This share has been constant since 1990.

Coal combustion is responsible for 40% of worldwide CO_2 emissions, and the share of energy generation in this emission is 42%. The second place in this rating is occupied by transport with a share of 23%.

In the EU, coal combustion and electricity generation entail the need to purchase emission allowances. This situation causes these purchase costs to affect the costs of electricity generation significantly. Emission allowance prices depend on a large number of factors that often have opposite effects. These factors destabilize the market. Among these factors are:
• Increased emission reduction targets in the EU by 2030 and 2050.
• Changes in energy resource prices, especially coal and gas.
• Price relationships between major energy resources (coal/gas).
• Uncertainty of the economic development of the EU and the global economy.
• Planned reform of the EU ETS system.
• Functioning of the Market Stability Reserve (MSR).
• Implementation of the energy efficiency directive by the European Commission.

CO_2 emissions caused by coal combustion in power plants entail the need to purchase EUA allowances. The research described in the article shows:
• How current market conditions (variable prices of coal and electricity) shape the profitability of generating electricity from coal.
• How CDS changes as a function of changes in energy and coal prices at the assumed levels of emission and prices of EUA allowances.

The result tables highlight three areas of results where the CDS values are:
• Negative—the prices of electricity do not even cover the costs of fuel and CO_2 emission allowances.
• Over 12.5 USD/MWh (minimum value of the theoretical producer's margin), which allows for covering all electricity generation costs.
• Positive, but below 12.5 PLN/MWh—prices do not cover all fixed costs associated with electricity generation.

A comparison of the results of CDS calculations in two variants shows how big an impact has power plant efficiency on the achieved result: with higher efficiency, CO_2 emissions are lower (emission factor: 0.722 t/MWh). The costs of purchasing fuel required to generate 1 MWh of electricity are also lower with higher power plant efficiency. In such case, a power plant can achieve profitability of electricity generation, even with relatively high prices of coal.

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