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Costs and benefits of reducing air pollutant emissions as a result of bringing coal and lignite-fired power plants into compliance with BAT LCP conclusions

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Abstract
The analysis carried out regarding the costs of adapting to the best available technique (BAT) conclusions in relation to the benefits achieved (external costs) showed that these benefits significantly exceed the cost of investments necessary to meet the required levels of permissible best available technique-associated emission levels (BAT-AELs). In the case of sulfur dioxide, the ratio of costs incurred to benefits obtained is only 3%, for nitrogen oxides 7%, and for dust it is less than 1%. This is primarily due to a significant increase in external costs, published in 2021 by the EEA. Nevertheless, it should be remembered that a precise assessment of external costs should be based on the analyses of individual facilities, taking into account their local specificity.
The analysis showed that the most cost-effective way was to adapt the coal-fired power plant sector to the requirements related to reducing dust emissions. Significant benefits were achieved as a result of small investment outlays.

1. INTRODUCTION

Directive 2010/75/EU of the European Parliament and of the Council of Industrial Emissions (integrated pollution prevention and control) on 24 November 2010—The Industrial Emissions Directive (IED) [Directive... 2010]—introduced several changes for the largest producers of electricity and heat derived from fossil fuels. The most important are:

- tightening emission standards for large combustion plants (with a rated thermal input ≥ 50 MW),
- the introduction of best available technique (BAT) conclusions as binding legal provisions to comply with by installations, with particular reference to the emission limit values (BAT-AELs: best available techniques-associated emission levels).

The published BAT conclusions, under Article 14(3) of the IED, without separate transposition into the national law of EU Member States, are the basis for setting emission limit values (BAT-AELs) in integrated permits. Article 204(1) of the Act of 27 April 2001 Environmental Protection Law [Ustawa... 2001] states: "Installations requiring an integrated permit shall meet the environmental protection requirements arising from the BATs and, in particular, shall not cause emission limit values to be exceeded."
According to Article 21(3) of the IED and Article 215(4)(1) of Poland's Environmental Protection Law, installations, including large combustion sources, i.e., large combustion plants (LCPs), should in principle be brought into compliance with BAT conclusions within 4 years from the publication of the decision on BAT conclusions in the EU Official Journal. The introduction of BAT-AELs (the achievable emission level associated with the application of the BATs) is a further step towards a significant reduction of air pollutant emissions from fossil fuel combustion.
The reduction of pollutant emissions is intended to improve air quality, and consequently, to decrease human health risks and limit environmental degradation. This requires specific financial outlays in the form of investment and operational costs incurred for flue gas cleaning systems. The present study shows an estimate of the costs of reducing emissions of the main air pollutants (SO_2, NO_x, total suspended particulate TSP) from coal- or lignite-fired power plants, related to the implementation of BAT conclusions, as well as the benefits of emission reduction in the form of decreased external costs of air

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pollution. The test methods applied and the materials used are described in Section 2. The analysis of the emission reduction potential of the studied air pollutants as a result of the implementation of BAT conclusions is presented in Section 3. Sections 4 and 5 refer to the costs and benefits of expected emission reductions, respectively, whereas Section 6 provides the summary of the analyses carried out.

2. STUDY METHODS, ASSUMPTIONS, AND DATA SOURCES

2.1 Basic assumptions for the analysis

The analysis concerned the national sector of public power plants fired by coal or lignite, classified as LCPs (with a rated thermal power ≥ 50 MW), consistent with the aggregation of capacities resulting from combining sources connected to one chimney (the so-called "common stack"). The sources were grouped by the fuel and boiler types (including nominal power).

As the study focused on emission reductions in line with BAT conclusions, the year of their first publication (17 August 2017) was taken as the baseline year (before the implementation of the conclusions). Starting from 2017, LCPs had 4 years to comply with the conclusions. The calculations were performed assuming that in all the analysed categories of the plants, there will be implemented BAT-AELs, and electricity and heat production level will remain unchanged with respect to the baseline year. This approach allowed an unambiguous assessment of costs and benefits, irrespective of the effects of production changes on emissions.

2.2 Analysis of the emission reduction potential

The reductions in emissions of the air pollutants under the study were determined as the difference between their emissions in the base year (before the implementation of BAT conclusions) and their emissions afterward (see the assumptions presented in the previous section). Baseline data for 2017 on electricity production; heat production; fuels used and their calorific values; power of sources connected to the common stack; SO_2, NO_x and TSP emissions; date of commissioning and first emission permit; combustion technology, and operating hours were obtained from the National database on greenhouse gases and other substances emissions at the National Centre for Emissions Management (KOBiZE).

To calculate emissions after adjusting installations to the BAT conclusions, the studied plants were assigned to a range of power introduced in the fuel, types of fuel combusted, date of commissioning, and obtaining the first emission permit, combustion technology, and operating hours. Subsequently, respective BAT-AELs were assigned to the plants in accordance with Article 204(1) of the Environmental Protection Law [Act... 2001] which states that installations should not cause the emission limit values to be exceeded. The emission limit values are understood as the highest of the emission values related to the BATs defined in the BAT conclusions, achieved under normal operating conditions using the BAT or a combination of the BATs.

Moreover, it was necessary to determine the total flue gas volume. The unit flue gas volumes for a given fuel were adopted analogously to the analyses used for the preparation of the Transitional National Plan [TNP]:

- 360 Nm^3/GJ – for coal,
- 420 Nm^3/GJ – for lignite.

In the determination of the product emission factors, the relationships defined in the TNP were used, i.e.:

$$W_{prod.} = (em \cdot V_s)/\eta \cdot 10^{-6} \text{ [kg/GJ]}$$

where: $W_{prod.}$ - product emission factor [kg/GJ]; em - air emission limit value (BAT-AEL or emission standard) [mg/Nm^3]; V_s - specific emission factor [Nm3/GJ]; and η - generation efficiency.

The emission projection takes into account the most recent plants commissioned and planned after the adaptation period to the BAT conclusions, i.e.:

- coal and lignite blocks at power plants: EZ Kozienice II, EZ Opole II, EZ Jaworzno II, and EZ Turów II,

whereby the power balance was determined (replacement of the depleted blocks with the above-mentioned new ones) based on data from Polish electricity network operator - Polskie Sieci Elektroenergetyczne S.A. [PSE S.A. 2018].

Due to the fact that the year 2017 was the last year of operation of the Adamów power plant, this installation was not included in the analyses as regards the baseline year and the period of adjustment to the BAT conclusions.

2.3 Estimation of emission reduction costs

The total costs of emission reduction were calculated as the sum of the capital expense (CAPEX) and operating expense (OPEX). CAPEX refers to the costs related to capital expenditure incurred to upgrade an existing flue gas treatment plant or build a new one. Capital expense includes expenditure related to, inter alia: project preparation, purchase of equipment, construction and installation works, and investment financing. OPEX refers to operating costs related to the operation of a new or upgraded flue gas treatment installation. OPEX includes fixed costs of the maintenance of assets and operation, i.e., those of materials and services, such as installation, upkeeping/servicing/repairing, license and insurance fees, as well as variable costs related to the operation of an installation for air pollution reduction, e.g., costs of consumed materials (reagents) and costs of energy

additionally consumed for running the flue gas cleaning system.

The values of the changes in unit costs related to investments in flue gas cleaning installations were calculated based on data from the guidebook on the rules for granting derogations from emission limit values contained in the BAT conclusions for large combustion sources [Podręcznik dotyczący zasad udzielania odstępstw… 2017]. The use of data from this guidebook was dictated by the fact that it denotes the official position of Poland's power industry, which is represented by economic associations of power plants, combined heat and power plants (CHPs), district heating plants, as well as the Ministry of Climate and Environment, which presented to the European Commission the issue of the costs of adjusting Polish installations to the BAT conclusions.

Taking into account the most up-to-date macroeconomic indicators available, published by Statistics Poland (the Central Statistical Office - GUS), it was decided to recalculate the costs with the use of prices in 2021, i.e., with reference to the last year when installations had to be brought into compliance with BAT requirements (4 years from the first publication of BAT LCP Conclusions in 2017). In addition, the results of the calculations were consulted with several operators of installations that had completed the investment process of compliance with BAT LCP Conclusions. The consultation confirmed the validity of the approach taken. In general, the installation operators observed that until 2021, the prices increased in a balanced manner in line with inflation rates. In some cases, due to local investment conditions, the theoretical cost of conversions differed by ±20% from the actual investment expenditure. This was related to individual conditions and the scope of modernisation works (e.g., demolition of old flue gas cleaning systems or a specific solution applied in a specific plant).

The calculation of the consumer price index uses the Classification of Individual Consumption by Purpose, adopted for the Harmonised Index of Consumer Prices (COICOP/HICP) [GUS 2022a]. A similar measure is the Harmonised Index of Consumer Prices (HICP), which has the advantage that is calculated by Member States according to the consistent methodology applied in the European Union. The basis for the HICP for Poland is:

- observation of changes in prices of representative consumer goods and services,
- the system of weights based on the structure of individual consumption in the household sector, from the statistics of national accounts two years ago [GUS 2022b].

Taking all the above considerations into account, HICP was used for the calculations performed in this study.

The unit costs of dedusting, desulphurisation and denitration of flue gas were determined for existing LCP plants with no high-efficiency flue gas cleaning installations, i.e., those not compliant with the BAT conclusions.

The total reduction costs were calculated by multiplying the unit costs by the calculated reduction volume.

2.4 Identifying emission reduction benefits

The report published by the European Environment Agency entitled Costs of Air Pollution from European industrial facilities 2008-2017 [EEA 2021; the third in the series] provides information on the external costs of air emissions from industrial installations, based on improved research methodologies and recommendations from expert assessments presented in other reports, e.g., Mortality Risk Valuation in Environment, Health and Transport Policies [OECD 2012]. The EEA report aimed to provide up-to-date data with regard to the cost of emissions in relation to the unit mass of a given pollutant, taking into account impacts on human health, materials, and ecosystems.

Consistent with the marginal abatement costs method, the estimated damage costs take into account, inter alia, the effects of regional pollution on human health, crops, forests, and ecosystems (eutrophication), as well as the influence of SO_2 and NO_x on materials.

In this study, the Value of Life Year (VOLY) was used to estimate the value of external costs. This method is one of the human capital methods based on evaluating the magnitude of environmental changes that affect the income of persons and societies. VOLY is determined by identifying a measurable causal relationship between the environment and human health. The Value of a Statistical Life (VSL) and VOLY are estimated based on the willingness to pay method (WTP). VOLY is defined as the amount of money people are willing to pay for one year added to their life expectancy.

The use of the VOLY method, rather than the related VSL (the amount of money a community of people is willing to pay to reduce the risk of premature death in the community), is dictated by arguments about methodological logic as well as the frequency and preference of using both methods in the context of air pollution valuations. As CONCAWE Report 4/06 points out, in reference to a long-lasting debate among scientists on the advantages and disadvantages of both methods [Rabl 2003, IER 2004, ExternE Externalities of Energy 2005], in the context of air pollution, VOLY is a more suitable method than VSL for the reason that the effects of air pollution are not immediate and do not result in a certain number of deaths that can be directly attributed to a given factor, but constitute the cumulative result of years of exposure (the so-called chronic mortality). Consequently, it is not possible to determine whether a given exposure has caused a small number of people to lose a significant part of their life expectancy or many people to lose a small part of their life expectancy. Only the average number of life years lost can be calculated, for that reason, VOLY is a more accurate measure for assessing the damage costs of air pollution from industrial facilities.

In order to calculate the overall benefits of the reduction of pollutant emissions related to compliance with the

Table 1. Product emission factors for coal- and lignite-fired power plants in 2017 and after adjustment to the BAT conclusions

Fuel type	2017			After adjustment to the BAT conclusions		
	SO_2 Pcee [kg/GJ]	NO_x Pcee [kg/GJ]	TSP Pcee [kg/GJ]	SO_2 Pcee [kg/GJ]	NO_x Pcee [kg/GJ]	TSP Pcee [kg/GJ]
Coal	0.186	0.254	0.0113	0.119	0.135	0.0075
Lignite[1)]	0.282	0.231	0.0120	0.146	0.187	0.0086

[1)] Production emission factors without Adamów plant
Pcee – gross equivalent production (Pc+Pee)

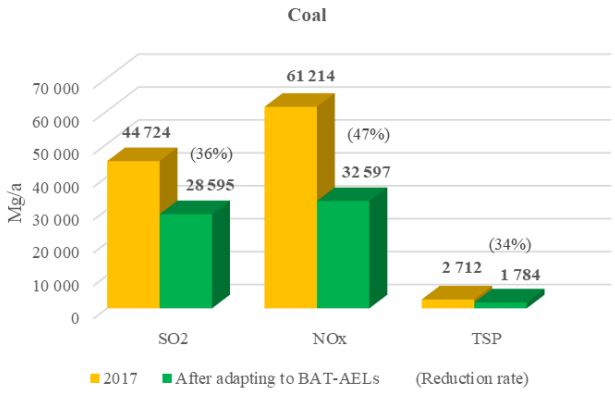


Figure 1. Emission volumes for examined pollutants from the sector of main activity producer electricity plants fired by coal in 2017 and after adjustment to the BAT conclusions and percentage reduction rates

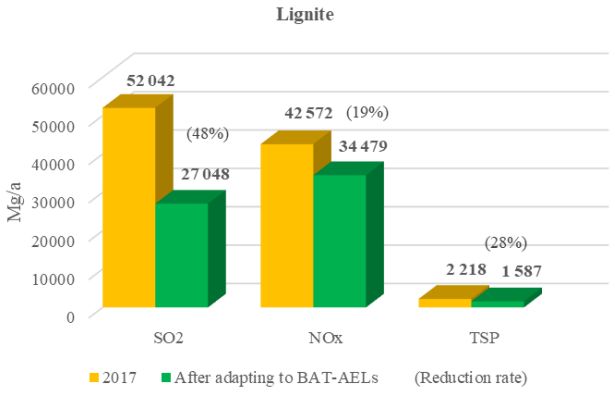


Figure 2. Emission volumes for examined pollutants from the sector of main activity producer electricity plants fired by lignite in 2017 and after adjustment to the BAT conclusions and percentage reduction rates

BAT conclusions, the unit external costs of the emissions of SO_2, NO_x and particulate matter derived from the EEA [2021] report were multiplied by the amount of avoided emissions. As BAT-AELs refer to the emissions of total suspended particulate (TSP) and the external costs identified in the aforementioned report refer to PM_{10} and $PM_{2.5}$ fractions, it was assumed that by mass these fractions account for 70% and 30% of TSP, respectively. This was confirmed by the studies of Lewandowski et al. [2022b] and Lewandowski et al. [2022c].

3. EMISSION REDUCTION POTENTIAL

In the baseline year 2017, before adjustment to the BAT conclusions, the highest product emission factors for specific pollutants came from the combustion of lignite, as a consequence of the characteristics of this fuel.
Table 1 shows the product emission factors for electricity and heat (equivalent production converted into GJ) for the year 2017 and after adjustment to the BAT conclusions, in relation to the fuel analysed. After adjustment to the BAT conclusions, according to the assumptions presented in Sections 2.1 and 2.2, the product emission factors will decrease significantly.
Figures 1-3 show the emission volumes determined in conformity with the assumptions taking into consideration

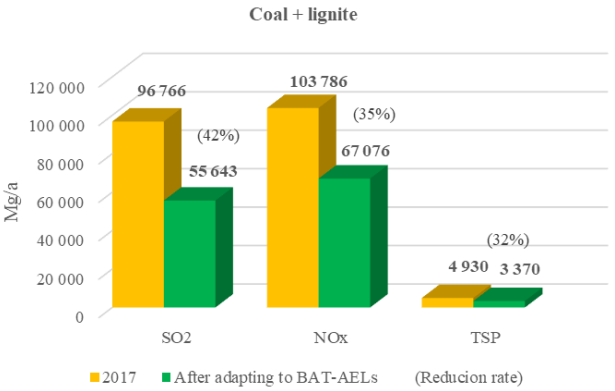


Figure 3. Total emissions of pollutants from the sector of main activity producer electricity plants, fired by coal and lignite in 2017 and after adaptation to BAT LCP conclusions and percentage reduction rates

the conditions before and after adjusting to the BAT conclusions (see Sections 2.1 and 2.2), as well as the percentage reduction rates in the sector of main activity producer electricity plants fired by coal or lignite and the total emissions for both fuels.

Table 2. Avoided emissions from combustion of the examined fuels in different types of boilers due to compliance with the BAT LCP conclusions

Type of boiler and fuel	Power rate [MWt]	Avoided emissions [Mg/year]		
		SO_2	NO_x	TSP
KP-WK	300–1000	7 407	3 760	389
KP-WK	≥1000	8 403	24 491	540
KF-WK	300–1000	319	350	0[1)]
KF-WK	≥1000	0[1)]	16	0[1)]
KP-WB	300–1000	1 111	706	49
KP-WB	≥1000	22 423	7 387	152
KF-WB	≥1000	1 460	0[1)]	430
Total		**41 123**	**36 710**	**1 560**

[1)] BAT-AELs were met in the baseline year
KP – pulverized coal boiler, KF – fluidized bed boiler, WK –coal, WB – lignite

Table 3. Average operating hours of facilities based on data from the Ministry of Environment [Podręcznik dotyczący zasad udzielania odstępstw… 2017]

Technology	Operating hours [h/year]
KP-WK	4000
KF-WK	5500
KP-WB	5800
KF-WB	6500

[1)] The assumed.operating hours: 1000 h/year
KP - pulverized coal boiler, KF - fluidized bed boiler, WK - coal, WB - lignite

To calculate emission reduction costs, the avoided emissions were expressed separately for the different fuels and boiler types, as shown in Table 2.
It should be noted that, as a result of the aggregation of installations combusting particular fuels in particular boiler types, the calculated emission reductions may be underestimated. In fact, some of the LCP combustion sources in a given category met BAT-AELs in the baseline year (e.g., in the case of TSP—installations combusting coal in fluidised bed boilers), so bringing the remaining installations of the plants into compliance with the BAT conclusions may result in a greater emission reduction compared to the results of the group analysis presented in this study.

4. COSTS OF EMISSION REDUCTIONS

The total cost of emission reduction in 2021 in the case of the pollutants analysed in reference to the unit of energy input in fuel was calculated based on the unit costs of CAPEX and OPEX, which are determined based on the guidebook on the rules for granting derogations from emission limit values contained in the BAT conclusions for large combustion sources [Podręcznik dotyczący zasad udzielania odstępstw… 2017], CSO data [CSO 2022c], and the operating hours of installations (Table 3). The depreciation period of 20 years was assumed for fixed CAPEX. Due to several specific considerations related to the ability to raise finances, the cost of investment loans for installation construction were not included in the calculations.
The costs per Mg of pollutant removed were determined based on the above assumptions. The results of the calculations for SO2, NOx, and TSP are presented in Table 4. Based on the results in Table 2 and Table 4, the total costs of reducing emissions of the pollutants examined from the combustion of coal and lignite were calculated (Table 5).
The highest costs of reducing emissions are for coal in relation to NO_x and the lowest are for lignite in relation to TSP.

5. BENEFITS OF EMISSION REDUCTIONS

The benefits of pollutant emission reductions were calculated (see Table 6) based on the method and the data presented in Section 2.4, and with the use of the data from the report published by the EEA [2021].
The unit external costs are the highest in the case of reducing the emission of particulate matter $PM_{2.5}$, which is justified by its highly negative impact on health. The unit costs for particulate matter are many times higher than those for SO_2 or NO_x.
The total benefits of emission reductions due to compliance with BAT LCP conclusions are highest for SO_2, almost twice as high as for NO_x, and more than 10-fold higher than for particulate matter fractions. This is principally due to the high values of avoided SO_2 emissions and the relatively high unit external cost of these emissions.

Table 4. Unit costs of SO_2, NO_x, and TSP emission reductions for existing LCP facilities with no high-efficiency flue gas cleaning systems

Type of boiler and fuel	Power rate [MWt]	CAPEX and OPEX 2021 [EURO/Mg]		
		SO_2	NO_x	TSP
KP-WK	300–1000	565.53	720.11	6.60
KP-WK	≥1000	630.49	605.88	4.50
KF-WK	300–1000	379.61	968.25	4.73[1)]
KF-WK	≥1000	363.68[1)]	764.28	3.20[1)]
KP-WB	300–1000	388.39	576.90	10.04
KP-WB	≥1000	330.79	479.67	6.81
KF-WB	300–1000	350.07	694.67	4.05
KF-WB	≥1000	291.20	549.01[1)]	2.75

[1)] Due to the fulfillment of BAT-AELs in the baseline year, the category not included in further calculations
KP – pulverized coal boiler, KF – fluidized bed boiler, WK –coal, WB – lignite

Table 5. Total costs of reducing emissions of the examined pollutants from coal and lignite combustion, related to compliance with BAT LCP Conclusions

Type of fuel	Costs of reducing emissions [EURO/year]		
	SO_2	NO_x	TSP
Coal	9 608 019	17 897 638	4 996
Lignite	8 274 080	3 950 497	2 715
Total	**17 882 099**	**21 848 135**	**7 710**

Table 6. Unit external costs of air pollution and total benefits of reductions due to compliance with BAT LCP conclusions.

Pollutants	SO_2	NO_x	PM_{10}	$PM_{2.5}$
Avoided emission [Mg/year]	41 123	36 710	1 092	468
Unit external costs of emissions [EURO/Mg]	14 289	8 457	27 684	42 634
Total benefits [EURO/year]	**587 613 339**	**310 458 410**	30 230 085	19 952 156
			50 182 241[1)]	

[1)] Total reduction of PM_{10} and $PM_{2.5}$ fractions

6. CONCLUSIONS

The study shows that the costs of complying with the BAT conclusions are lower in comparison to the benefits achieved. For sulphur dioxide, the ratio of costs incurred to benefits achieved is only 3%, for nitrogen oxides it is 7%, and for particulate matter it is less than 1%. This is primarily due to a significant increase in external costs. For sulphur dioxide, for example, the external costs increased by 280%, for nitrogen oxides by 130%, and for particulate matter (fine size fraction) by more than 70%, in comparison to the first study on this topic, i.e., the ExternE [2005] report. The current EEA [2021] report on external costs referred to in the present study was prepared based on improved research methodologies and recommendations from expert assessments published in other relevant reports. The development of the methodology has allowed for the inclusion of further types of effects and impacts, e.g.,

the effects on ecosystems, and effects on health related to direct exposure to NO_x. Nonetheless, it should be borne in mind that an accurate assessment of external costs should be based on a site-by-site analysis taking into account local specificities, i.e:

- height of the emitter,
- velocity and temperature of flue gas at emitter outlet,
- concentrations of pollutants in emitted flue gases,
- terrain,
- atmospheric conditions, and
- population density.

This analysis showed that it was most cost-effective to bring the coal-fired power plant sector into compliance with requirements related to the reduction of particulate matter emissions. Significant benefits were achieved as a result of the small investment. This is dictated, inter alia, by the low cost of retrofitting electrostatic precipitators, as installations of this type have been in operation and modified for many years in order to gradually adapt them to tightening emission standards. For NO_x, derogations (treaty derogations) have been in place for many years, which has translated into accumulated costs for the construction of highly efficient denitrification installation. In the case of desulphurisation, necessary installations are technically very complex, so the modernisation of absorbers involves significantly more money than in the case of electrostatic precipitators.

On the other hand, the unit external costs for particulate matter are the highest, as PM_{10} emissions are valued almost twice as high as SO_2 emissions and three times higher than those of NO_x. For $PM_{2.5}$ emissions, the external costs are three times higher than those for SO_2 and as much as five times higher than those for NO_x.

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