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Hard coal supplies and selected environmental regulations: A Case Study of the Polish Power Sector

Nomenclature

List of sets, parameters and variables used in the model formulae.

- Sets of model elements:

pp – a set of customers (units) including: public power plants (power generating units aggregated into homogeneous classes of units, CHP plants aggregated into provinces level and other recipients of the energy sector (autoproducing power plants, public heating plants, non-public heating plants) aggregated into provinces level, $pp \in PP$;

s – a set of suppliers (domestic and import) offering fine coal for power plants, $s \in S$;

c – a set of fine coals offered for power plants, $c \in C$;

pi – a set of parameters of environmental installations, $pi \in PI = \{alfaS, etaS\ fugA, etaA, etaCl, etaF, etaHg\}$;

y – years, $y \in Y = (2023, ..., 2040)$.

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- Parameters of model:

$Instalations_{pp,pi}$ – aggregate of parameters characterizing the operation of environmental installations (effectiveness, availability, conversion factors) is for each customers *pp*, [–];
$Demand_{pp,y}$ – demand for chemical energy of the customer pp in the year *y*, [GJ];
$CV\_Avg_{pp,y}$ – average calorific value of coal used by the customer pp in the year *y*, [–];
$C\_Avg_{s,c,y}$ – average content of element C in fine coals c from suppliers in year *y*, [–];
$Q\_Avg_{s,c,y}$ – average calorific value in fine coals c from suppliers in year *y*, [–];
$A\_Avg_{s,c,y}$ – average ash content A in fine coals c from suppliers in year *y*, [–];
$S\_Avg_{s,c,y}$ – average sulfur content S in fine coals c from suppliers in year *y*, [–];
$Cl\_Avg_{s,c,y}$ – average chlorine content Cl in fine coals c from suppliers in year *y*, [–];
$Hg\_Avg_{s,c,y}$ – average mercury content Hg in fine coals c from suppliers in year *y*, [–];
$F\_Avg_{s,c,y}$ – average fluorine content F in fine coals c from suppliers in year *y*, [–];
$Factor_{EmSO2}$ – conversion factor for calculating SO_2 emissions, [–];
$Factor_{EmCO2}$ – conversion factor for calculating CO_2 emissions, [–];
$Factor_{EmPm}$ – conversion factor for calculating PM emissions, [–];
$Coef_{ox}$ – oxidation coefficient, [–].

- Positive Variables:

$Purchase_{s,c,pp,y}$ – purchase volume of fine coals c from suppliers to customer *pp* in year *y*, [Mg];
$EmFactorSO2_{pp,y}$ – SO_2 emission factor in year *y*, [g/GJ];
$EmFactorPM_{pp,y}$ – PM emission factor in year *y*, [g/GJ];
$EmFactorCO2_{pp,y}$ – CO_2 emission factor in year *y*, [g/GJ];
$EmFactorHCl_{pp,y}$ – HCl emission factor in year *y*, [g/GJ];
$EmFactorhf_{pp,y}$ – HF emission factor in year *y*, [g/GJ];
$EmFactorHg_{pp,y}$ – Hg emission factor in year *y*, [g/GJ].

Introduction

Since the beginning of the 21st century, EU countries have been undertaking decarbonization activities aimed at replacing fossil fuels in electricity production. The energy transformation is heading in the long-term direction, namely a zero-emission energy system. However, in selected EU countries and many other countries around the world, the share of fossil fuels in electricity generation is high. The requirements for generating units related to environmental protection and fluctuations in fuel markets mean that new tools are being sought to support the purchasing decisions of energy companies using fossil fuels to produce electricity.

Optimizing the supply and use of hard coal in the process of electricity production has already been the subject of many studies. The optimization problem was formulated from the perspective of the coal supplier (Kasana and Kumar 2004; Kozan and Liu 2012; Blom et al. 2019) the commercial intermediary (Cheng et al. 2016; Amini et al. 2022), and the consumers. The common point of the published works is an attempt to make management decisions in selling or purchasing raw material, following the adopted optimization criterion, which is most often maximizing profit (of a coal company or an intermediary), minimizing transport costs, or minimizing the cost of coal purchase by the recipient.

Optimization problems in hard coal supply are by far the most frequently considered from the perspective of energy companies – coal consumers (Sherali and Puri 1993; Lai and Chen 1996; Shih 1997). In these models, while minimizing the total costs, not only purchase and transport costs were considered, but also the costs of storage and ash disposal. The restrictions most often included the generating units' demand, the port's unloading capacity, and the requirements for meeting quality parameters in terms of calorific value, ash, and sulfur content.

Mathematical models in hard coal supply have been repeatedly developed in subsequent years, and the results have been presented in the literature. The optimization of coal purchase from various sources, considering the mixing of coal at the recipient, was discussed by Cao et al. (2006). Liu (2008) considered the supplies in terms of seaport capacity and the limitation of foreign contracts for the supply of coals. The change in purchase and transport prices and the change in demand were considered in the optimization problem presented by Yabin (2010) and Huang and Wu (2016). Multi-criteria optimization, considering many suppliers, multiple routes, many products, and coal quality constraints, was formulated by Yucekaya (2013), but without taking changes in prices and demand for coal into account. The purchase price of coal was the main optimization criterion for all these models. However, nowadays, there is a need to pay attention to other costs associated with the use of fossil fuels by power generation units.

Currently, the allocation of coal for generating units in European countries (in addition to commercial and technological conditions) strictly depends on the solutions adopted at the international level in environmental regulations directly affecting the energy sector and, indirectly, the hard coal mining sector. This particularly applies to implementing climate and energy policies aimed at decarbonizing the European Union Member States' economies. Its main element is a long-term vision of striving for climate neutrality. Its implementation is carried out by indicating guidelines and creating tools and instruments implemented due to respective agreements within the Community (Malec 2019). Implementing climate and energy policy objectives translates into the functioning of energy companies. The introduced regulations affect the cost of electricity production through the need to adapt to accepted standards for emissions of harmful substances into the environment and pay for these emissions. An important factor affecting the costs of energy companies is also the need to purchase CO_2 emission allowances. The way to meet the requirements is to modernize the environmental protection installation and the appropriate allocation of fuel for generating units.

The literature review shows that in the published articles, the authors have thus far focused on the costs of coal purchase, transport costs, and quality parameters required by boilers of generating units. However, one can notice the lack of an approach to the costs resulting from the use of hard coal in the energy sector (environmental costs) in these works. However, the created tools should consider not only the cost of purchase and transport or the selection of the appropriate quality raw material but also the additional costs resulting from the consequences of these choices. Such action may enable the reduction of costs associated with fuel use by initiating solutions reducing environmental fees already at the stage of planning the acquisition of raw materials. However, such an approach is currently not a common practice of energy companies, and from the perspective of pressure to reduce emissions, it is necessary not only in European but also in Asian countries, which are leaders in using hard for electricity production.

The article aims to quantitatively analyze the potential for reducing costs associated with supplying and using hard coal in public power plants by considering the costs of environmental protection and CO_2 emission allowances in planning this fuel supply. In order to achieve this goal, a method based on the concept of mathematical modeling of fuel and energy systems was developed. Thanks to the created mathematical model for optimizing hard coal supply considering environmental regulations – using the linear programming approach – it was possible to determine the impact of coal allocation on the emission of substances into the environment and, consequently, the costs incurred by energy companies. The optimization model was implemented in the GAMS (General Algebraic Modeling System).

1. Mathematical model

The presented mathematical model for optimizing hard coal supplies by power generation units, considering environmental regulations, reflects the key relations between the hard coal supplier sector and the public power plants, which is the sector of the main recipients of this raw material. The model's main objective is to minimize the total costs associated with acquiring and using hard coal in public power plants as a result of considering the costs of environmental protection and CO_2 emission allowances in the process of planning this fuel's supply. Simultaneously, the model must meet certain limitations. The most important is the balance between hard coal purchase and the demand for power generation units, considering the expected quality parameters and the need to meet emission standards imposed by BAT conclusions. A simplified diagram of the model is presented in Figura 1.

On the supply side, suppliers offer power coal with individualized parameters, and on the demand side – hard coal-fired power plants. The diagram also shows the model variables whose values will be determined as part of the calculations, constraints, and the objective function of the model. The diagram also presented the results that can be obtained from model calculations.

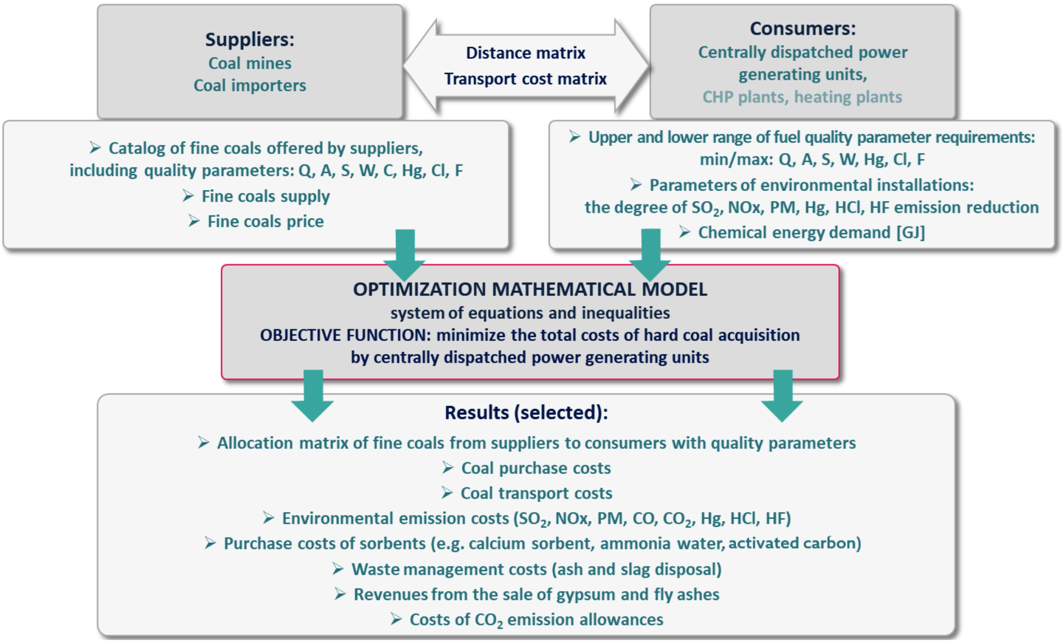

Fig. 1. Simplified diagram of the mathematical model
Source: own study

Rys. 1. Uproszczony schemat modelu matematycznego

The model's time horizon covers the years 2023–2040, while its time resolution is one year. The length of the analysis period is appropriate for long-term studies. The choice of this period is dictated by the need to reflect the assumptions of the functioning of the power sector and adopt appropriate forecasts for its development.

The volume of emissions of harmful substances resulting in the calculation of the emission fee was determined based on the calculated values of the model variables – the volume of coal purchase – their quality parameters, and the emission reduction degree as a result of the use of environmental installations. In addition to unit fees for harmful substances emissions, the model also calculates costs related to the maintenance of environmental protection installations (e.g., costs of purchasing substrates), waste management costs, and costs of CO_2 emission allowances. The model calculations also consider revenues related to the sale of gypsum (for units using a wet flue gas desulfurization installation) and potential revenues from the sale of fly ash with appropriate properties desirable from the perspective of market demand.

It was assumed that the model's objective function is to minimize the total costs of hard coal acquisition by centrally dispatched power generating units, i.e., public power plants connected to the transmission grid or coordinated 110 kV grid, subject to central dispatch by the Transmission System Operator throughout the analysis time horizon.

1.1. Implementation of environmental emissions in the model's mathematical equations

The model includes all typical equations occurring in this type of tool for decision support when purchasing fuels: demand balance, limitations of generating units, and transport constraints. The model's key element is the implementation of the fuel quality parameters' impact on emissions of harmful substances into the environment. The focus was on pollutants whose emission limits are imposed by the BAT conclusions (SO_2, dust, NO_x, HCl, Hg, HF). In the model's equations, respective limits were adopted to meet the emission limits for each power generation unit depending on its type and installed capacity. Moreover, the model determines emission factors used to determine the volume of emissions and their cost.

The emission factors of SO_2 were determined according to the formula (GDEP 2007; Frigge et al. 2017; Ken and Nandi 2018). The emission factor SO_2 $EmFactorSO2_{pp,y}$ is calculated based on the sulfur content of the coal delivered to power plants *pp* in year *y* (Equation 1).

$$\forall_{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}>0} \forall_{pp\in PP} \forall_{y\in Y} \sum_{s,c} \frac{Purchase_{s,c,pp,y} \times C\_Avg_{s,c,y}}{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}} \times Factor_{EmSo2} \times \tag{1}$$

$$\times (1 - Installations_{pp,"alfaS"}) \times (1 - Installations_{pp,"betaS"} \times Installations_{pp,"etaS"}) =$$

$$= EmFactorSO2_{pp,y} \times CV\_Avg_{pp,y}$$

Another relationship is aimed at determining the CO_2 emission factor ($EmFactorCO2_{pp,y}$) for power plants *pp* in year *y* (Equation 2). Its determination was based on the dependencies described in (Radović 1997; Lelek and Kulczycka 2020).

$$\forall_{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}>0} \forall_{pp\in PP} \forall_{y\in Y} \sum_{s,c} \frac{Purchase_{s,c,pp,y} \times C\_Avg_{s,c,y}}{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}} \times Factor_{MMCo2:C} \times \tag{2}$$

$$\times Factor_{EmCo2} \times Coef_{Ox} = EmFactorCO2_{pp,y} \times CV\_Avg_{pp,y}$$

NOx emissions are most often estimated using the averaged emission factors indicated by KOBIZE (KOBIZE 2022). Their determination should consider the type of fuel used, the installation's power, and the combustion technology (Lorenz 1999). The model calculations assume that the NO_x emission factor complies with the average power generation unit value (ARE 2022a). In the next equation, the dust emission factor $EmFactorPM_{pp,y}$ for consumer *pp* in year *y* (Equation 3) is determined.

$$\forall_{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}>0} \forall_{pp \in PP} \forall_{y \in Y} \sum_{s,c} \frac{Purchase_{s,c,pp,y} \times A\_Avg_{s,c,y}}{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}} \times$$ (3)

$$\times Factor_{EmPM} \times \left(Installations_{pp,\text{“}fugA\text{”}} \right) \times$$

$$\times \left(1 - \left(\frac{Installations_{pp,\text{“}etaA\text{”}}}{100} \right) \right) = EmFactorPM_{pp,y} \times CV\_Avg_{pp,y} \times 1000$$

The emission values of other substances (Hg, HCl, HF) – equation (Equation 4, 5 and 6) – can also be determined at a known value of elements Hg, Cl, F in the burned fuel. In model issues, mass balance equations are used to determine the emission indicators of these elements. In addition to knowing the content of the analyzed element in carbon, the fuel's calorific value will also be important, and consequently – the content of ballast, which is moisture and mineral substance. These emissions can also be determined using the amount of exhaust emissions. The flue gas cleaning installations and the sorbents will influence the degree of emissions reduction of these substances.

$$\forall_{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}>0} \forall_{pp \in PP} \forall_{y \in Y} \sum_{s,c} \frac{Purchase_{s,c,pp,y} \times Cl\_Avg_{s,c,y}}{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}} \times Factor_{MMHCl:Cl} \times$$ (4)

$$\times \left(1 - Installation_{pp,\text{“}etaCl\text{”}} \right) = EmFactorHCl_{pp,y} \times CV\_Avg_{pp,y}$$

$$\forall_{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}>0} \forall_{pp \in PP} \forall_{y \in Y} \sum_{s,c} \frac{Purchase_{s,c,pp,y} \times F\_Avg_{s,c,y}}{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}} \times Factor_{MMHF:F} \times$$ (5)

$$\times \left(1 - Installation_{pp,\text{“}etaF\text{”}} \right) = EmFactorHF_{pp,y} \times CV\_Avg_{pp,y}$$

$$\forall_{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}>0} \forall_{pp \in PP} \forall_{y \in Y} \sum_{s,c} \frac{Purchase_{s,c,pp,y} \times Hg\_Avg_{s,c,y}}{\frac{Demand_{pp,y}}{CV\_Avg_{pp,y}}} \times \tag{6}$$

$$\times \left(1 - Installation_{pp,\text{“}etaHg\text{”}}\right) = EmFactorHg_{pp,y} \times CV\_Avg_{pp,y}$$

2. Case study – Poland

The calculations were carried out for Polish conditions. The model's time horizon (2023––2040) coincides with the analyses available in the strategic document setting out the sector's development, which is Poland's Energy Policy until 2040 (EPP 2021). The long-term time horizon proposed in the article also allows for assessing the effects of activities related to the implementation of the Social Agreement regarding the transformation of the hard coal mining sector and selected transformation processes of the Silesian Province (Agreement 2021). Therefore, the adopted model's time horizon makes it possible to assess changes in the context of the planned reduction of production in hard coal-fired power generating units and the indicated dates of mine decommissioning (Malec 2022).

In the model, on the supply side, mines producing hard coal (steam coal) in specific classes were identified. They are characterized by defined quality parameters specific to a given domestic mine/mining area (23 elements of the set) and importers (12 elements of the set). A given product's availability depends on the forecasted mining capacity of the mine/mining area and the potential of coal supplies imported from particular directions at available border crossings (sea and land). It enables the analysis of the entire domestic supply of steam coal in the fine coal assortment. The annual extraction volume was adopted based on the Balance of Mineral Resources Deposits in Poland (Balance 2021) and information obtained from coal companies on the planned extraction volume in individual mines. The transshipment capacity of seaports and border crossings limits this raw material's availability on the domestic market. It should also be noted that part of the import capacity is allocated to another type of raw material, e.g., coking coal.

The coals offered by suppliers are characterized by key quality parameters, which are important from the perspective of power generation units. The description of the coal is carried out using the coal class. The products' distinguishing parameters:

- Qmin – minimum calorific value (MJ/kg);
- Amax – maximum ash content (%);
- Smax – maximum sulfur content (%);
- W – moisture content (average) (%);
- Cl – chlorine content (average) (%);

- Hg – mercury content (average) (%);
- F – fluorine content (average) (%).

On the demand side, hard coal-fired power plants and combined heat and power plants belonging to the group of centrally dispatched power-generating units were identified. For the model's purposes, units of the same class (e.g., 200, 500 MW) located in one power plant were aggregated into homogeneous blocks, and a total of 16 elements of the set were obtained. Moreover, the model considers other units (autoproducing power plants, combined heat and power plants, and heating plants) by aggregating their demand to the level of NUTS level 2 areas, i.e., provinces (also 16 elements of the set). Such an approach makes it possible to analyze the entire domestic demand for hard coal for energy purposes in the fine coal assortment, thanks to which the supply-demand balance of this sector is considered. The characteristics of each unit include the volume of fuel demand (chemical energy demand) expressed in GJ, the required limits (minimum and maximum) of fuel quality parameters, and the parameters of environmental installations affecting the degree of reduction of harmful substances. The demand for chemical energy was determined based on data on electricity production of power generating units in 2021, the hard coal consumption index for electricity production (ARE 2022), and forecasts of demand for hard coal for electricity and heat production (EPP 2021). Therefore, the generating units have been described, i.a., by the following parameters: volume of demand for chemical energy (GJ) estimated based on forecasted electricity and heat production of a given power generating unit (MWh); required calorific value range (MJ/kg) of coal, minimum and maximum (ash, sulfur, moisture, chlorine, mercury and fluorine content (%) in the coal.

Emission reduction installations have been identified for all power plants considered in the model. For each of the substances (SO_2, dust, NO_x, HCl, Hg, HF), the degree of emission reduction (installation efficiency) has been assumed following the values published in the environmental declarations of the EMAS system (*EcoManagement and Audit Scheme*), the Catalogue of Power Plants and Combined Heat and Power Plants, and on the websites of energy companies (ARE 2022). If this information was not made available, the average indicator for the national power industry or literature data would be adopted (Radović 1997; Lorenz 1999; Bustard et al. 2003; Qi et al. 2003; Pavlish et al. 2008; Chmielniak and Pilarz 2014; Deng et al. 2014; Burmistrz et al. 2016; Wichliński et al. 2017; Fu et al. 2018; Kim et al. 2019; Zhou et al. 2022; GDEP 2022; RAFAKO 2022).

For wet flue gas desulfurization installations, limestone powder was used as a sorbent, the price of which is USD 35/Mg (LHOIST 2022). For other installations, hydrated lime was used as a sorbent, for which the price of USD 125/Mg has been assumed (LHOIST 2022). The model also includes revenues from the sale of gypsum. Its sales price has been assumed at USD 5/Mg (TAURON 2023). Fees for the emission of harmful substances were adopted under the current Regulation of the Ministry of Climate and Environment (MKiŚ 2023). The analysis of the fee rate indicates that their volatility over a longer period is not high. Therefore, they were adopted as a constant value throughout the analyzed period (2023–2040). Due to the lack of reliable forecasts, the costs of sorbents have also been assumed to be constant.

Due to the lack of a coherent forecast of coal prices on the European market covering the analyzed time horizon, i.e., 2023–2040, on an annual basis, the model's calculations assumed values based on two forecasts. In the medium term (until 2027), the forecast published by the Australian Department of Industry, Science, Energy and Resources (Australian Government 2023) was selected, while in the long term, the forecast published by the International Energy Agency (IEA) was adopted (IEA 2022). Coal prices have been individualized for each product according to the commercial rules in force on the hard coal market. The national price formula differentiating coal prices depending on changes in delivery parameters was discussed in the literature (Grudziński 2009). Table 1 shows the reference price of hard coal adopted in the assumptions of the model for the following parameters: net calorific value 6,000 kcal/kg; ash content 11%, sulfur content <1%.

Due to consistency with fuel price forecasts, a decision was taken to implement the carbon dioxide emission allowance price paths published by the International Energy Agency (IEA) in the World Energy Outlook 2022 (IEA 2022). A price path consistent with the IEA's reference analysis scenario was adopted (Table 2). This forecast indicates the price in 2030 and 2040, which is why an upward trend in the prices of allowances was assumed for 2023–2030.

Table 1. Reference coal price forecasts (NCV 6,000 kcal/kg, ash content 11%, sulfur content <1%) – model assumptions (USD/Mg)

Tabela 1. Referencyjne prognozy cen węgla (NCV 6000 kcal/kg, zawartość popiołu 11%, zawartość siarki <1%) – założenia modelowe (USD/Mg)

Parameter	2023	2024	2025	2026	2027	2028	2029	2030	2040
Domestic coal reference price forecast	68	68	68	68	68	68	68	68	65
Imported coal reference price forecast *CIF ARA (DISER + WEO)*	89	69	61	57	53	–	–	58	57
Imported coal reference price forecast calculated by Polish conditions EXW Gdańsk/Gdynia seaport	97	77	69	65	61	63	64	66	65

Source: own calculation based on (Australian Government 2023; IEA 2022).

Table 2. Forecast of the price of CO_2 emission allowances, 2023–2040 (USD/Mg CO_2)

Tabela 2. Prognoza cen uprawnień do emisji CO_2 na lata 2023–2040 (USD/Mg CO_2)

Parameter	2023	2024	2025	2026	2027	2028	2029	2030	2040
The price of CO_2 emission allowances	99	103	108	112	117	121	126	130	205

Source: IEA 2022.

The model also maps the connection matrix between places of demand and supply. The model assumes deliveries by rail, and it is possible to take deliveries by road transport into account. However, in practice, they are carried out only for smaller power generating units (heating plants and supplementary for smaller combined heat and power plants) in case of the absence of an available railway siding. The matrix was used to assign the distance between the places of demand and supply, which, considering the individual transport costs, allows for the calculation of the cost of transporting raw materials. The price of coal transport to a specific recipient – in this case, to individual consumers from the power industry sector – is determined in individual contracts (Stala-Szlugaj 2013). The main domestic carrier and, simultaneously, the price maker is PKP Cargo (PKP Cargo 2022), whose price list was used to determine the transport costs for each rail connection.

2.1. Research scenarios

A scenario analysis was proposed to assess the effects of considering environmental protection costs and purchasing CO_2 emission allowances in the optimization model for the optimal allocation of coal for power generation units. The difference between them is reflected in the proposed approach to minimizing the total costs of hard coal supply (and the costs of environmental protection and the purchase of CO_2 emission allowances) by the professional power industry.

The model distinguishes three cost components:

- costs of coal supply: purchase and transport of coal,
- environmental protection costs: environmental fees for harmful substances emissions, costs of consuming sorbents used in environmental protection installations, cost of waste management considering revenues from the management of by-products of coal combustion,
- costs of CO_2 emission allowances.

Formulated research scenarios

In the first scenario, Sup_Cost, the mathematical model **only minimizes the cost of coal supply**, including the purchase and transporting of coal costs. The other components of the total cost, i.e., the cost of environmental protection and CO_2 emission allowances, are calculated after the model is solved (based on the allocation of coals). This scenario is a reference point for other scenarios, enabling the analysis of the effects of considering additional cost components when supplying hard coal for power plants.

In the second scenario, Sup_Emi_Cost, **in addition to the cost of coal supply, environmental protection costs are also minimized**. The cost of CO_2 allowances is calculated after the model is solved (based on the allocation of coals).

In the third scenario, Sup_Emi_CO$_2$_Cost, **all analyzed total cost components are included in the model's objective function**.

The proposed approach makes it possible to analyze the impact of individual components on the total costs associated with acquiring and using coal for electricity production. Table 4 compares the elements differentiating individual research scenarios. Simultaneously, it should be noted that in each scenario, the assumptions and defined constraints remain unchanged.

Table 3. Assumption of objective function components for individual research scenarios

Tabela 3. Założenia składowych funkcji celu dla poszczególnych scenariuszy badawczych

Objective function component	SUP_COST	SUP_EMI_COST	Sup_Emi_CO_2_Cost
Costs of coal supply (purchase and transport of coal)	YES	YES	YES
Environmental protection costs	NO	YES	YES
Costs of CO_2 emission allowances	NO	NO	YES

YES – it is optimized in the objective function; NO – is not optimized (calculated after solving the model).

3. Results and discussion

The basic result of the model, affecting the determination of the harmful substances emission volume, and consequently, the costs incurred by the power industry, is the allocation of coal for the combustion process. The total volume of coal purchases must be consistent with the demand assumed in the model for individual units. The coal blend selected by the model must also meet all the requirements of power plant boilers in terms of the quality parameters of fuel, which have been specified in the input data.

The calculation results are analyzed in relation to the values obtained for the Sup_Cost scenario. It corresponds to a situation in which energy companies making decisions on the purchase of raw materials focus only on minimizing the cost of coal purchase and its transport. In subsequent scenarios, the objective function assumes the optimization of environmental protection costs and the costs of CO_2 emission allowances to examine the possible effects.

3.1. Emissions of harmful substances into the environment

This section presents the results of individual scenarios in terms of the emission volumes of harmful substances to the environment. The results concern pollutants emitted by power generation units. Emission volumes directly impact the total cost of environmental protection and, consequently, on the total costs of obtaining and using coal.

The results of the total volumes of sulfur oxides emitted by the centrally dispatched power generating units in subsequent years are presented in Figure 2. The level of SO_2 emissions in scenarios incorporating environmental costs as the objective function shall be significantly lower than in the Sup_Cost scenario. For the Sup_Emi_Cost scenario, it is on average 9% lower, while for the Sup_Emi_CO_2_Cost scenario, it is on average 11%. In the Sup_Emi_CO_2_Cost scenario, the level of emissions for most of the analyzed period is the lowest, but the availability of coals with appropriate parameters and the possibility of selecting coals affecting the reduction of CO_2 emissions means that in 2024–2025, the level of SO_2 emissions is slightly higher than the total emissions in the Sup_Emi_Cost scenario. The results on the volumes of dust emitted by power generation units in subsequent years of analysis are presented in Figure 3. The level of dust emissions in the scenario taking into account environmental costs as the objective function – Sup_Emi_Cost – for most of the analysis

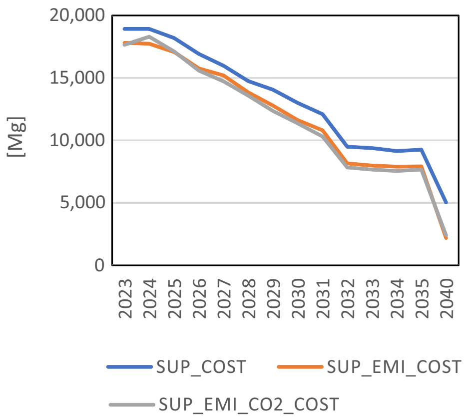

Fig. 2. SO_2 emissions from centrally dispatched power generation units in the analyzed period (2023–2040), (Mg)
Source: own study

Rys. 2. Emisje SO_2 z jednostek wytwórczych centralnie dysponowanych (JWCD) w analizowanym okresie (2023–2040), (Mg)

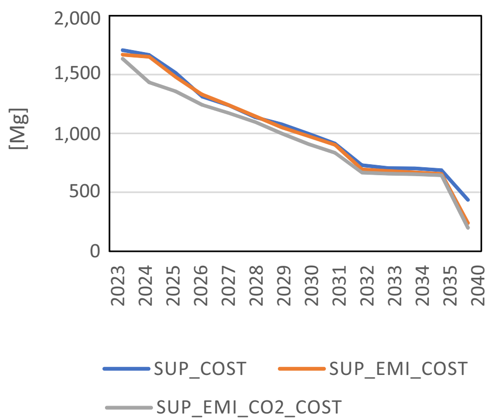

Fig. 3. PM emissions from centrally dispatched power generation units in the analyzed period (2023–2040), (Mg)
Source: own study

Rys. 3. Emisja pyłu z jednostek wytwórczych centralnie dysponowanych (JWCD) w analizowanym okresie (2023–2040), (Mg) period is lower than the values obtained in the Delivery Cost scenario. The level of dust emissions in the Sup_Emi_CO_2_Cost scenario is significantly lower (by 10% on average).

The results on the volumes of mercury emissions by the centrally dispatched power generating units in subsequent years of analysis are presented in Figure 4. The emissions in the environmental cost scenario as the objective function (Sup_Emi_Cost) shall be below the emission level Hg in the Delivery Cost scenario for most of the analyzed period. By contrast, in the Sup_Emi_CO_2_Cost scenario, the volume of Hg emissions in the initial years of the analyzed period is higher than in the other scenarios, despite including a criterion minimizing costs caused by the emissions of harmful substances in the objective function. This is because the fees for Hg emissions are relatively low. Therefore, if the remaining restrictions

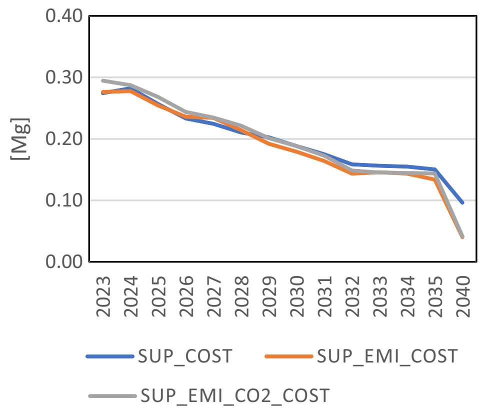

Fig. 4. Hg emissions from centrally dispatched power generation units in the analyzed period (2023–2040), (Mg)
Source: own study

Rys. 4. Emisja Hg z jednostek wytwórczych centralnie dysponowanych (JWCD) w analizowanym okresie (2023–2040), (Mg)

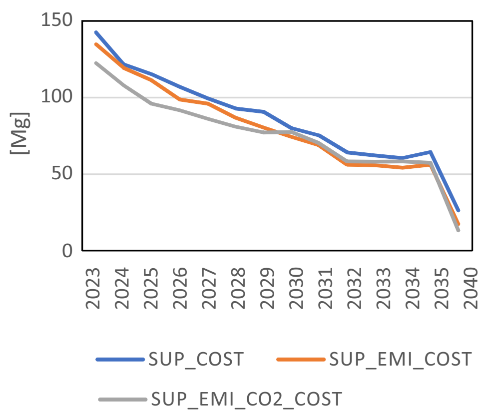

Fig. 5. HCl emissions from centrally dispatched power generation units in the analyzed period (2023–2040), (Mg)
Source: own study

Rys. 5. Emisja HCl z jednostek wytwórczych centralnie dysponowanych (JWCD) w analizowanym okresie (2023–2040), (Mg) (boiler limit parameters, emission standards) were met, selecting coal with a higher mercury content would be possible, but still within the required limits of centrally dispatched power generating units' boilers defined by the BAT conclusions. As a consequence, despite the combustion of fuel with an increased share of mercury, the impact on the total costs of obtaining and using coal was negligible, and the cost reduction was achieved mainly due to the reduction of other costs of environmental protection and CO_2 emission allowances. An analysis of the summary results of the volume of HCl emitted by the centrally dispatched power generating units in subsequent years is presented in Figure 5. HCl emissions in the Sup_Cost scenario are by far the highest. The inclusion of HCl emission charges in the objective function, despite the low unit cost of the environmental fee, leads to a reduction in emissions of this substance into the environment. In the Sup_Emi_Cost scenario, the average emission volume is lower by 9%, while in the Sup_Emi_CO_2_Cost scenario, by 13%.

The curve showing the aggregate volume of HF emissions from the centrally dispatched power generating units in 2023–2040 (Figure 6) follows a similar course to the previously presented curve representing the volume of Hg emissions. Also, in this case, in the early years of the analysis, there were periods in which HF emissions from centrally dispatched power generating units in the Sup_Emi_CO_2_Cost scenario were higher than the scenario in which the component related to emissions of harmful substances into the environment was not included in the objective function. The reason for this behavior is the low cost of the unit fee for HF emissions. Consequently, the model allows the selection of a coal blend with a higher fluorine content in coals due to the potential for cost reduction resulting from lower emission volumes of other substances. However, over a longer analysis period, the volume of HF emissions in the Sup_Emi_Cost scenario is lower than that obtained in the Sup_Cost scenario. The total volumes of carbon dioxide (CO_2) emissions for centrally dispatched power generating units in subsequent years are presented in Figure 7. The level of CO_2 emissions

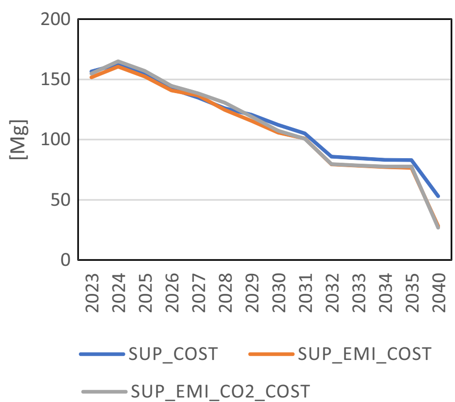

Fig. 6. HF emissions from centrally dispatched power generation units in the analyzed period (2023–2040), (Mg)
Source: own study

Rys. 6. Emisja HF z jednostek wytwórczych centralnie dysponowanych (JWCD) w analizowanym okresie (2023–2040), (Mg)

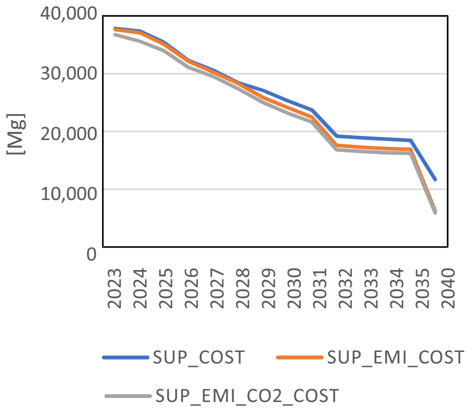

Fig. 7. CO_2 emissions from centrally dispatched power generation units in the analyzed period (2023–2040), (Mg)
Source: own study

Rys. 7. Emisje CO_2 z jednostek wytwórczych centralnie dysponowanych (JWCD) w analizowanym okresie (2023–2040), (Mg)

in the Sup_Emi_CO_2_Cost scenario is by far the lowest, influenced by the inclusion of the costs of purchasing CO_2 allowances in the objective function. The fee for CO_2 emissions to the environment is not very high. Therefore, in the initial period of analysis (2023–2031), the reduction of CO_2 emissions in the results of the Sup_Emi_Cost scenario, in which the component – the purchase of CO_2 emission allowances – is not subject to minimization (it is not included in the target function), is limited.

3.2. Costs of supplying and using hard coal in power generation units

3.2.1. Coal supply costs

Figure 8 presents differences – compared to the Sup_Cost scenario – of coal supply costs (purchase and transport) for other research scenarios in subsequent years of the analysis' time horizon. Including additional cost components in the objective function increases the total costs of purchasing and transporting coal. This increase is compensated by a decrease in the cost value of the other components included in the objective function. The differences between the Sup_Emi_Cost and Sup_Cost scenarios are insignificant and amount to approximately USD 0.5 million on average per year. Distinct differences, amounting to an annual average of about USD 16.4 million, are visible when comparing the Sup_Emi_CO_2_Cost and Sup_Cost scenarios. In 2032–2035, they amount to about USD 25 million per year. After 2030, there is an evident decrease in demand for coal for power generation units, with a milder downward trend in the supply of coal. It enables the appropriate selection of coals, whose quality parameters affect the decrease in CO_2 emissions. The lower volume of CO_2 emissions translates directly into a reduction of the total

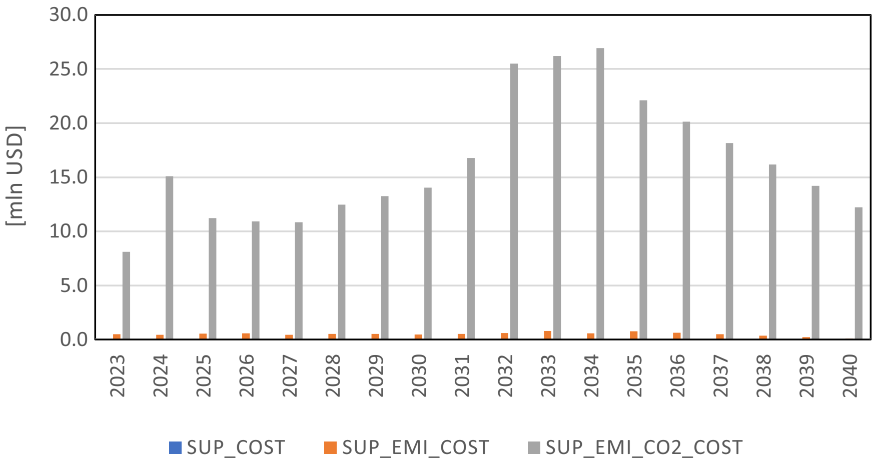

Fig. 8. Comparison of coal supply costs (purchase + transport) for centrally dispatched power generation units under the analyzed research scenarios – difference related to the SUP_COST scenario (mln USD)
Source: own study

Rys. 8. Porównanie kosztów dostaw węgla (zakup + transport) dla jednostek wytwórczych centralnie dysponowanych (JWCD) w ramach analizowanych scenariuszy badawczych – różnica w odniesieniu do scenariusza SUP_COST (mln USD)

cost of acquiring and using fuel in the centrally dispatched power-generating units defined in the article.

3.2.2. Environmental costs

Figure 9 presents a comparison of the differences in environmental costs for the analyzed scenarios compared to the Sup_Cost scenario. For the Sup_Emi_Cost scenario, the average annual decrease in these costs is USD 2.6 million over the entire analysis period. There is an evident decrease in the difference in subsequent years (from USD 4.1 to 0.8 million), caused by a decrease in the volume of hard coal purchases for centrally dispatched power generating units. This is also influenced by the decommissioning of selected mines and the decrease in coal supply, which consequently limits the allocation of coal with quality parameters affecting emission costs. Adding the cost of CO_2 allowances to environmental costs (the Sup_Emi_CO_2_Cost scenario) does not substantially change the results regarding differences in environmental costs (in relation to the Sup_Cost scenario). However, it is interesting to note that in the selected years (2024–2026 and 2032–2040), the reduction in environmental costs in the Sup_Emi_Cost scenario (relative to the Sup_Cost scenario) is higher than if environmental costs and CO_2 allowances were taken into account as the objective function (Sup_Emi_CO_2_Cost). The reason for this is that the model selects coals in such a way as to reduce the total cost of acquiring fuel, which may lead to the selection of coals, the combustion of which will result in higher costs of emission fees and sorbents'

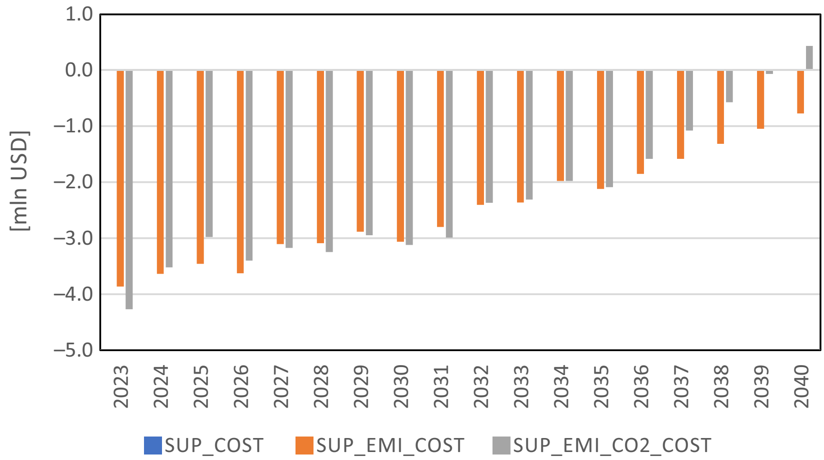

Fig. 9. Comparison of environmental protection costs for centrally dispatched power generation units under the analyzed research scenarios – difference related to the SUP_COST scenario (mln USD)
Source: own study

Rys. 9. Porównanie kosztów ochrony środowiska dla jednostek wytwórczych centralnie dysponowanych (JWCD) w analizowanych scenariuszach badawczych – różnica w odniesieniu do scenariusza SUP_COST (mln USD)

consumption. However, in this case, there is an evident saving in the cost of purchasing CO_2 emission allowances. Therefore, in 2040, the reduction in environmental costs – compared to the Sup_Cost scenario – in the Sup_Emi_Cost scenario is about USD 0.8 million. Despite including this component in the objective function of Sup_Emi_CO_2_Cost, environmental costs are higher by USD 0.4 million. This is influenced by the comparison of only one of the considered components. The total cost reduction is evident, which will be presented in the following sections of the results analysis.

3.2.3. Costs of CO_2 emission allowances

Figure 10 presents a comparison of the differences in the costs of purchasing CO_2 emission allowances calculated for the analyzed scenarios. These differences were determined relative to the results of the Sup_Cost scenario. Despite the absence of a component related to the cost of CO_2 emission allowances, this cost is slightly reduced in the objective function of the Sup_Emi_Cost scenario. It is related to the selection of coals with appropriate quality parameters affecting the reduction of fees for carbon monoxide and dioxide emissions to the environment (CO and CO_2) – taken into account in the objective function of this scenario. However, due to the low unit cost of emission of those pollutants, this requirement does not significantly affect the minimization of environmental costs. In the Sup_Emi_CO_2_Cost scenario, the objective function includes the cost of purchasing CO_2 emission allowances.

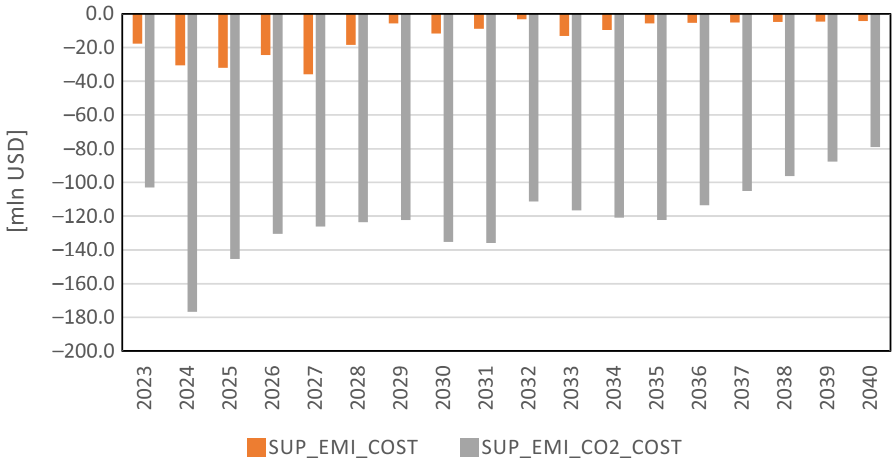

Fig. 10. Comparison of CO_2 Emission Allowances costs for centrally dispatched power generation units under the analyzed research scenarios – difference related to the SUP_COST scenario (mln USD)
Source: own study

Rys. 10. Porównanie kosztów uprawnień do emisji CO_2 dla jednostek wytwórczych centralnie dysponowanych (JWCD) w analizowanych scenariuszach badawczych – różnica w odniesieniu do scenariusza SUP_COST (mln USD)

This is of great importance compared to other cost components (high prices of CO_2 emission allowances are of key importance). As a consequence, the change in the selection of coals (as presented in section 3.1.1.) and a reduction in the costs associated with this component are clearly visible. As noted in section 3.2.1. and 3.2.2. the allocation of coal for power generation units, taking into account this cost component, often increases supply costs and environmental protection costs. However, these increases are compensated by significant cost savings incurred for the purchase of CO_2 emission allowances.

3.2.4. Total costs

The summary of the analysis is to present the impact of taking into account the costs of environmental protection and CO_2 emission allowances in the model's objective function on the total costs of acquiring and using coal in energy production. The total cost was determined as the sum of costs incurred for coal supplies (purchase and transport), environmental protection costs, and costs of CO_2 emission allowances. The results are presented in Table 4.

The total costs of coal acquisition and use in 2023–2040 for the Sup_Cost scenario amounted to just over USD 70.6 billion. These costs are nearly USD 0.3 billion lower in the Sup_Emi_Cost scenario and nearly USD 2 billion lower in the Sup_Emi_CO_2_Cost scenario.

Table 4. Total costs of supplying and using coal for centrally dispatched power generation units (thousand USD)

Tabela 4. Całkowite koszty pozyskania i wykorzystania węgla dla jednostek wytwórczych centralnie dysponowanych (JWCD) (tys. USD)

Scenario	2023	2024	2025	2026	2027
SUP_COST	5,123,970	5,180,712	5,021,081	4,704,781	4,564,466
SUP_EMI_COST	5,102,831	5,146,921	4,986,212	4,677,266	4,525,826
SUP_EMI_CO_2_COST	5,024,792	5,015,729	4,883,947	4,581,910	4,445,921
Scenario	2028	2029	2030	2035	2040
SUP_COST	4,367,946	4,279,782	4,112,492	3,637,834	2,671,585
SUP_EMI_COST	4,346,934	4,271,732	4,098,121	3,630,795	2,666,608
SUP_EMI_CO_2_COST	4,253,522	4,167,579	3,988,231	3,535,592	2,605,231
Scenario	2023–2040				
SUP_COST	70,661,219				
SUP_EMI_COST	70,383,896				
SUP_EMI_CO_2_COST	68,762,813				

Source: own study.

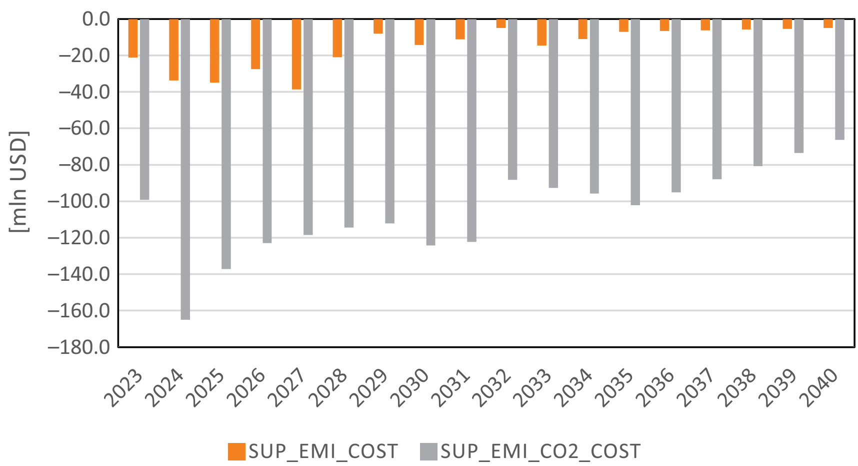

Fig. 11. Comparison of total costs for centrally dispatched power generation units under the analyzed research scenarios – difference related to the SUP_COST scenario (mln USD)
Source: own study

Rys. 11. Porównanie kosztów całkowitych jednostek wytwórczych centralnie dysponowanych (JWCD) w analizowanych scenariuszach badawczych – różnica w odniesieniu do scenariusza SUP_COST (mln USD)

Figure 11 presents cost differences in individual years of analysis – compared to the Sup_Cost scenario. The absolute differences for the Sup_Emi_Cost scenario are significantly lower than those calculated for the Sup_Emi_CO_2_Cost scenario. In the first case, they range from USD 5.0 million to USD 38.6 million over the entire analysis period, while in the second case, the difference ranges from USD 66.4 million to USD 165.0 million. The maximum values of the difference between the total costs obtained in the Sup_Cost and Sup_Emi_CO_2_Cost scenarios appear in 2024–2031. It is because of the possibility of selecting coals with appropriate quality parameters affecting the reduction of emissions (mainly CO_2). Such a selection of coal is possible due to the oversupply of raw materials, which is related to the falling demand for coal with a relatively stable supply and low import coal prices in this period.

Conclusions

The possibilities of reducing the costs of acquiring and using coal by the power industry in the era of rising prices of raw materials are particularly important for ensuring the effective functioning of energy companies. Actions aimed at reducing these costs are also desirable due to the high prices of CO_2 emission allowances, resulting from the consistently pursued climate and energy policy aimed at reducing the negative impact of burning fossil fuels on the environment. In selected countries, coal-fired units will be the basis of the generation structure of the national power system for the next dozen or so years. Therefore, it is necessary to minimize the costs incurred in the energy production process to improve the competitiveness of coal energy. However, actions taken to reduce environmental costs must be consistent with the requirements for fuel quality parameters for which the technological systems of the power plant have been designed. Complying with the emission standards required by sector-specific regulations is also crucial. Knowledge of the requirements of individual customers in terms of expected coal quality parameters should also be an important reference point for the raw material supplier sector. It allows for optimizing activities related to the extraction and enrichment of produced coal. Furthermore, the results of optimizing coal supplies to power generating units and their proper interpretation may constitute a significant contribution for entities shaping national energy policy.

The research demonstrated in the article has shown that optimizing coal supplies in terms of selecting raw materials with appropriate quality parameters, affecting the reduction of costs of acquiring and using this raw material, can bring measurable benefits. Considering the cost components related to environmental protection and the purchase of CO_2 emission allowances in optimizing the supply of raw material indicates the optimal selection of the raw material not only in terms of the cost of its purchase and transport, but also its further use in electricity production by power generation units.

The application of the constructed mathematical model, combined with the developed research scenarios, made it possible to carry out a quantitative assessment of the impact of considering the costs of environmental protection and CO_2 emission allowances in planning coal supplies on the reduction of costs related to acquiring and consuming this fuel by public power plants. The results of the calculations clearly indicate that the appropriate selection of coals, taking into account the quality parameters determining the amount of emissions of harmful substances, reduces the amount of these emissions and the total costs of acquiring and using coal in electricity production. However, depending on the considered scenario, the scale of this impact varies.

Including components related to environmental protection and the cost of CO_2 emission allowances in the objective function increases the component's value related to supply costs. Nevertheless, the benefit achieved by reducing the costs associated with fuel use is significantly higher. As a consequence, it leads to a significant reduction in the total cost of acquiring and using coal by power generation units, as well as lower emissions of harmful substances into the environment.

The analyses conducted and results obtained also allow for the formulation of potential further research directions. The first identified research direction is to conduct analyses of the impact of environmental regulations on the costs of obtaining coal in the context of the planned tightening of emission standards for fuel combustion sources. It is also assumed that it will be possible to examine the effects of decisions regarding the future of power generation units, such as the modernization of emission reduction installations or work as a peak unit. The second potential research direction is the adaptation of the developed tool to market, political, and social criteria. Consequently, for Polish conditions, it will be possible to develop the right selection of coals for units included in the National Energy Security Agency, which will take over the management of domestic hard coal-fired power generation units in the near future.

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HARD COAL SUPPLIES AND SELECTED ENVIRONMENTAL REGULATIONS: A CASE STUDY OF THE POLISH POWER SECTOR

Keywords

environmental regulations, hard coal, mathematical modeling, coal supply, energy sector

Abstract

The volatility of raw material prices and the rising prices of CO_2 emission allowances when using fossil fuels to produce electricity and heat are still relevant problems for owners of generating units. The decision-making tools are used in the fuel purchase process. However, these tools should also consider environmental issues.

The article's main objective is a quantitative analysis of the potential for reducing costs associated with supplying and using hard coal in public power plants as a result of considering the costs of environmental protection and CO_2 emission allowances in the process of planning this fuel supply. A mathematical model was developed to optimize the supply of hard coal for the power industry. The tool and elaborated research scenarios made it possible to calculate and analyze the impact of considering the costs of emissions of harmful substances into the environment and CO_2 emission allowances on the planning of coal supplies and the reduction of costs related to acquiring and using coal by public power plants. The calculation results were presented on the example of the Polish power sector.

The model's results confirm that the appropriate selection of coals, taking into account the quality parameters determining the amount of emissions of harmful substances, reduces the amount of these emissions and the total costs of acquiring and using coal in electricity production. However, depending on the considered scenario, the scale of this impact varies. The results of the optimization of coal supplies to power plants and their proper interpretation may constitute an important contribution to making management decisions in energy companies.

POZYSKIWANIE WĘGLA KAMIENNEGO Z UWZGLĘDNIENIEM WYBRANYCH REGULACJI ŚRODOWISKOWYCH – STUDIUM PRZYPADKU POLSKIEGO SEKTORA ENERGETYCZNEGO

Słowa kluczowe

węgiel kamienny, regulacje środowiskowe, modelowanie matematyczne, dostawy węgla, sektor energetyczny

Streszczenie

Problem zmienności cen surowców, wzrastających cen uprawnień do emisji CO_2 oraz zaostrzanych limitów emisji przy wykorzystywaniu paliw kopalnych do produkcji energii elektrycznej i ciepła jest wciąż aktualny dla właścicieli jednostek wytwórczych. Budowane narzędzia wspomagające proces podejmowania decyzji przy doborze surowców do procesu spalania powinny jednak uwzględniać również kwestie środowiskowe.

Głównym celem artykułu jest ilościowa analiza potencjału redukcji kosztów związanych z pozyskaniem i wykorzystaniem węgla kamiennego w elektrowniach zawodowych, w rezultacie uwzględnienia w procesie planowania dostaw tego paliwa, kosztów ochrony środowiska oraz uprawnień do emisji CO_2. Opracowano model matematyczny do optymalizacji pozyskiwania węgla kamiennego przez energetykę zawodową. Zbudowane narzędzie oraz opracowane scenariusze badawcze umożliwiły przeprowadzenie obliczeń i wykonanie analizy wpływu uwzględnienia kosztów ochrony środowiska oraz uprawnień do emisji CO_2 w procesie planowania dostaw węgla, na redukcję kosztów związanych z pozyskaniem i zużyciem węgla w elektrowniach zawodowych.

Wyniki modelu potwierdzają, że odpowiedni dobór węgli wpływa na redukcję całkowitych kosztów pozyskania i wykorzystania węgla w procesie produkcji energii elektrycznej. Wyniki optymalizacji dostaw węgla do jednostek wytwórczych i ich właściwa interpretacja mogą stanowić istotny wkład w podejmowaniu decyzji zarządczych w przedsiębiorstwach energetycznych.