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EVALUATION OF ENVIRONMENTAL PERFORMANCE IN COKE PRODUCTION – TOWARDS EMISSION REDUCTION AND INPUT RATIONALIZATION

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Purpose: Coke production is hindered by a number of serious environmental nuisances. It is also a capital- and cost-intensive production. Despite these complex production conditions, coke is regarded as a critical raw material due to its key importance in steel production worldwide and there are few circumstances nowadays that indicate a possibility of rapid change of the existing state of affairs. For these reasons, it is becoming extremely important in coke production to look for investment solutions that will enable the reduction of environmental hazards while at the same time rationalizing the economic outlays incurred in their implementation. Thus, the goal of this article is to present a methodology for evaluating the environmental effectiveness of investments in coking plants, making it possible to balance environmental and economic benefits.
Design/methodology/approach: The research made use of an analysis of environmental hazards in process terms, an index for evaluating environmental effectiveness and rules for assessing compliance with the Best Available Techniques (BAT) conclusions. In order to verify the proposed methodology, a multi-variant analysis was used relating to selected pro-environmental investment projects.
Findings: Against the background of previous analyses in this area, the considerations and research carried out are distinguished by the inclusion of a process approach to sources of emissions in coke production, rather than a point approach, and simultaneous consideration of environmental and economic criteria.
Practical implications: The presented methodology can also be applied to coking plants without major difficulties and additional costs, which is an additional, application value added of the article.

Keywords: environmental efficiency in coke production; reduction of pollutants in coke production.

Category of the paper: Research paper.

1. Introduction

Coke production is a technology for the high-temperature airless degassing of hard coal at a final temperature above 1,000°C, which takes place in a coking plant. In the commonly used so-called classic coking technology, from 1 Mg of dry coal an average of 750 kg of coke, 350 m^3 of gas, 35 kg of tar, 10 kg of benzol, 2.5 kg of ammonia and 50 kg of water containing many coal decomposition products, mainly phenolic compounds and ammonia, is obtained (Szlęk et al., 2009).

The basic production tasks of a coking plant boil down to the preparation of a coal mixture and the production of:

- Coke.
- Purified coke oven gas.
- Chemical coking products.

The main production branches of a coking plant include:

a) The coal plant.
b) The furnace plant.
c) Coal washing plant.
d) Sorting plant.

The process of proper coke production (Dudek-Dyduch, Dyduch, 2005) consists of the following basic technological operations:

- Filling the coking chambers with the coal mixture.
- Firing the coke oven battery.
- Coking of the coal mixture.
- Pushing out the coke.
- Cooling of the coke.
- Extracting gas from coking chambers.

The activity of coking plants can be classified as one of the most environmentally burdensome (Kwiecińska et al., 2017; Yang et al., 2018, 2019). The process of coke production is accompanied by the release of numerous air pollutants into the air, including very harmful ones, namely, carcinogenic (Mu et al., 2017; Dehghani et al., 2020; Lovreglio et al., 2018). This release takes the form of channeled and fugitive emissions of gaseous and particulate pollutants (Kozielska, Konieczyński, 2015). Channeled emission occurs when substances are introduced into the air in an organized manner through an emitter (stack) and it is measurable with standard measurement methods. Despite these complex production conditions, coke is treated as a critical raw material due to its key importance in steel production worldwide and currently there are few circumstances indicating that the status quo is likely to change quickly (Ozga-Blaschke, 2016; Blaschke, Ozga-Blaschke, 2015; Warzecha, Jarno, 2014).

Given the circumstances presented above, coke production plants are classified as those likely to cause significant environmental pollution, which clearly imposes on the plant operator the obligation to obtain a so-called integrated permit for the activities conducted.

Integrated permits are an instrument introduced by European Community Council Directive 96/61/EC on integrated pollution prevention and control. In the following years, as part of law enforcement, on November 24, 2010, the European Parliament and the Council adopted Directive 2010/75/EU, i.e., *The Industrial Emissions Directive* (IED). On January 6, 2011, the provisions of this directive became binding on all Member States (*Guidance on Assessment under the EU Air Quality Directives*).

The IED unifies the principles for establishing the conditions for the operation of industrial plants of relevance to environmental quality. In accordance with para. 12 of the Directive, the permit should include all measures necessary to achieve a high level of protection of the environment as a whole and to ensure that the plant complies with the general principles governing the basic obligations of the operator. The permit should include emission limit values for polluting substances or equivalent parameters or technical measures, appropriate requirements to protect the soil and groundwater and monitoring requirements. The permit conditions should be based on the best available techniques (BAT).

In light of the above, the environmental expectations on industrial plants are constantly increasing, therefore it is becoming increasingly important to manage coke production in the idea of sustainable development (Li et al., 2020; Makgato et al., 2019; Li, Cheng, 2020). It concerns the development conditioned by the ecological space, and through the assumed synergy of economic, environmental and social aspects, one which is safe and beneficial for people, the environment and the economy. The basic way of influencing and stimulating the operators of industrial plants in the field of environmental protection are environmental management instruments which can be divided into direct (legal-administrative) and indirect (economic-market) ones.

From the point of view of a coke plant operator, the most important direct instruments include: emission standards, air quality standards and technological requirements (Osmólski, Morel, 2013). Emission standards are strictly defined for individual emission sources and pollutants often in dedicated, activity-specific legal regulations. In order to check if the standard is met, emission measurements are performed (Wang et al., 2012; Yuan et al., 2017; Rychlewska et al., 2021). Emission measurements are commonly performed and technically unproblematic, but they do not give a complete picture of the impact of plants on air quality (Martins, Fonseca, 2018; Iraldo et al., 2009). They mostly concern single facilities in the production chain and a single emitter. Meanwhile, as already mentioned, in environmentally burdensome industries, which also include coking, emissions have many sources and concern many pollutants simultaneously. Under these circumstances, the need arises to improve the methods of assessing the environmental impact of industrial plants in the direction of taking into account the entire production process and many different criteria.

Another instrument is air quality standards, the values of which are defined on the basis of medical and biological diagnosis of the elements of the environment to the dose of a given pollutant, which allows to formulate acceptable levels of air pollution, which should not be exceeded (Amodio et al., 2013; Pilarczyk et al., 2013). The assessment of the impact of a plant on air quality is obtained by performing pollutant dispersion modeling, which is performed when applying for an integrated permit or its update (Żeliński et al., 2018). Deterministic models are mainly used in this assessment, which requires data on the unambiguous environmental effects of the projects introduced. These models are cheap and time efficient and at the same time work well in practice as forecasting models. Their basic task is to determine concentrations of pollutants in the air by solving equations describing physical and chemical phenomena occurring in the atmosphere, using independent variables describing conditions, types and amounts of emissions (dimensions of the emitter, temperature and velocity of gases at its outlet, emissions of particular pollutants), meteorological parameters, topographical and other parameters (Ma et al., 2019; Bailey et al., 2018; Van Donkelaar et al., 2016). Currently, these methods are being refined to assess the spread of pollutants in transboundary areas due to uneven implementation of environmental targets by countries (Mostafanezhad, 2021; Chen, Taylor, 2018). It is worth mentioning at this point that most existing models are mathematically complex, require a lot of data and time to calculate. For these reasons, they are best suited for regional, national and international analyses, and less often find direct practical application.

Technological requirements (Babich, 2021) include, among others, legal requirements such as BAT conclusions and their list of best available techniques to be implemented by a specific type of production activity (Sobolewski et al., 2006; Dellise et al., 2020; Evrard et al., 2016; Evrard et al., 2018; Huybrechts et al., 2018). The implementation of BAT in the process of implementation of environmental governance in the energy law of the European Union is currently postulated, which would definitely increase the rank and impact of these regulations (Giljam, 2018). Compliance of industrial plants with the requirements of the above-mentioned direct instruments provides a guarantee of safe, innovative use of the environment (Kuznetsov et al., 2019; Generalova et al., 2019; Zabelina, Sergienko, 2021), but also creates a risk for production activities that the required solutions will be too costly and therefore not always implementable. In this way, there is very often a clear separation between legal standards and industrial considerations.

Indirect instruments of an economic-market nature are instruments that stimulate rather than prescribe (Wasiuta, 2015; Chornomaz et al., 2017). These instruments are most often in the form of fees per unit of pollution introduced into the environment and are the main financial tool for influencing production facilities. Environmental charges were introduced mainly to encourage production plants to use natural resources rationally and economically and to finance environmental protection projects. The results of various environmental studies indicate that the use of fees and taxes is effective in reducing emissions (Brizga et al., 2021; Hu et al., 2019; Niu et al., 2016).

Direct and indirect instruments are an important element in the management of a coking company and can be selection criteria when investment decisions have to be made. These instruments are also guidelines for the development of environmental management strategies and multi-annual investment plans. Nevertheless, as already mentioned and as highlighted in the literature (Deng et al., 2017; Zhang, Wu, 2020) environmental management standards are not able to regulate all aspects related to industrial emissions. So, their application requires coke producers to take a responsible approach to environmental investments and decision makers to continuously improve existing standards.

In connection with the presented legal and environmental conditions, all coking plants operating in the European Union have been obliged to comply with the aforementioned regulations and existing environmental protection standards. Due to the cost-intensive nature of coking production, adapting production to the environmental requirements set out in EU legislation is a difficult challenge. The more so as additional legal restrictions are expected in the future for companies operating in sectors with exceptional environmental nuisance. Therefore, the goal of this article is to present a methodology for evaluating the environmental effectiveness of investments in coking plants, which enables the balancing of environmental and economic benefits and provides decision-making support for coke producers in the investment decision-making process. In the context of the thus formulated objective of consideration and research, the main research problem is as follows: *How to holistically assess a technological investment in the coking industry, taking into account environmental requirements and the investor's capital capabilities, bearing in mind the entire production process and its accompanying emissions?*

The viewpoint presented in this article is therefore not the more common regional or economic one. Nor does it refer exclusively to environmental or technological aspects. The authors of the study attempt to assess pro-environmental solutions for coking plants from a sustainable perspective, taking into account both current legal and environmental conditions, as well as capital constraints determining the final decisions of coke producers. It is worth noting that all environmental standards and norms must ultimately be translated into practical measures implemented in the industry. Otherwise, no environmental management instruments will be effective.

The research included: (1) Environmental hazard analysis from a process perspective; (2) Environmental performance evaluation index; and (3) The degree of compliance with *Best Available Techniques* (BAT) conclusions (Giljam, 2018; Mavrotas et al., 2009). In order to verify the proposed methodology, a variant analysis was used relating to selected pro-environmental investment projects. The considerations and research carried out - against the background of previous analyses in the area in question - stand out above all:

- Inclusion of a process-based (Li et al., 2020) and not a point approach (concerning 1 emitter) to emission sources in coke production.
- Considering several pollutants simultaneously.

- Analyzing environmental, technological and economic criteria in parallel.
- Taking into account the investor (decision-making) point of view.

The presented methodology may also be applied in coking plants without major difficulties and additional costs, which is an additional, practical value of the article.

2. Data and Methods

2.1. Environmental and investment assumptions

According to the literature, the results of the quantitative analysis indicate an apparent dominance of the share of emissions of CO_2 (99,2%) over the sum of other substances (CO, NO_x/NO_2, SO_x/SO_2, HCN, NH_3, CH_4, benzene, NMVOC, dust) (Zhong et al., 2013; Hu et al., 2014; Telenga-Kopyczyńska et al., 2010). Outside of CO_2, emissions of SO_x/SO_2, NO_x/NO_2, CO and dust present the highest share of emissions in a coke plant. The results of the qualitative analysis indicate PM10 and BaP as environmental nuisance substances (Hys et al., 2018). The main source of particulate emissions including BaP is fugitive emissions from the filling, coking and pushing out processes. In contrast, channeled emissions are mainly from the battery firing process with NO_X/NO_2 and SO_X/SO_2 emissions. Taking into account the recurrence, quantity and environmental nuisance of pollutants under current legal conditions, 4 pollutants were selected for environmental performance analysis: BaP, PM10, NO_2, SO_2, as substances both characteristic for coke production and having quantitative and qualitative impact on the state of air cleanliness. The further analysis did not include total dust due to the lack of a permissible level for this pollutant in the air and research results showing that the PM10 fraction accounts for almost all the total dust.

The pollutants selected as a result of the analysis were assigned to each of the technological processes mentioned in the introduction, according to their emission characteristics, which is presented in Table 1.

Table 1.
Selected pollutants from specific technological processes

Process	Pollution
Preparation of the coal mixture	PM10
Filling of coke oven batteries	SO_2, PM10, BaP
Coking of the coal mixture	NO_2, SO_2, PM10, BaP
Firing of coke oven batteries	NO_2, SO_2, PM10, BaP
Pushing out the coke	NO_2, SO_2, PM10, BaP
Wet cooling of the coke	SO_2, PM10, BaP
Coke sorting	PM10
Burning coke gas	NO_2, SO_2, PM10

Source: Own elaboration based on Przewodnik metodyczny (2010): Uwalnianie i transfer zanieczyszczeń do środowiska będących efektem eksploatacji instalacji koksowniczych w Polsce. Zabrze, Zabrze, Published by the Institute for Chemical Processing of Coal.

For further analysis it was assumed that the coking plant under study is characterized by the technological output parameters listed in Table 2. Within the analyzed coking plant there are 5 coke oven batteries without dedusting and desulphurization plants, which reflects the maximum environmental harmfulness of coke production.

Table 2.
Baseline techniques in the coke oven output plant

Process	Baseline techniques
Carbon plant, batch preparation	No dedusting plant
Filling	Hydroinjection
Coking	Exhausted coke oven batteries, large leaks
Firing	Discharged coke oven batteries, no flue gas recirculation, no desulphurization plant
Pushing	No dedusting plant
Wet cooling	Extinguishing towers with depleted filling
Sorting and transportation of coke	No dedusting plant
Burning coke gas	No coke gas desulphurization plant, poor condition of burners

Source: own work.

Next, 6 investment projects were proposed which would enable the modernization of the adopted coking plant in order to reduce its environmental nuisance, taking into account the characterized technological processes. These variants constitute a compilation of possible technical and investment measures including (a detailed description of individual investment projects is presented in the study results section):

- Construction of new coke oven batteries.
- Construction of a desulphurization plant.
- Construction of a dedusting plant.
- Installation of an inertial dust collector.
- Partial overhaul of coke oven batteries.
- Partial overhaul of the heads.
- Replacement of doors.
- New filling trucks.
- New quenching towers.
- Sealing of charging and technological openings.

Compilation of the above-mentioned activities within the framework of the assessed variants was aimed at presenting a catalog of solutions possible to be applied in the whole coke production process, oriented at simultaneous reduction of channeled and fugitive emission for all pollutants listed in Table 1. The developed variants are therefore process-oriented and take into account the multi-emission nature of coke production (Kulczycka, Smol, 2015). This approach is not used either theoretically or in practice due to the fact that the applicable standards and regulations refer to channeled emissions, single emitters and unit emission sources. Nevertheless, from the point of view of the need to protect the environment, tightening standards and principles of sustainable development, it should be considered advisable from a theoretical and practical point of view.

Environmental inconvenience of the baseline variant and proposed investment variants was characterized by:

- Total emissions of a given pollutant [Mg/year].
- Number of points with exceedances of acceptable standards for a given pollutant using indicators presented in Table 3.

Table 3.
Ratios adopted in the analysis of environmental nuisance for individual pollutants in process terms

Process	Ratio for individual pollutants [g/Mg coke].			
	BaP	SOx	NOx	PM10
Firing	0.003	990	900	80
Pushing	0.018	45	15	30
cooling	0.003	20	-	20
Sorting plant	-	-	-	5
Coal plant	-	19	15	20
Filling	0.006	7	-	5
Coking	0.270	19	15	5

Source: own work.

2.2. Research phases and principles for assessing environmental performance

Having made the aforementioned environmental and investment assumptions, an assessment of environmental performance was undertaken. As part of its calculation, the following variables were used:

1. Investment outlays [in PLN] **(I)** for the implementation of individual projects, which were determined on the basis of current prices of necessary assets and labor on the basis of a market survey.
2. Value of avoided emission [in Mg/year] **(Em)** calculated as the difference of the emission in the baseline scenario and the emission obtained after the implementation of the technological changes planned in the given scenario.
3. Cost of avoided emission **(C_{Em})** (external cost of pollution) [in PLN/Mg] is an estimated value which includes, among others, costs of hospitalization, sick leaves, rehabilitation and lost years of life connected with the emission of a given pollutant - its amount was given in the report of the European Environment Agency - (*EEA Technical report, Costs of air pollution from European Industrial facilities 2008-2012 - an updated assessment,* p. 26).
4. Environmental benefit **(B_{env})** [PLN/year] which is the product of the avoided emission **(Em)** and the cost of avoided emission **(C_{Em})**.

The adoption and definition of the above variables made it possible to calculate the so-called environmental effectiveness (**Ef_{env}**), which is the ratio of the environmental benefits obtained to the investment outlays incurred:

$$Ef_{env} = \frac{B_{env}}{I} = \frac{E_m \times C_{Em}}{I} \tag{1}$$

This method was proposed for large combustion plants as a guideline for obtaining a derogation from compliance with BAT (*Podręcznik dotyczący zasad udzielania odstępstw od granicznych wielkości emisyjnych zawartych w Konkluzjach BAT dla dużych źródeł spalania (LCP)*) due to the possibility of the so-called disproportion of costs to environmental benefits. In the article it was used to assess the environmental effectiveness of individual investment variants, as it reflects the proportion between the achieved emission reduction and the expenditures incurred to achieve it. However, the original variant of this method was modified by calculating the following:

- The environmental benefit as the sum associated with the reduction of all described pollutants accompanying the production of coke.
- Investment outlays as a sum related to the implementation of all technological changes proposed in a given variant.

The results obtained after calculating the environmental effectiveness allow to economically and environmentally assess the profitability of the given investment variant. However, they do not provide grounds for assessing the degree to which a given solution fulfills the concessions included in the BAT guidelines. For these reasons, the authors propose a further modification of the calculation and correction of the calculated value of environmental effectiveness by the degree of compliance of a given investment variant with the BAT conclusions (BAT%):

$$Ef'_{env} = \frac{B_{env}}{I} \times BAT_{\%} \tag{2}$$

At the same time, it is postulated that the degree of meeting the BAT conclusions should be calculated as a resultant for all technological processes in coke production due to the circumstances mentioned in the introduction. In practice, this will be done by calculating the arithmetic mean for the fulfillment of BAT conclusions in the processes of firing, planting, coking, pushing, quenching, desulphurization and in the processes carried out in the sorting plant and the coal plant. Such an approach was applied in the following part of this article.

3. Results

As already mentioned, 6 investment projects were proposed as part of the presentation of the methodology for evaluating investment efficiency in the coke production process. The scope of changes and technical modifications characterizing the adopted investment variants is presented in Table 1.

For all these variants and the baseline variant, a pollutant dispersion analysis was conducted and the number of points where acceptable emission standards were exceeded was determined. This was done taking into account the multi-emission nature of coke production for such emitters as: BaP, SO_2, PM10 and NO_2. The COPDIMO software was used to achieve the goal. The obtained results for each of the variants are included in Table 4.

Additionally, Table 4 presents all the economic parameters necessary for calculating the environmental effectiveness in a single, non-aggregated approach, i.e., the investment outlays determined on the basis of market research and the value and cost of avoided emissions.

Next, Table 5 presents the results of the assessment of compliance with the BAT conclusions by all analyzed variants in process terms - covering 8 key production processes - and in summary terms, calculated as an arithmetic mean of all processes.

The results of the corrected environmental effectiveness (including the above-mentioned degree of compliance with the BAT conclusions) are presented in Table 6. This table also ranks all the analyzed variants according to the following criteria:

1. Partial, used in the calculation of effectiveness, i.e., inputs, environmental benefit, and the degree of meeting the BAT conclusions.
2. Aggregated to environmental effectiveness and adjusted environmental effectiveness.

Table 4.
Evaluation of environmental and economic aspects of the analyzed investment alternatives

Pollution	**BaP**	**SO_2**	**PM10**	**NO_2**
Baseline variant: 5 coke oven batteries used, including accompanying devices, without dedusting and desulphurization plants				
Number of points with exceedances	102	3	0	0
Variant 1: Construction of 5 new coke oven batteries and dedusting plants, new charging cars and new quenching towers, desulphurization plant, dedusting of sorting and coal plants				
outlays [million PLN]	73.6			
Avoided emissions [Mg/year]	1.05	4,498.90	559.79	3,051.21
Costs of avoided emission [PLN/Mg]	5,499,700.00	42,105.60	98,857.00	19,001.70
Environmental benefit [PLN/year]	5,769,185.30	189,428,883.84	55,339,160.03	57,978,177.06
Environmental effectiveness	0.11	2.57	1.05	1.31
Number of points with exceedances	0	0	0	0
Variant 2: 1. Partial overhaul of coke oven batteries 2. Replacement of all doors using the original solution, sealing of charging and technological holes, inertial separator.				
outlays [million PLN]	7.9			
Avoided emissions [Mg/year]	0.52	114.47	192.38	1,033.13
Costs of avoided emission [PLN/Mg]	5,499,700.00	42,105.60	98,857.00	19,001.70
Environmental benefit [PLN/year]	2,846,644.72	4,819,828.03	19,018,109.66	19,631,226.32
Environmental effectiveness	0.36	1.07	2.41	2.49
Number of points with exceedances	60	1	0	0

Cont. table 4.

Variant 3: 1. Construction of 2 new coke oven batteries 2. Partial overhaul of batteries and heads with adjustment 3. Replacement of the door using the original solution of batteries 4. Sealing of charging and technological holes 5 Inertial dedusting plant				
outlays [million PLN]	21.2			
Avoided emissions [Mg/year]	0.71	128.06	250.93	1,831.61
Costs of avoided emission [PLN/Mg]	5,499,700.00	42,105.60	98,857.00	19,001.70
Environmental benefit [PLN/year]	3,891,587.72	5,392,043.14	24,806,187.01	34,803,703.74
Environmental effectiveness	0.18	0.28	1.17	1.64
Number of points with exceedances	36	1	0	0
Variant 4: 1.Construction of 3 new coke oven batteries 2.Partial overhaul of heads 3. New construction doors 4. New charging truck 5. dedusting plant for 3 batteries				
outlays [million PLN]	32.8			
Avoided emissions [Mg/year]	0.94	171.18	299.90	2,241.57
Costs of avoided emission [PLN/Mg]	5,499,700.00	42,105.60	98,857.00	19,001.70
Environmental benefit [PLN/year]	5,175,217.70	7,207,636.61	29,647,214.30	42,593,640.67
Environmental effectiveness	0.16	0.23	0.91	1.38
Number of points with exceedances	8	2	0	0
Variant 5: 1.Partial overhaul of coke oven battery heads 2. New construction doors 3. New charging truck on all batteries 4. Dedusting plant for all batteries 5. Building a desulphurization plant				
outlays [million PLN]	36.4			
Avoided emissions [Mg/year]	0.87	4,422.10	258.04	1,070.91
Costs of avoided emission [PLN/Mg]	5,499,700.00	42,105.60	98,857.00	19,001.70
Environmental benefit [PLN/year]	4,762,740.20	186,195,173.76	25,509,060.28	20,349,110.55
Environmental effectiveness	0.26	5.12	1.41	1.38
Number of points with exceedances	18	0	0	0
Variant 6: 1. Partial overhaul of the heads of all batteries 2. Doors of new construction of all batteries 3. New charging truck on all batteries 4. Dedusting and desulphurization plant on all batteries 5. New quenching towers				
outlays [million PLN]	40.8			
Avoided emissions [Mg/year]	0.88	4,487.80	321.13	1,070.91
Costs of avoided emission [PLN/Mg]	5,499,700.00	42,105.60	98,857.00	19,001.70
Environmental benefit [PLN/year]	4,812,237.50	188,961,511.68	31,745,948.41	20,349,110.55
Environmental effectiveness	0.21	4.63	1.41	1.38
Number of points with exceedances	18	0	0	0

Source: own work.

Table 5.
Assessment of compliance with the environmental criteria laid down in BAT

Processes	**Variants**					
	1	**2**	**3**	**4**	**5**	**6**
Firing	100%	50%	75%	90%	85%	85%
Filling	100%	50%	50%	100%	100%	100%
Coking	100%	50%	75%	90%	85%	85%
Pushing	100%	50%	50%	100%	100%	100%
Quenching	100%	0%	0%	0%	0%	100%
Desulphurization	100%	0%	0%	0%	100%	100%
Sorting plant	100%	0%	0%	0%	0%	0%
Coal plant	100%	0%	0%	0%	0%	0%
Total fulfillment	100%	25%	31.25%	47.50%	58.75%	71.25%

Source: own work.

Table 6.
Summary of environmental and economic assessment results

Variants	Assessment criteria									
	1	2	3	4	5	6	7	8	9	10
	outlays [million PLN]	Ranking acc. to 1	Environmental benefit [PLN/year]	Ranking acc. to 3	Environmental effectiveness	Ranking acc. to 5	Meeting the BAT conclusions [%]	Ranking acc. to 7	Holistic effectiveness assessment	Ranking acc. to 9
1	73.6	1	308,515,406.23	1	4.19	4	100.00	1	4.19	2
2	7.9	6	46,315,808.73	6	5.87	3	25.00	6	1.47	4
3	21.2	5	68,893,521.60	5	3.25	5	31.25	5	1.02	6
4	32.8	4	84,623,709.28	4	2.58	6	47.50	4	1.23	5
5	36.4	3	236,816,084.79	3	6.51	1	58.75	3	3.82	3
6	40.8	2	245,868,808.14	2	6.03	2	71.25	2	4.30	1

Source: own work.

Thus, taking into account the expenditures, the most expensive option is 1, which assumes the most advanced modification of the basic coking installation, including construction of 5 new batteries. The expenses incurred for its implementation are over PLN 73 million. However, its use is connected with elimination of all excess points and the highest value of environmental benefit. This variant is also characterized by 100% compliance with BAT conclusions. Therefore, it can be stated that it is the most beneficial for the natural environment. Nevertheless, from the economic point of view, it will certainly not be chosen by the investor, because in practice it means construction of a new coking plant from scratch, which with the current environmental requirements - relating to individual emission sources and types of pollution - is not legally necessary and will not be economically viable.

The cheapest option is Variant 2, which assumes only a partial overhaul of the battery, replacement of doors and sealing of charging and technological openings and installation of an inertial dust collector. Nevertheless, the implementation of this variant would mean the lowest reduction of exceedance points for BaP, the lowest value of environmental benefits and the lowest degree of meeting the BAT conclusions in terms of process. Therefore, the investment expenditure incurred would bring negligible environmental benefits.

Therefore, in the context of the obtained partial results, it is worth looking at the value of the aggregated assessment of individual variants performed with the use of environmental effectiveness and adjusted environmental effectiveness taking into account, apart from the investment outlays and environmental benefits, also the degree of meeting the BAT conclusions.

Taking into account the original form of economic effectiveness, the most beneficial variants are Variants 5 and 6. The environmental effectiveness for the first of the mentioned options is 6.51, and for the second - 6.03, which means that the value of environmental benefits obtained thanks to these options exceeds the value of investment outlays by more than six times.

Variant 5 - the most beneficial in terms of environmental effectiveness - assumes: partial overhaul of the battery heads, insertion of doors of a new design, installation of a new charging truck and use of the dedusting and desulphurization plant. The expenditures related to this variant amount to over 36.4 million PLN and are over 50% lower than in case of Variant 1, while ensuring a comparable environmental effect. In Variant 5, the number of exceedance points for BaP was significantly reduced (from 102 to 18) and points with exceedances for other emitters were eliminated: SO_2, PM10 and NO_2. This variant is also characterized by a high (third highest, after Variant 1) degree of meeting the BAT conclusions, amounting to 58.75%.

Variant 6 - the second in terms of environmental effectiveness - assumes the renovation of all batteries, installation of the dedusting and desulphurization system, replacement of all doors with new ones and purchase of a new charging truck for all batteries. The expenditures related to this variant amount to over PLN 40.7 million and are over 44% lower than in case of Variant 1, while ensuring a comparable environmental effect. In Variant 6, the number of exceedance points for BaP was significantly reduced (from 102 to 18) and points with exceedances for other emitters were eliminated: SO_2, PM10 and NO_2. This variant is also characterized by a high (second highest, after Variant 1) degree of meeting the BAT conclusions, amounting to 71.25%.

Bearing in mind the identified imperfection of the measurement of environmental effectiveness, the article proposes its correction by the degree of compliance with the BAT conclusions in process terms, which strengthens the importance of environmental criteria in the assessment and selection of the final investment variant. After the application of the indicated adjustment, the best variant turns out to be Variant 6 which gives the best effects in terms of outlays, environmental effectiveness and meeting the BAT conclusions. Additionally, we also avoided indicating Variant 2 as third in the hierarchy of importance, which was the case when measuring environmental effectiveness in the unadjusted option. In this case, Variant 1 - the most expensive and most beneficial from the environmental point of view - takes the second place, followed by Variant 5, which offers environmental benefits very similar to the leader of the ranking at a slightly lower level of meeting the BAT conclusions but lower investment outlays.

4. Conclusions and discussion

The methodology of environmental effectiveness assessment described in the article can be a valuable tool for coking plants, supporting the process of making investment decisions. The considerations presented in the introduction show that these plants - due to significant environmental nuisance (Kwiecińska et al., 2017; Yang et al., 2018, 2019) – must be guided in their choices by both economic and environmental criteria. The proposed method of evaluating investment projects in the coking industry is therefore adapted to current social and legal-environmental requirements. In addition - due to its more restrictive nature assuming a process approach and the multi-carbon nature of coke production - it is also forward-looking in nature related to tightening environmental requirements and social needs and expectations (Li et al., 2020; Makgato et al., 2019, Li, Cheng, 2020).

The investment options presented and their evaluation also allow us to see the multiplicity of decision options available and quickly assess their environmental and economic impacts. They also create a spectrum of possibilities from among which the decision-maker can choose those that are suited to his financial possibilities, but at the same time give the best possible environmental effect.

The presented methodology and the obtained results can also be used in an accessible and quick way in the context of indirect (economic-market) instruments of environmental management, as the choice of an appropriate investment option allows to optimize the burden of environmental charges for pollutant emissions in production processes (Wasiuta, 2015; Chornomaz et al., 2017). Especially since previous studies expose the effectiveness of financial restrictions in reducing emissions (Brizga et al., 2021; Niu et al., 2016), which increases the likelihood of their increase in subsequent years. Investors in environmentally burdensome industries should therefore take the above circumstances into account in order to take actions which are socially responsible, but also optimal in economic terms.

In a broader context, the considerations presented in this article draw attention to a certain fragmentary character of the assessment of the environmental harmfulness of coking plants and other industrial installations referred to in the legal regulations mentioned in the introduction. They omit the occurrence of sources of fugitive emissions and do not take into account parallel occurrence of many sources of pollution in successive production processes. Therefore, on the basis of the obtained results and observations, direct (administrative and legal) instruments of environmental management may be improved in order to eliminate the shortcomings mentioned above (Wang et al., 2012; Yuan et al., 2017; Rychlewska et al., 2021; Martins, Fonseca, 2018; Iraldo et al., 2009). Environmental assessment should be carried out in a comprehensive manner, taking into account the entire production process. If it concerns only single emitters and production facilities, it has in fact an illusory dimension. Although it meets the existing standards, it does not allow to minimize environmental risks, which gives rise to serious consequences for human health and life (Dehghani et al., 2019; Yang et al., 2019).

Further research in the context of environmental performance of industrial facilities can be pursued as a benchmarking study for other industries. They can also relate to guiding the improvement of direct and indirect environmental management tools. They should also be oriented towards the actual assessment of the harmfulness of industrial processes, carried out not only in the context of current legal-environmental standards, but taking into account their holistic impact on the quality of the environment and human life.

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