sustainability

MDPI

Article

Configurational Path of Decarbonisation Based on Coal Mine Methane (CMM): An Econometric Model for the Polish Mining Industry

Katarzyna Tobór-Osadnik [1,*], Bożena Gajdzik [2] and Grzegorz Strzelec [3]

[1] Department of Safety Engineering, Silesian University of Technology, 44-100 Gliwice, Poland
[2] Department of Industrial Informatics, Silesian University of Technology, 40-019 Katowice, Poland; bozena.gajdzik@polsl.pl
[3] Jastrzębska Spółka Węglowa S.A., 44-330 Jastrzębie-Zdrój, Poland; gstrzelec@jsw.pl
* Correspondence: katarzyna.tobor-osadnik@polsl.pl

Abstract: This study presents the econometric model for the Polish mining industry on the topic of the configuration path of decarbonisation based on coal mine methane (CMM). CMM is released from coal mines around the world, including Poland. CMM is taken into account in the decarbonisation of countries with the highest underground coal production. Over the past ten years, CMM emissions have been gaining greater attention due to their status as We accept greenhouse gas (GHG) and their potential use as a clean energy resource. The very important problem for the mining plants is the system of controlling the level of methane. In this paper, we present an econometric model for mine production linear programming, taking into account both market considerations and controlling the amount of methane released into the air from mines. This model can use to control methane in the Polish mining industry. Moreover, this model can be used in the strategy of decarbonisation of the Polish industry according to the European strategy toward net zero (2050).

Keywords: decarbonisation; mining; coal mine methane (CMM)

check for updates

Citation: Tobór-Osadnik, K.; Gajdzik, B.; Strzelec, G. Configurational Path of Decarbonisation Based on Coal Mine Methane (CMM): An Econometric Model for the Polish Mining Industry. *Sustainability* **2023**, *15*, 9980. https://doi.org/10.3390/su15139980

Academic Editor: Chaolin Zhang

Received: 1 June 2023
Revised: 19 June 2023
Accepted: 21 June 2023
Published: 23 June 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Decarbonisation of economies is the process of reducing carbon emissions and improving the energy efficiency of energy and technological processes. To sharply reduce carbon emissions, economies need new energy production technologies. Decarbonisation, in macroeconomic (global) terms, concertedly reduces greenhouse gas emissions from all areas of human and industrial activity. Economies need to switch from fossil fuel-based energy sources to other non-GHG-emitting sources that result in a warming climate. Internationally, policy options for industrial decarbonisation are largely centred around national targets that will help achieve global emission reduction targets, as outlined in the Paris Agreement. In the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), the 2 °C scenario has been adopted [1]. According to the scenario, limiting global warming to within 2 degrees Celsius above preindustrial temperatures by the end of this century should be realised. In the scenario, the iron and steel industry is required to reduce CO_2 emissions by 50 Gt cumulatively by 2050, contributing the largest share (35%) of CO_2 emission reductions among all industrial sectors [2]. Radical policies lead governments in economies around the world to support investment in renewables [3]. These sources can be wind energy, photovoltaic and solar energy, hydropower, geothermal energy, biomass, and biofuels. Methane and hydrogen are also energy products. Many industries (power generation, steel, heating) need to switch from fossil fuels to non-GHG technologies, mainly to renewable energy. For the mining industry, which is included in the theme of this publication, the direction of methane recovery is being adopted. Mines use technologies to recover methane from coal seams. This direction is in line with the

climate neutrality policy addressed by the EU to all industries. Climate neutrality is a strategic goal for the EU economies to be achieved by 2050 [4]. Deep decarbonisation, as the climatic neutrality goal is called, requires strategic planning, preceded by diagnostic activities that will serve to develop several scenarios for achieving the net zero goal. Many sectors of the economy are looking for the best technologies to decarbonise areas of their business activities. The largest technological changes will be implemented in sectors that use coal, such as the steel sector [5–8]. The investments realised by manufacturers strongly reduced the energy intensity of production [9,10], although many manufacturers stopped investments after the COVID-19 pandemic [11] but proceeded again to build sustainability, both using digital technologies [12] and participating in deep decarbonisation [13]. Coal is also a source of energy that is recognised as black. Coal power accounts for 37% of the world's electricity production [14]. As the climate warms, economies are investing in green energy technologies, but power plants, mines and steel mills are still industries that need to change.

Concerting with the coal (mining) sector, the strategic direction for mines is the recovery of methane and the control of the amount of methane in the mine air released into the atmosphere. Coal mine methane (CMM) is a mixture of methane and air released during the process of coal mining and must be vented for safety reasons. Methane has a significant effect as a greenhouse gas, being 21 times higher than that of carbon dioxide; therefore, its capture and use in gas engines have significant environmental benefits. CMM typically has an oxygen content of 5–12%. The methane content ranges from 25–60% [15]. CMM is released from coal mines throughout the world, and often the largest emitters are countries with the highest production of high-rank underground coal (China, the US, Russia, Australia, Ukraine, and India) [16]. The amount of CMM generated at a specific operation depends on the productivity of the coal mine, the gassiness of the coal seam, and any underlying and overlying formations, operational variables, and geological conditions. Methane released from the worked coal face can be diluted and removed by large ventilation systems designed to move vast quantities of air through the mine. These systems dilute methane within the mine to concentrations below the explosive range of 5–15%, with a target for methane concentrations under 1%. The benefits of CMM capture and control relate to mine safety as well as to benefits for energy production and greenhouse gas (GHG) reduction [16]. Over the past decade, CMM emissions have been gaining increasing attention due to their status as greenhouse gas (GHG) and their potential as a source of clean energy. Many countries have begun to conduct periodic inventories of their CMM emissions (countries that are Parties to the United Nations Framework Convention on Climate Change UNFCCC [17]. Poland is a member, and mines in Poland supply more than 70% of the country's energy. The mines in Poland have been restructured, and technologies improved over the years [18] to increase productivity and safety [19]. Polish mines are highly methane-rich, hence the topic of this paper.

The introduction of methane emission restrictions according to EU regulations to standards of 5 tonnes of methane per 1000 tonnes of coal mined in 2027 and 3 tonnes in 2031 is a big problem for the Polish mining industry. Currently, Polish mines emit more—on average, from 8 to 14 tonnes of methane per 1000 tonnes of extracted coal. Although coking coal from Polish mines is classified as a critical European resource, methane emissions account for more than 70% of the reported carbon footprint. At the beginning of 2022, JSW SA updated its strategy, including the environmental area. Remedial work is moving towards working on better capture of methane from ventilation shafts and the development of alternative energy sources to balance the emitted CO_2e. Thus, methane emissions are an important problem both economically and environmentally.

We think that the problem is not well-known because researchers mainly concentrate their analysis on key renewable energy sources. However, we think the problem of methane is a very interesting and scientifically important research gap, especially in deep decarbonisation. We should know what such economies as Poland, where mines are still key suppliers of energy sources, are up to. The extraction activities of mines are accompanied

by released methane. On the one hand, there is a need to focus on methods for recovering methane and producing energy and heat from it, and on the other, to look for methods to control the amount of methane released. We see research gaps in these areas. On the basis of the identified research gap, we formulated the main goal of our research, which is to build a model for the programming of mine production in hard coal mines, taking into account the control of the amount of methane released into the atmosphere. To achieve this goal, we stated the following research questions (RQ):

RQ1. What are the political requirements for the decarbonisation of mines?
RQ2. What are the technological directions (the path) for methane recovery?
RQ3. What indicators should be used to build the objective function to make the model quickly applicable?

In this paper, we present an econometric model for mine production programming, taking into account both market considerations and controlling the amount of methane released into the air from mines.

Our research set out the following research hypothesis (RH)—it is possible to use mining production programming methods in an operational planning system to control the amount of methane released into the atmosphere from a group of pits or mines. At the same time, the aim of developing an econometric model was to use easy and low-cost tools to support management decision-making. This work consists of a theoretical part and a research part. This paper is structured as follows. It starts with an introduction (Section 1), followed by Section 2, presenting the background of decarbonisation. Section 3 provides information on the method of the study. Section 4 presents the results of our analysis, which is an econometric model. A discussion of our findings is provided in Section 5. Section 6 provides conclusions and limitations, as well as directions for future research.

The theoretical part was based on the literature review. The research part was a result of econometric modelling. The literature part was created in accordance with the SLR methodology using the keyword 'Decarbonisation coal'. The research area on the recovery of methane, which is a greenhouse gas, was identified from this collection. Methane emissions have a 25 times greater impact on the greenhouse effect (per unit mass) than carbon dioxide. Using methods to capture them and use them in the energy production process is one of the scenarios for Polish coal mines [5].

Therefore, the search for methods of capturing methane from mine air is the subject of many studies. The authors drew attention to a different approach to the problem—the optimisation of methane emissions during coal mining by controlling the volume of extraction while taking into account market requirements and meeting the current demand for given assortments.

The research part—the econometric model—was created on the basis of data obtained from Polish coal mines. Appropriately coded and modified to present the universality of the model, it can be used for planning activities at coal mines in the area of greenhouse gas emission reduction policy.

2. Background of Decarbonisation of the Mining Industry

The process of decarbonisation is usually considered a pathway for technological change of carbon-intensive sectors of the economy, as well as changes in the socio-economic structure [20,21]. The decarbonisation of industries has been on many policy agendas for many years now. The European climate law sets an ambitious emissions reduction target for 2030 while confirming the 2050 goal of achieving climate neutrality [22]. The EU legal framework and national legislation must help decarbonise the industry. It is important to take into account that there will be significant differences between the Member States and other regions in Europe in terms of the opportunities or resources that can be invested. The new regulatory framework must lead economies towards the goal of net climate neutrality in 2050 by creating the conditions to unlock vast resources—financial,

technological, and intellectual—for investment in low-carbon technologies, including carbon removal technologies [22].

The topic of decarbonisation in publications by researchers (search in the Scopus research database using the keyword 'Energy AND Transformation AND Decarbonisation'), in line with the theme of the special issue of the Journal '*Sustainability*', is clearly accelerating after 2018. A total of 250 publications (for Title, Abstract, and Keywords) were recorded in the database for this keyword. In 2010, the first publication for the keyword appeared in the Scopus research database: 'Energy AND Transformation AND Decarbonisation'. The book on global climate warming by Newell and Paterson [23] has the highest citation (first place) of 520. Other papers (top 5) are [24], with 414 citations; [25], with 194 citations; [26], with 171 citations; and [27], with 165 citations. This group includes papers on global warming [23], energy demand [26,27], energy transition costs [25], and new technological projects [24]. Table 1 summarises the number of publications between 2010 and 2023 (as of 14 May 2023).

Table 1. Number of documents for 'Energy AND Transformation AND Decarbonisation' in database Scopus.

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023 *
1	1	2	3	1	7	6	7	10	19	31	51	82	29 * F 84

* Until 14 May 2023. F-Forecast: average: about 7 papers per month; in December 2023, 84 papers.

A lot of papers were classified into one of the three main areas of study: Energy (30.8%); Engineering (17.6%); and Environmental Science (16.6%). Decarbonisation was recognised as a science that points in the direction of energy production with a focus on renewable energy sources. Ranking funding sponsors (top 5) opens Horizon 2020 Framework Programme (31 papers), European Commission (24 papers), Horizon 2020 (15 papers), Engineering and Physical Sciences Research Council (13 papers), and National Natural Science Foundation of China (11 papers). These founding sponsors are important forerunners of research on decarbonisation. The word 'Decarbonisation', regardless of spelling (English or American language), was used 252 times in publications. Keywords (decarbonisation together with other keywords) used by the authors in publications of the Scopus research database for the keyword 'Energy AND Transformation AND Decarbonisation' are presented in Table 2.

Table 2. Keywords used by authors of the papers in the Scopus database for the 'Energy AND Transformation AND Decarbonisation' (top 10).

Decarbonisation	Energy Efficiency	Energy Policy	Carbon	Climate Change	Carbon Dioxide	Renewable Energy	Emission Control	Gas Emission	Investments
252	55	48	48	44	39	35	33	29	28

The key to the transformation to net zero is the word decarbonisation. Decarbonisation means reducing thermal coal production. In general, thermal power plants are a major contributor to energy-related CO_2 emissions [28]. The world's coal reserves in 2020 were 1074.108 billion tonnes, and about 23.18% of this was in the United States, the most coal-rich country on the planet. The Russian Federation ranks second with a share of 15.1%. More than 90% of the world's total proven coal reserves are located in only ten countries (the US, Russia, China, Australia, India, Indonesia, Germany, Ukraine, Poland, and Kazakhstan) [29]. Poland's share in the world's coal reserves is 2.64% [29,30]. There are many scenarios for coal decarbonisation, ranging from coal deposit degassing to carbon storage, as well as hydrogen production [31–35]. Mine decarbonisation scenarios can play an important role in changing the use of the world's coal resources. One of them is Underground coal gasification

(UCG), one of the most promising clean coal technologies in decarbonising the coal industry, complementing shallow coal mining and coal bed methane production [36–38].

Using the key 'TITLE-ABS-KEY (decarbonisation AND coal AND mining) in the Scopus scientific database, 50 publications were obtained. The first paper was registered in 2005. The most publications were recorded in the last 3 years: 2020 (8 documents); 2021 (12 documents); 2022 (13 documents); and 2023 to 15 May (7 documents). In terms of citation frequency, the two publications with the highest citations were related to coal-fired power plants [39]: 70, [40]: 60. In the top 5 list, the first publication about mining transformation was about Australia [41]. Australia has been particularly active in deploying the power generation and oxidation systems currently available. Outside the top 5 list (in the top 10 list of most citations) was a publication on the region of Silesia (Poland), which has the largest number of mines in Poland [42]. We used the TITLE-ABS-KEY (coal AND mine AND methane AND mining) to obtain 2763 document results. The topic of mine de-methanation is very broad, as every coal deposit is different, and every mine is different. Every country with coal deposits is developing its pathway to decarbonise industries. Coal-related carbon emissions in recent decades have had a profound negative impact on the global climate. However, coal's central position in the energy system determines that a clean coal reduction strategy will inevitably lead to a systemic energy crisis. To this end, policy-makers, academics, and practitioners are exploring the mechanisms of joint strategies between coal companies, coal-fired power plants and other stakeholder groups in the strategic transition of energy decarbonisation from the perspective of the industrial chain and the sustainability of economies. Various measures are being implemented to reduce carbon emissions, and energy decarbonisation is an important topic in energy management and environmental sustainability research [43–45]. Numerous studies have been carried out on reducing CO_2 emissions and mitigating dependence on fossil fuels for sustainable energy transitions at the individual country level [46–48].

When the Paris Agreement came into force in 2016, many countries around the world, including Poland, pledged to reduce greenhouse gas emissions by 2050. Poland's GHG emissions decreased from 447 Mt CO_2e (megatonnes of carbon dioxide equivalent) in 1990 to 380 Mt CO_2e in 2017 [49]. This reduction was possible due to the transformation of a centrally planned economy based on industry into a largely service-based economy. It has also been possible to significantly improve the energy efficiency of industry, reduce the use of coal and lignite and increase the share of energy from renewable sources (RES). Currently, 15% of energy comes from renewable sources in Poland, but unfortunately, more than 70% still comes from hard coal and lignite [50,51]. In 2017, Poland ranked third among EU countries in terms of greenhouse gas emissions relative to GDP (800 g CO_2e for every euro of GDP). Decarbonising the Polish economy is a huge challenge. The country has no large rivers on which to build hydroelectric power plants, and the number of sunshine hours is 1.4–1.9 thousand per year [52]. Natural gas deposits are small. An opportunity for wind power is the Baltic Sea, which is located in the north of the country, but it is in the south that the most energy-intensive areas are found. Poland also does not have a nuclear power plant, unlike other EU countries from the former Eastern Bloc, such as Bulgaria, the Czech Republic, Hungary, Romania, and Slovakia [49]. In 2021, coal-fired power generation reached its highest level in 10 years—84 TWh (+1.4 p.p. relative to 2020). Coal's share of electricity generation was over 72.4% (+2.7 p.p. more than the previous year). The share of renewables fell to around 16.7% (17.7% in 2020), despite record production from these sources of 30 TWh [53]. The increase in coal-fired generation in 2021 was due, among other things, to increased electricity exports. The large scale of the increase was also due to low coal-fired generation in 2020. Among other things, coal-fired generation replaced gas-fired generation, which fell in 2021 for the first time in more than 10 years due to the very high price of gas fuel [54].

Mining is currently responsible for 4 to 7 per cent of global greenhouse gas emissions. CO_2 emissions from the sector in Scopes 1 and 2 (arising from mining activities and energy use, respectively) are 1%, and fugitive methane emissions from coal mining are estimated

at 3 to 6%. A significant proportion of global emissions—28%—could be considered Scope 3 (indirect) emissions, including coal combustion [55].

Decarbonisation implies a complete phase-out of coal use in electricity, heating, industry and households. This process will be particularly important for the labour market in the Silesian Region in Poland, which has the highest number of people working in mining in the European Union [56]. In addition, a significant proportion of hard coal-based manufacturing capacity and most of the companies associated with the mining sector are concentrated in the Silesia region in Poland. In 2018, the mining industry in the Silesian Region in Poland created 7% of added value [57]. A positive development is that this region has become a member of the EU Platform for Mining Regions in Transition (the Fair Transformation Platform) and is currently the most prepared to benefit from the Fair Transformation Fund. The Just Transition Fund provides support to all Member States. More than 100 regions in the EU, not only coal regions but also those dependent on carbon-intensive industries, have the opportunity to benefit from this funding. Coal units will increasingly switch to a backup/peak operation system. However, due to the destabilisation of the energy market (high energy prices), and the lack of nuclear power in the Polish electricity system, coal will be needed in Poland until 2030. After this period, mines must be prepared for the scenario of methane recovery, geothermal heat production, hydrogen production, etc.

In 2018, the programme for the hard coal mining sector in Poland was adopted, which covers the period until 2030. The aim of this programme is to improve the situation of the hard coal mining sector and to make efficient use of its resources. The implementation of the programme is monitored in annual cycles. In 2022, the programme was updated, taking into account the assumptions of PEP2040 (in Polish: Polityka Energetyczna Polski; in English: Energy Policy of Poland EPP2040) [58] and the provisions of the Social Agreement on the transformation of the hard coal mining sector and selected transformation processes of the Silesian Region, in which the planned dates of coal mine retirements were specified. According to PEP2040 (programme in Poland), the pace of the coal phase-out in the period from 2030 to 2040 will be as follows: 65% (2025); 56% (2030); 38% (2035); 28% (2040) (Table 3). As indicated in the (PEP2040) [58] programme, the decommissioning of coal mines should take place by 2049 [59]. Table 4 shows the number of mines being decommissioned in Poland.

Table 3. Rate of transition away from coal in Poland between 2030 and 2040.

2020	2025	2030	2035	2040
70%	65%	56%	38%	28%

Source: Energy Policy of Poland EPP2040 (abbreviation in Polish: PEP2040) [58].

Table 4. Deactivation of coal mines in Poland in the period 2028–2049.

2028	2029	2030	2034	2035	2036	2037	2039	2040	2041	2043	2046	2049
1	1	3×10^1	1	$1 + 1 \times 10^1$	$1 * + 1 \times 10^1$	1	1	2	1	1	1	4

* lignite mine, e-electricity plant. Source: [60].

One of the problems of mines in Poland is methane. Currently, the extraction of methane from abandoned hard coal deposits is about 5 million cubic metres, while the potential for its extraction should be estimated to be at least several billion cubic metres. The extraction of methane from closed mines can—and should—be an important addition to the national energy mix [60]. In Poland, the extraction of methane from decommissioned hard coal mines has so far been marginal. It is only carried out in two deposits, and the annual extraction volume is about 5 million m^3 (data for 2020), which represents 1 per mille of the national gas extraction and about 1.7% of the methane captured during coal mining [61]. Methane can be recovered from closed mines as well as active mines. In the case of closed mines, the amount of methane decreases year by year. During the first

year, the amount of methane emitted from a single longwall decreased to less than 20% of the average methane yield of that longwall from its exploitation period. After a few years, the amount of methane emitted was only a few per cent of the initial volume of emissions, and after a dozen or so years (estimated to be around 15 years), emissions virtually disappeared [61,62]. Decarbonisation of the mining industry would require a major effort on the part of the coal industry, especially in terms of solving the problem of fugitive methane. Solutions for capturing methane (and using it for energy production) exist but are not widely used. In many countries, government institutions are working with the coal industry to support project development and overcome technical and other barriers to implementation. However, there are no off-the-shelf solutions for all types of mines, and investment, in many cases, is uneconomic.

3. Study Method

The authors were looking to use a method that is already instrumented and not costly for building the model. Given the wide availability of the MsOffice package and the widespread ability to use it, the authors turned their attention to the Solver add-on, which allows the use of econometric model linear programming.

In linear programming [63], the aim is to make efficient use of limited resources or means while meeting the requirements. These problems are characterised by a large number of basic solutions. The prerequisite for selecting one of them is the definition of the objective and the formulation of constraints or requirements. A solution that satisfies both the conditions of the problem and the given requirements is called an optimal solution.

A characteristic feature of linear programming is the formulation of model (1) on the basis of relationships called rectilinear or linear. For the model, conditions written in Formula (1a,b) were fixed. The general formulation of a linear programming problem has the following form:
objective function $f(x)$ => maximise (minimise)

$$f(x) = C_1x_1 + C_2x_2 \ldots + C_kx_k \tag{1}$$

under the conditions

$$a_{11}x_1 + a_{12}x_2 + \ldots + a_{1k}x_k \leq b_1$$

$$a_{21}x_1 + a_{22}x_2 + \ldots + a_{2k}x_k \leq b_2$$

$$a_{m1}x_1 + a_{m2}x_2 + \ldots + a_{mk}x_k \leq b_m \tag{1a}$$

$$x_j \leq 0 \quad j = 1, 2, \ldots\ldots, k \tag{1b}$$

The mathematical model of linear programming contains three components, ((2) and (2a,b))

$$\text{Objective function } f(x) = C_jx_j \quad j = 1, 2, \ldots, k \tag{2}$$

$$\text{Set of restrictions } b_i \; i = 1, 2, \ldots, m \tag{2a}$$

$$\text{Condition of non-negativity of variables } x_j \geq 0 \quad j = 1, 2, \ldots, k \tag{2b}$$

If a solution satisfies the constraint function and the non-negativity condition for the variables, such a solution is called admissible. On the other hand, when the solution satisfies all three of these parts, we are dealing with an optimal solution. When formulating the task in the linear programming language, it should be remembered that if the task involves k variables and m constraints, with $k > m$, then at most m variables will have a positive value in the optimal solution, and the remaining $k - m$ (read: k minus m) variables will be equal to zero. The following requirements should be kept in mind when formulating a linear programming task:

- the performance indicator—the optimality criterion—should be strictly formulated and quantified in the task;
- all decisive factors and constraints should be included in the conditions and constraints, so that the simplified model does not lose its reality and practical value;
- the specific conditions of the task allow freedom of choice of variants (the variables in the model are interchangeable);
- the model contains only linear equations and inequalities.

Using the linear programming method, we obtain a set of solutions for the decision variables under study, given known constraints.

The model assumes that the variables will be the output from individual excavations. Of course, the values obtained in the model simulation will be verified based on the limitations of mining and geological conditions and the art of mining exploitation. The parameters included in the econometric model are, on the one hand, market requirements (quality of assortments), specific coal quality parameters for individual headings, and methane output from individual longwalls or, if not possible, estimated using available data.

To develop an example model, sample order data for a selected month, the results obtained in the coal processing department at the level of the coal company and based on the analysis of available data from the ventilation department were used. It was not possible to include full data on methane emissions for individual longwalls due to data secrecy. Therefore, estimates for the entire company are provided. However, this has no significance for the essence of the constructed model because if this model were used, real data would be entered.

Linear programming was chosen for modelling because it is understandable and does not require much additional analysis. You can use existing and measured indicators in operating mines.

The key assumptions in the proposed econometric model are based on the assumption that the volume of methane emissions is related to the volume of production, which is directly related to the ability to meet market needs. Of course, one can consider whether only the amount of coal extracted should be taken into account. However, the authors tried to propose a combination of meeting market needs with reducing methane emissions. This would allow the optimisation of the economic result and, at the same time, take into account the reduction or elimination of environmental penalties.

The main limitation of the model is the variability of mining and geological conditions and the adaptation of modelling to the mining plant operation plan. The authors assume that the proposed model is a tool for supporting management decisions at the operational and tactical levels. The obtained calculations are accurate for a given situation, but it is also possible to calculate variables for various assumptions and, thanks to the obtained sets of results, build mining plans.

The authors analysed which methane ratio should be included in the model, especially since methane is released into the atmosphere not only with the ventilation air. As a result of discussions and talks with the ventilation department in a mining company, the M coefficient was selected as having a direct impact on the effectiveness of modelling the volume of extraction from a given longwall. If it is not possible to directly determine the coefficient M for each analysed wall, it is possible to calculate the assignment coefficient of a given M for each of the walls. Such calculations would be carried out by ventilation departments in a given mine. Earlier studies [64] show that they can be effectively predicted.

This tool is simple to understand and can be quickly implemented at different decision-making levels in coal mines. Therefore, a mining production programming model was developed based on it, taking into account the control of the amount of methane released into the atmosphere from coal mines. The following chapter presents a proposal on how to build objective and constraint functions on selected data. The built functions allow the data to be entered into the Solver and the expected quantities to be modelled.

4. Results of Analysis

This chapter presents a proposal for using linear programming to simulate the amount of methane output for a group of coal workings.

In order to realise the simulation goal by minimising the amount of methane for a group of headings, it is possible to adopt a selected coal methane index for individual mines, together with an analysis of customer needs in a given month (abbreviation: M) [65]. This information is contained in Table 5. The code indicating the type of coal consists of three two-digit numbers. They denote, in turn, the following:

- net calorific value in MJ/kg;
- ash content in %;
- sulphur (S) content, expressed in %.

Table 5. Coal methane indexes.

	Orders per Month M					
Coal quality	31-7-08	30-8-08	30-7-08	23-20-08	22-22-08	20-25-08
Coal quantity (tonnes)	27,500	42,000	15,000	57,000	75,000	10,000

In order to determine the constraint function, information on coal quality data from each mining branch and the mining capacity of each branch are needed (Table 6).

Table 6. Data used in model.

Name od Branch Mine	**O1**	**O2**	**O3**	**O4**	**O5**	**O6**	**O7**	**O8**
Carbon calorific value MJ/kg	31.6	26.7	33.5	32.6	26.6	26.6	26.5	26.8
Coal ash content [%]	6.06	17.83	6.4	6.82	17.83	18.24	18.24	17.83
Sulphur content of coal [%]	0.83	0.70	0.81	0.80	0.75	0.90	0.90	0.70
Max. daily extraction (tonnes/day)	3700	2300	1900	2300	3800	2500	2600	1900
Max. monthly output (tonnnes/month)	82,000	50,000	42,000	50,000	84,000	55,000	57,000	42,000

We accept a sample set of orders consisting of six quality groups with different order quantities:

- coking coal with qualitative parameters—calorific value 31 MJ/kg, ash content 7%, sulphur content 0.8%—order quantity 27,500 tonnes;
- coking coal with the qualitative parameters—respectively, as for the first group 30-8-08—order quantity 42,000 tonnes;
- thermal coal intended for small customers and for the implementation of coal allowances with the parameters—respectively, 30-7-08—order quantity 15,000 tonnes;
- energy mix with the parameters—23-20-08—order quantity 57,000 tonnes, respectively;
- energy mix with parameters—respectively, 22-22-08—order quantity 75,000 tonnes;
- energy mix with parameters—20-25-08—order quantity 10,000 tonnes.

For the calculation of the orders, we assume the scheduled monthly number of orders (abbreviation: *M*). When creating the constraint functions, we group the extraction volumes based on similar coal quality parameters from the individual pits—
group three:

$$NW_{01} = 51{,}600 \text{ tonne/month} \quad (3)$$

groups one and two (due to similar quality parameters):

$$N(W_{01} + W_{03} + W_{04}) = 109{,}600 \text{ tonnes/month} \quad (4)$$

groups four and five:

$$N(W_{02} + W_{05} + W_{06} + W_{07} + W_{08}) = 181{,}400 \text{ tonnes/month} \quad (5)$$

group six (we can allocate to all seams because it is produced by treating all the coal going into the processing plant; a share of 8% of the coal can be assumed):

$$0.08\ N(W_{01} + W_{02} + W_{03} + W_{04} + W_{05} + W_{06} + W_{07} + W_{08}) = 23{,}284.8 \text{ t/month} \quad (6)$$

where:

W_{01}—extraction from the mining branch j;

N—the index of commercial coal to raw coal.

In all cases, the quantitative condition is met.

Taking the magnitude of the coefficient N = 0.63, we obtain a set of functions constituting a constraint system for further calculations:

$$0.63(W_{01}) \geq 15{,}000 \quad (7a)$$

$$0.63(W_{01} + W_{03} + W_{04}) \geq 69{,}500 \quad (7b)$$

$$0.63\ (W_{02} + W_{05} + W_{06} + W_{07} + W_{08}) \geq 132{,}500 \quad (7c)$$

$$8.08\ \times\ 0.63(W_{01} + W_{02} + W_{03} + W_{04} + W_{05} + W_{06} + W_{07} + W_{08}) \geq 10{,}000 \quad (7d)$$

$$0.63(W_{01} + W_{02} + W_{03} + W_{04} + W_{05} + W_{06} + W_{07} + W_{08}) \geq 226{,}500 \quad (7e)$$

$$W_{01} \leq 82{,}000;\ W_{02} \leq 50{,}000; W_{03} \leq 42{,}000;\ W_{04} \leq 50{,}000;\ W_{05} \leq 84{,}000;\ W_{06} \leq 55{,}000;\ W_{07} \leq 57{,}000;\ W_{08} \leq 42{,}000 \quad (7f)$$

$$f(x)_{min} = M_1W_{o1} + M_2W_{o2} + \ldots + M_jW_{oj} \quad (8)$$

where:

M_j-ventilation methane index Q_w of branch j;

The objective function is, therefore, in the following form:

$$f(x)_{min} = M_1W_{o1} + M_2W_{o2} + M_3W_{o3} + M_4W_{o4} + M_5W_{o5} + M_6W_{o6} + M_7W_{o7} + M_8W_{o8} \quad (9)$$

Calculations can be performed in the Solver programme available from the Excel package. This reduces the cost of purchasing professional software and allows simulations to be performed at almost no cost.

Key to the correct operation of the model is the appropriate choice of methane factor and the way it is determined (Table 7). The variability of methane emissions should also be taken into account. The calculated *Mj* coefficients should result from the current and past measurements, as well as from forecasted values. If it is not possible to determine the methane rate for each longwall, the ventilation methane rate of the average mine can be taken as a single factor *M*. However, this reduces the accuracy of the calculation. The part of the total methane that results from the de-methanisation efficiency ratio should also be added to the final prediction according to Formula (10) [66].

$$Q_c = Q_w + Q_o \quad (10)$$

where

Q_c—absolute methane;

Q_w—ventilation methane;

Q_o—total methane.

Table 7. Designations used in the model (9).

Mining Branch	O1	O2	O3	O4	O5	O6	O7	O8
Ventilation methane ratio Q_w of branch j	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8

According to data from JSW SA for the full year 2022 [67],

Q_w—ventilation methane 904.64 m^3/min or 475.48 mln m^3/year;

Q_o—total methane 557.38 m^3/min or 303.47 mln m^3/year,

with a de-methanation efficiency of 38.9%.

These figures indicate the importance of seeking to manage the amount of methane from which mines are held accountable for their greenhouse gas emissions.

Of course, simulation results cannot be taken for granted. They will only be used to support management decision-making. In a coal mine, the mining and geological conditions and the conduct of mining operations in accordance with the art of mining are important for the determination of the output from individual pits.

5. Discussion

At present, there are more than 220 Working Mine Methane projects worldwide in 14 countries. These projects help to avoid around 3.8 billion cubic metres of methane emissions every year. Australia has been particularly active in deploying the power generation and oxidation systems currently available [15].

Forecasting the amount of methane released from active mines is difficult insofar as it is conditioned by changing mining and geological conditions. In contrast, forecasting the amount of methane from sealed mines, flooding mines, and venting mines is a different matter. In these cases, it is possible to take as indicators those determined at their closure. One method is that of the U.S. EPA [68]. This method makes it possible to make emission forecasts and supports economic analyses and operational planning. Of course, this is an example of a method used in the US mining environment. However, the management and corporate responsibility for methane emissions from closed mines will be an important issue in the coming years. Therefore, in parallel, decision-support methods for managing greenhouse gas emissions from both existing and closed mines should be sought [16]. The EU's ever-improving circular economy policy [69] (the European Union is working on proposals to help move towards a stronger closed-loop economy, in which resources are used more sustainably and production substances are reused) can help mines build a methane recovery and processing systems [70]. A key role in methane recovery is the possibility of using it as a heat and energy source (methane can be used in gas turbines to produce electricity and heat). Methane can help mines build a new energy and heat supply chain and save energy in the economy. The benefits of a more sustainable mining industry also include new and innovative revenue streams (money from its use of methane in the industry). The capture of methane from closed mines can—and should—be an important addition to the national energy mix.

In light of the new direction of the EU in the field of methane emissions (a regulation that introduces a methane emission standard of 5 tons of this gas per 1000 tons of mined coal; a regulation introduced in 2027 and in 2031 as standard for coking coal mines), coal mine forms of response to these commitments. This is especially important when we know that 90% of methane emissions reports in Poland come from hard coal mines. Methane emission is appropriate to the mining and geological conditions of the exploited seams. Therefore, the size of the limit will increase by 28% in 2021 compared to 2011. The direct approach to methane emissions does not take into account the specificity of the industry, and the natural conditions of the coal deposits that manage the coal lines are not affected. Therefore, looking for methods to reduce or optimise the amount of released methane meets their needs. Operation and scientific research are carried out in two versions, developing a

method of capturing methane from the release of mine air and optimising the amount of methane for coal extraction alone.

Greenhouse gas emissions, which include methane, are particularly important in light of the climate policy of the International Panel on Climate Change (IPCC) 2023 [71]. This is important for the development of all EU countries [72].

Methane not only pollutes the air but also affects the amount of ozone in the atmosphere. During the period of rising to the level of Los Angeles-type smog, which contributed to death, it became clear that the expulsion of methane has side effects, economic and social.

The European Commission has set two directions for the main tasks [73]:

- Reform of the reporting system—in the discussed topic, it is a higher task of the Mining Office;
- Control of material and emissions from coal mines—this aspect is a proposed econometric model.

Attention should also be paid to the existing problems with the unification of methane emission data reporting. Repeatedly, data is duplicated, and misreporting can occur. A large number of reporting entities has a large impact on this state.

Thanks to the result of 1, the amount of methane emission is variable and depends on the parameters of the mined seams. Therefore, the proposed model takes into account such parameters as well as economic and environmental parameters.

This model focuses on measurable parameters at the level of mines and allows for relatively effective modelling of methane emissions. Calculation of methane emissions for a group of mines or the entire mining industry is extremely difficult due to reporting problems. Therefore, the search for methods and tools to optimise methane emissions 'at source' is part of the general trend of building cleaner production systems (CP).

6. Conclusions

Coal mine methane (CMM) is the term given to methane produced or emitted in connection with coal mining operations from the coal seam itself or from other gas-bearing underground formations. The amount of CMM generated from a particular operation depends on the capacity of the coal mine, the gassiness of the coal seam and any underlying and overlying formations, operational variables, and geological conditions. CMM can be captured by engineering boreholes that support the mine ventilation system, or it may be emitted into the mine environment and discharged from the mine. The methane removed from working mines via this technique is known as Ventilation Air Methane (VAM). The VAM is released through the ventilation shafts and can then be captured for utilisation rather than allowing it to be released directly into the atmosphere, as may have occurred in the past VAM is released through ventilation shafts, and so, where possible, can be captured for use rather than released directly into the atmosphere, as has been the case in the past. Mine methane can, therefore, provide an energy source as an alternative to simply consuming gas through combustion systems. New energy sources are constantly being sought in sustainable economies around the world. Technologies to recover methane and use it as an energy source can be viable in post-mining countries, and Poland, which will close its last mine in 2049, will be one such country.

The coal (hard) mining industry, similar to the steel industry, is still being restructured in Poland [74–76]. Radical changes have been introduced to Polish mines since 1990 when the economy was changed to a market economy and mines became capital companies. It can be expected that with Poland's radical energy policy (moving away from coal as an energy source), which is in line with European policy, mines need to be restructured again [77,78]. This time, methane may have to be used as a gas. The model we prepared can be used for planning methane management in Poland. The data for the model came from the largest mine in Poland, which is listed on the Warsaw Stock Exchange, which can be considered as a benchmark. A well-known econometric methodology was used to develop the model. Using the applied linear programming method does not require any additional software. It is so intuitive that it can be quickly implemented and used

in hard coal mines. This is of particular importance due to the organisational structure prevailing in these mining plants. However, this model will require testing on selected mines and verification of emerging mining and organisational restrictions. Further research will be carried out in this direction. From linear programming, you can move to complex multivariate econometric models. The planned future scope of research will concern the optimisation of methane management in mines. The authors plan to use two analysis segments: segment 1 will concern mines excluded from coal production; and segment 2 will concern active mines. The obtained models will be used to forecast the variables under study until 2049, i.e., until the mines in Poland are closed for mining (hard coal mining) according to Polish Energy Policy [58].

Author Contributions: Conceptualisation, K.T.-O. and B.G.; methodology, K.T.-O.; software, B.G.; validation, K.T.-O. and B.G.; formal analysis, K.T.-O. and B.G.; investigation, B.G.; resources, B.G. and K.T.-O.; data curation, G.S., K.T.-O. and B.G.; writing—original draft preparation, K.T.-O. and B.G.; writing—review and editing, K.T.-O. and B.G.; visualisation, K.T.-O. and B.G.; supervision, B.G. and K.T.-O.; project administration, B.G., K.T.-O. and G.S.; funding acquisition, K.T.-O. All authors have read and agreed to the published version of the manuscript..

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the use of internal company data.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. UNFCCC. Adoption of the Paris Agreement. Report No. FCCC/CP/2015/L.9/ Rev.1. 2015. Available online: http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf (accessed on 15 May 2023).
2. International Energy Agency. Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems. Available online: https://www.worldsteel.org/en/dam/jcr:66fed386-fd0b-485e-aa23-b8a5e7533435/Position_paper_climate_2018.pdf (accessed on 15 May 2023).
3. LechLechtenböhmer, S.; Schneider, C.; Vogl, V.; Pätz, C. Climate Innovations in the Steel Industry. REINVENT Deliverable Project no 730053. 2018. Available online: https://static1.squarespace.com/static/59f0cb986957da5faf64971e/t/5be40340352f531a564c9a2e/1541669701888/D2.2+Climate+innovations+in+the+steel+industry.pdf (accessed on 20 May 2023).
4. Industrial Transformation 2050—Towards an Industrial Strategy for a Climate Neutral Europe. Institute for European Studies, Vrije Universiteit Brussel. Available online: https://www.ies.be/files/Industrial_Transformation_2050_0.pdf (accessed on 20 May 2023).
5. Gajdzik, B. Comprehensive classification of environmental aspects in a manufacturing enterprise. *Metalurgija* **2012**, *51*, 541–544.
6. Gajdzik, B.; Burchart-Korol, D. Eco-innovation in manufacturing plants illustrated with an example of steel products development. *Metalurgija* **2011**, *50*, 63–66.
7. Gajdzik, B.; Sroka, W. Resource Intensity vs. Investment in Production Installations-The Case of the Steel Industry in Poland. *Energies* **2021**, *14*, 443. [CrossRef]
8. Gajdzik, B. Environmental aspects, strategies and waste logistic system based on the example of metallurgical company. *Metalurgija* **2009**, *48*, 63–67.
9. Gajdzik, B.; Wolniak, R.; Grebski, W.W. Electricity and Heat Demand in Steel Industry Technological Processes in Industry 4.0 Conditions. *Energies* **2023**, *16*, 787. [CrossRef]
10. Gajdzik, B.; Sroka, W.; Vveinhardt, J. Energy intensity of steel manufactured utilising EAF technology as a function of investments made: The case of the steel industry in Poland. *Energies* **2021**, *14*, 5152. [CrossRef]
11. Gajdzik, B.; Wolniak, R. Influence of the COVID-19 Crisis on Steel Production in Poland Compared to the Financial Crisis of 2009 and to Boom Periods in the Market. *Resources* **2021**, *10*, 4. [CrossRef]
12. Gajdzik, B.; Wolniak, R. Digitalisation and Innovation in the Steel Industry in Poland-Selected Tools of ICT in an Analysis of Statistical Data and a Case Study. *Energies* **2021**, *14*, 3034. [CrossRef]
13. Gajdzik, B.; Wolniak, R.; Grebski, W. Process of Transformation to Net Zero Steelmaking: Decarbonisation Scenarios Based on the Analysis of the Polish Steel Industry. *Energies* **2023**, *16*, 3384. [CrossRef]
14. Coal & Electricity. Report of World Coal Association. Available online: https://www.worldcoal.org/coal-facts/coal-electricity/ (accessed on 26 May 2023).

15. Kohler, Working Mine Methane/Coal Mine Methane. Clarke Energy. Available online: https://www.clarke-energy.com/applications/coal-gas/working-mine-methane/ (accessed on 25 May 2023).
16. Karacan, C.Ö.; Ruiz, F.A.; Cotè, M.; Phipps, S. Coal Mine Methane: A Review of Capture and Utilization Practices with Benefits to Mining Safety and to Greenhouse Gas Reduction. Available online: https://www.cdc.gov/niosh/mining%5C/UserFiles/works/pdfs/cmmar.pdf (accessed on 27 May 2023).
17. Parties to the United Nations Framework Convention on Climate Change UNFCCC. Available online: https://unfccc.int/process/parties-non-party-stakeholders/parties-convention-and-observer-states (accessed on 20 May 2023).
18. Brodny, J.; Tutak, M. Analysing the utilisation effectiveness of mining machines using independent data acquisition systems: A case study. *Energies* **2019**, *12*, 2505. [CrossRef]
19. Gajdzik, B.; Sujova, E.; Małysa, T.; The accident rate in Polish mining. Current status and forecast. *Acta Montan. Slovaca* **2022**, *27*, 620–634. [CrossRef]
20. GWP. *Global Warming Potential, Report*; IPCC (AR4): Geneva, Switzerland, 2022. Available online: https://www.ipcc.ch/report/ar6/wg2/ (accessed on 26 May 2023).
21. Rosenbloom, D. Pathways: An emerging concept for the theory and governance of low-carbon transitions. *Glob. Environ. Chang.* **2017**, *43*, 37–50. [CrossRef]
22. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. *A Green Deal Industrial Plan for the Net-Zero Age, 1.2.2023 COM(2023) 62 Final*; European Commission: Brussels, Belgium, 2023. Available online: https://commission.europa.eu/system/files/2023-02/COM_2023_62_2_EN_ACT_A%20Green%20Deal%20Industrial%20Plan%20for%20the%20Net-Zero%20Age.pdf (accessed on 25 May 2023).
23. Newell, P.; Paterson, M. *Climate Capitalism: Global Warming and the Transformation of the Global Economy*; Cambridge University Press: Cambridge, UK, 2010; pp. 1–205.
24. Bailera, M.; Lisbona, P.; Romeo, L.M.; Espatolero, S. Power to Gas projects review: Lab, pilot and demo plants for storing renewable energy and CO_2. *Renew. Sustain. Energy Rev.* **2017**, *69*, 292–312. [CrossRef]
25. Bogdanov, D.; Ram, M.; Aghahosseini, A.; Traber, T.; Breyer, C. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy* **2021**, *227*, 120467. [CrossRef]
26. Geels, F.W.; Schwanen, T.; Sorrell, S.; Jenkins, K.; Sovacool, B.K. Reducing energy demand through low carbon innovation: A sociotechnical transitions perspective and thirteen research debates. *Energy Res. Soc. Sci.* **2018**, *40*, 23–35. [CrossRef]
27. Bobmann, T.; Staffell, I. The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain. *Energy* **2015**, *90*, 1317–1333.
28. Muhammad, B. Energy Consumption, CO_2 Emissions and Economic Growth in Developed, Emerging and Middle East and North Africa Countries. *Energy* **2019**, *179*, 232–245. [CrossRef]
29. Countries with the Biggest Coal Reserves. Report Mining Technology. 6 January 2020. Available online: https://www.mining-technology.com/analysis/feature-the-words-biggest-coal-reserves-by-country/ (accessed on 20 May 2023).
30. Dale, S. *BP Statistical Review of World Energy*; BP International Limited: London, UK, 2021.
31. Jiang, L.; Chen, Z.; Farouq Ali, S.M. Modelling of reverse combustion linking in underground coal gasification. *Fuel* **2017**, *207*, 302–311. [CrossRef]
32. Jiang, L.; Chen, Z.; Farouq Ali, S.M.; Zhang, J.; Chen, Y.; Chen, S. Storing carbon dioxide in deep unmineable coal seams for centuries following underground coal gasification. *J. Clean. Prod.* **2020**, *378*, 134565. [CrossRef]
33. Roddy, D.J.; Younger, P.L. Underground coal gasification with CCS: A pathway to decarbonising industry. *Energy Environ. Sci.* **2010**, *3*, 400–407. [CrossRef]
34. Younger, P.L. Hydrogeological and geomechanical aspects of underground coal gasification and its direct coupling to carbon capture and storage. *Mine Water Environ.* **2011**, *30*, 127–140. [CrossRef]
35. Durucan, S.; Korre, A.; Shi, J.Q.; Idiens, M.; Stańczyk, K.; Kapusta, K.; Zavsek, S. TOPS: Technology options for coupled underground coal gasification and CO_2 capture and storage. *Energy Proc.* **2014**, *63*, 5827–5835. [CrossRef]
36. Jiang, L.; Xue, D.; Wei, Z.; Chen, Z.; Mirzayev, M.; Chen, Y.; Chen, S. Coal decarbonization: A state-of-the-art review of enhanced hydrogen production in underground coal gasification. *Enegry Rev.* **2022**, *1*, 100004. [CrossRef]
37. Moore, T.A. Coalbed Methane: A Review. *Int. J. Coal Geol.* **2012**, *101*, 36–81. Available online: https://www.scopus.com/inward/record.url?eid=2-s2.0-84865049192&partnerID=10&rel=R3.0.0 (accessed on 20 May 2023). [CrossRef]
38. Xue, D.; Chen, Z.; Lu, C. Establishment of the comprehensive material balance equation for coalbed methane reservoirs at the gas desorption stage. *Fuel* **2022**, *326*, 124979. Available online: https://www.scopus.com/record/display.uri?eid=2-s2.0-85132912517&origin=inward&txGid=91eb1c3395912a78231767098bfba4c7 (accessed on 21 May 2023). [CrossRef]
39. Hanak, D.P.; Biliyok, C.; Manovic, V. Calcium looping with inherent energy storage for decarbonisation of coal-fired power plant. *Energy Environ. Sci.* **2016**, *9*, 971–983. [CrossRef]
40. Hanak, D.P.; Manovic, V. Calcium looping with supercritical CO_2 cycle for decarbonisation of coal-fired power plant. *Energy* **2016**, *102*, 343–353. [CrossRef]
41. Della Bosca, H.; Gillespie, J. The coal story: Generational coal mining communities and strategies of energy transition in Australia. *Energy Policy* **2018**, *120*, 734–740. [CrossRef]

42. Skoczkowski, T.; Bielecki, S.; Kochański, M.; Korczak, K. Climate-change induced uncertainties, risks and opportunities for the coal-based region of Silesia: Stakeholders' perspectives. *Environ. Innov. Soc. Transit.* **2020**, *35*, 460–481. [CrossRef]
43. Ćorović, N.; Urošević, B.G.; Katić, N. Decarbonization: Challenges for the Electricity Market Development—Serbian Market Case. *Energy Rep.* **2022**, *8*, 2200. [CrossRef]
44. Sun, H.; Edziah, B.K.; Sun, C.; Kporsu, A.K. Institutional Quality, Green Innovation and Energy Efficiency. *Energy Policy* **2019**, *135*, 111002. [CrossRef]
45. Savina, N.; Sribna, Y.; Pitel, N.; Parkhomenko, L.; Osipova, A.; Koval, V. Energy Management Decarbonization Policy and its Implications for National Economies. In Proceedings of the IOP Conference Series: Earth and Environmental Science (IOP Publishing), Surakarta, Indonesia, 24–25 August 2021.
46. Vatalis, K.I.; Avlogiaris, G.; Tsalis, T.A. Just Transition Pathways of Energy Decarbonization under the Global Environmental Changes. *J. Environ. Manag.* **2022**, *309*, 114713. [CrossRef] [PubMed]
47. Bompard, E.; Botterud, A.; Corgnati, S.; Huang, T.; Jafari, M.; Leone, P.; Mauro, S.; Montesano, G.; Papa, C.; Profumo, F. An Electricity Triangle for Energy Transition: Application to Italy. *Appl. Energy* **2020**, *277*, 115525. [CrossRef]
48. Fang, Y.; Xu, H. Research on Decarbonization Pathway of China's Coal-Fired Power Industry From the Perspective of Conflict Mediation. *Front. Environ. Sci.* **2022**, *10*, 994. [CrossRef]
49. *Report (Title in Polish) Neutralna Emisyjnie Polska 2050*; McKinsey & Company: New York, NY, USA, 2020. Available online: https://www.mckinsey.com/pl/~/media/mckinsey/locations/europe%20and%20middle%20east/polska/raporty/carbon%20neutral%20poland%202050/neutralna%20emisyjnie%20polska%202050_raport%20mckinsey.pdf (accessed on 27 May 2023).
50. *Report (Title in Polish) Statystyka Elektroenergetyki Polskiej 2018*. PSE, KSE 2018 Report. Available online: https://www.pse.pl (accessed on 24 March 2020).
51. *Gospodarka Paliwowo-Energetyczna w Latach 2017 i 2018*; Statistics Poland: Warsaw, Poland, 2019; p. 279. Available online: https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/gospodarka-paliwowo-energetyczna-w-latach-2017-i-2018,4,14.html (accessed on 20 May 2023).
52. PGIE. Nasłonecznieni. 2020. Available online: http://www.pgie.pl/naslonecznienie/ (accessed on 15 May 2023).
53. *Transformacja Energetyczna w Polsce, Edycja*. 2022. Available online: https://www.forum-energii.eu/public/upload/articles/files/Raport_Transformacja%20energetyczna%20Polski_2022.pdf (accessed on 29 September 2022).
54. *Report (Title in Polish) Zmiany na Rynku Pracy Wynikające ze Wdrażania Koncepcji Zrównoważonego Rozwoju*; PARP: Warszawa, Poland, 2022. Available online: https://www.parp.gov.pl/storage/publications/pdf/Zmiany-na-rynku-pracy-wynikajce-z-wdraania-koncepcji-zrwnowaonego-rozwoju.pdf (accessed on 20 May 2023).
55. Delevingne, L.; Glazener, W.; Grégoir, L.; Henderson, K. *Report: Climate Risk and Decarbonization: What Every Mining CEO Needs to Know*; Mc Kinsey: New York, NY, USA, 2020. Available online: https://www.mckinsey.com/capabilities/sustainability/our-insights/climate-risk-and-decarbonization-what-every-mining-ceo-needs-to-know (accessed on 20 April 2022).
56. Alves Dias, P.; Kanellopoulos, K.; Medarac, H.; Kapetaki, Z.; Miranda Barbosa, E.; Shortall, R.; Czako, V.; Telsnig, T.; Vazquez Hernandez, C.; Lacal Arantegui, R.; et al. *EU Coal Regions: Opportunities and Challenges Ahead, EUR 29292 EN*; Publications Office of the European Union: Luxembourg, 2018. [CrossRef]
57. IBS Research Report 2021. Available online: https://ibs.org.pl/app/uploads/2021/01/IBS-Research-Report-01-2021.pdf (accessed on 20 May 2023).
58. *Energy Policy of Poland (EPP2040) until* 2040, (Title in Polish) *Polityka Energetyczna Polski do 2040 r*. (PEP2040). Available online: https://www.gov.pl/web/klimat/polityka-energetyczna-polski (accessed on 21 May 2023).
59. *Report (Title in Polish) Polska ścieżka transformacji energetycznej*; Polski Komitet Energii Elektrycznej: Warszawa, Poland, 2022. Available online: https://pkee.pl/publications/raport-ey-i-pkee-polska-sciezka-transformacji-energetycznej/ (accessed on 27 May 2023).
60. *Terytorialny Plan Sprawiedliwej Transformacji Województwa Śląskiego*; Urząd Marszałkowski Województwa Śląskiego: Katowice, Poland, 2022. Available online: https://transformacja.slaskie.pl/images/Dokumenty/1646921120_terytorialny_plan_spr.04.pdf (accessed on 25 May 2023).
61. Jureczka, J. *Metan z Zaniechanych Złóż Węgla Kamiennego—Wsparcie dla Transformacji Energetycznej*; Państwowy Instytut Geologiczny: Warszawa, Poland, 2021. Available online: https://www.pgi.gov.pl/aktualnosci/display/13314-metan-z-zaniechanych-zloz-wegla-kamiennego-wsparcie-dla-transformacji-energetycznej.html (accessed on 27 May 2023).
62. Brodny, J.; Tutak, M. Analysis of methane emission into the atmosphere as a result of mining activity. In Proceedings of the International Multidisciplinary Scientific GeoConference: SGEM, Albena, Bulgaria, 30 June–6 July 2016; Volume 3, pp. 83–90.
63. Vanderbei, R.J. *Linear Programming*; Springer International Publishing: New York, NY, USA, 2020. [CrossRef]
64. Badura, H. *Stężenie Metanu na Wylotach z Rejonów Ścian w Górnictwie Węglowym*; STE Group: Warszawa, Poland, 2023.
65. Tobór-Osadnik, K. Planowanie produkcji górniczej wykorzystujące metody badań operacyjnych. In *Moderni Matematicke Metody v Inzenyrstvi: 3mi. SBORNIK z 25. Seminare, 30 May–1 June 2016*; VSB–Technical University of Ostrava: Ostrava, Czechia, 2016.
66. Wierzbiński, K. Zastosowanie wyników modelowania numerycznego stref odprężenia eksploatacyjnego w prognozowaniu emisji metanu z warstw otaczających do ścian zawałowych. *Przegląd GÓRniczy* **2020**, *76*, 1–12.
67. Internal data from JSW SA documentation.
68. U.S. Environmental Protection Agency. Available online: https://www.epa.gov (accessed on 26 May 2023).

69. Circular Economy Action Plan. In *European Parliament Resolution of 10 February 2021 on the New Circular Economy Action Plan (2020/2077(INI)*; European Commission: Brussels, Belgium, 2021. Available online: https://www.europarl.europa.eu/doceo/document/TA-9-2021-0040_EN.html (accessed on 16 June 2023).
70. Markevych, K.; Maistro, S.; Koval, V.; Paliukh, V. Mining sustainability and circular economy in the contest of economic security in Ukraine. *Min. Miner. Depos.* **2022**, *16*, 101–113. [CrossRef]
71. International Panel on Climate Change (IPCC) 2023. Available online: https://www.ipcc.ch/ (accessed on 16 June 2023).
72. Bluszcz, A. Conditions for maintaining the sustainable development level of EU member states. *Soc. Indic. Res.* **2018**, *139*, 679–693. [CrossRef]
73. Balcerowski, J.; Charkowska, Z. W Poszukiwaniu Źródeł Emisji Metanu w Polskim Górnictwie Węgla Kamiennego i Systemy Raportowania. In *Instrat Policy Paper*; Instrat: Warszawa, Poland, 2023. Available online: https://instrat.pl/wp-content/uploads/2023/02/Instrat-Policy-Paper-01-2023-W-poszukiwaniu-zrodel.-Emisje-metanu-....pdf (accessed on 18 June 2023).
74. Gajdzik, B. The road of Polish steelworks towards market success -changes after restructuring process. *Metalurgija* **2013**, *52*, 421–424.
75. Zientara, P. Restructuring the Coal Mining Industry: Unionism, Conflict, and Cooperation: Evidence from Poland. In *Eastern European Economics*; Taylor & Francis, Ltd.: Abingdon, UK, 2009; Volume 47, pp. 41–59.
76. Smolec, Z. Restructuring of the European coal and thermal power sectors, with particular attention to member countries in transition. E/ECE/]ENERGY/GE.1/1999/2 5, UN Geneva. Available online: https://digitallibrary.un.org/record/1494170?ln=ru (accessed on 18 June 2023).
77. Kaczmarek, J.; Kolegowicz, K.; Szymla, W. Restructuring of the Coal Mining Industry and the Challenges of Energy Transition in Poland (1990–2020). *Energies* **2022**, *15*, 3518. [CrossRef]
78. Kaczmarek, J. The Balance of Outlays and Effects of Restructuring Hard Coal Mining Companies in Terms of Energy Policy of Poland PEP 2040. *Energies* **2022**, *15*, 1853. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.