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European Climate Policy in the Context of the Problem of Methane Emissions from Coal Mines in Poland

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Abstract: This paper presents a thorough examination of methane capture from Polish coal mines, contextualized within the framework of the European Union's (EU) climate policy objectives. Through a strategic analysis encompassing the interior of coal mines, the surrounding environment, and the macro environment, this study elucidates the complex dynamics involved in methane emissions and capture initiatives. The key findings include a declining trend in absolute methane emissions since 2008, despite fluctuations in coal extraction volumes, and a relatively stable level of methane capture exceeding 300 million m^3/year since 2014. The analysis underscores the critical role of government support, both in terms of financial incentives and streamlined regulatory processes, to facilitate the integration of methane capture technologies into coal mining operations. Collaboration through partnerships and stakeholder engagement emerges as essential for overcoming resource competition and ensuring the long-term success of methane capture projects. This paper also highlights the economic and environmental opportunities presented by methane reserves, emphasizing the importance of investment in efficient extraction technologies. Despite these advancements, challenges persist, particularly regarding the low efficiency of current de-methanation technologies. Recommendations for modernization and technological innovation are proposed to enhance methane capture efficiency and utilization.

Keywords: methane capture; climate policy; energy utilization; environmental sustainability; coal mining

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1. Introduction

Increased interest in the effects of human activity on the environment can be traced back to the late 1960s and early 1970s. They became the main theme of the First UN Conference Environment and Development, held in Stockholm in 1972. This event gave rise to international environmental cooperation. At this conference, "the outline of a new idea of development was put forward, taking into account the negative dimension of anthropocentric pressures on nature" [1]. When the Paris Agreement came into force in 2016, many countries around the world, including Poland, pledged to reduce greenhouse gas emissions by 2050. The European Union's climate policy, reflecting the UN Paris Agreement, implies many legislative and technological changes in many sectors of the economy, including mining. Among the objectives of the European Green Deal is the one to significantly reduce greenhouse gas emissions by 2030 and 2050. To achieve the EGD targets, the European Commission has prepared a set of legislative proposals whose implementation should contribute to a zero-carbon economy [2]. In the communication 'Fit for 55', it shows the way to achieve these reduction targets. The EU's 'Fit for 55' package is a unique set of policies and instruments aimed at reducing greenhouse gas emissions by 55% in 2030 compared to 1990 and achieving net zero emissions by 2050 [3]. The package prepared includes a set of policies addressing every aspect of society and the operation of the economy [4].

The capturing of methane from coal mines is closely connected to the climate policy objectives of the European Union (EU). The EU has been at the forefront of global efforts to combat climate change and transition towards a low-carbon economy [5]. Methane is a potent greenhouse gas, and its capture aligns with the EU's commitment to reducing emissions and mitigating the impacts of climate change [6]. The EU's climate policy framework, including the European Green Deal and the 2030 Climate Target Plan, emphasizes the need to decarbonize various sectors, including energy production. Coal mines are significant sources of methane emissions, especially during extraction and processing activities [7]. By capturing methane from coal mines, the EU aims to minimize the release of this potent greenhouse gas into the atmosphere, contributing to the overall reduction in emissions, in line with its climate goals [8]. It can be stated that the EU has set ambitious targets to achieve climate neutrality by 2050. This involves not only reducing carbon dioxide emissions but also addressing other potent greenhouse gases like methane [9]. Methane has a higher warming potential than carbon dioxide in the short term, making its capture an important aspect of the EU's broader strategy to combat climate change. The EU has established regulations and directives to address methane emissions, and these policies encourage the adoption of technologies and practices that capture methane from various sources, including coal mines [10–12]. Companies operating within the EU are subject to stringent environmental standards and regulations, creating a regulatory environment that promotes the implementation of methane capture technologies [13,14].

The novelty of this paper lies in its comprehensive examination of methane capture from Polish coal mines within the context of the European Union's climate policy objectives. While the existing literature on methane emissions from coal mining operations often focuses on individual aspects such as technological solutions or regulatory challenges, this paper offers a holistic analysis that considers various interconnected factors.

An important aspect of novelty is the strategic analysis framework adopted in the study. By examining methane emissions at multiple levels—the interior of coal mines, the surrounding environment, and the macro environment—this paper provides a nuanced understanding of the complexities involved. This strategic approach allows for a more comprehensive assessment of the challenges and opportunities associated with methane capture initiatives. Also, this paper's empirical analysis of methane emissions trends over a significant timeframe (2008–2022) provides valuable insights into the effectiveness of current mitigation efforts. By analyzing data from Polish coal mines, this study offers empirical evidence to support its findings and recommendations. This empirical approach adds credibility to the paper's conclusions and contributes to the scientific understanding of methane capture in coal mining operations.

It can be stated that the paper's emphasis on the need for collaboration and stakeholder engagement underscores its practical relevance. By advocating for partnerships between mining companies, government agencies, research institutions, and the private sector, this paper recognizes the importance of collective action in addressing methane emissions from coal mines.

2. Methane as One of the Main Greenhouse Gases

It has been 200 years since the discovery of the greenhouse effect. The greenhouse effect was described by French mathematician Joseph Fourier in 1824 [15]. The greenhouse effect is caused by a group of gases called greenhouse gases. Three main categories of gases are responsible, to a very large extent, for this effect, with these gases being carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Among these gases, carbon dioxide ranks first in terms of negative environmental impact, followed by methane. Carbon dioxide (CO_2) is scientifically estimated to be responsible for approximately 66% of global warming and methane for 30% of global warming (IEA data) [16,17]. In EU countries, methane is estimated to contribute more than 12% to global warming [18], and in Poland, it is

10.7% [19]. The relative contribution to the greenhouse effect of this gas over the last 100 years has been 15%. Methane (CH_4) is a potent GHG but has a short lifetime compared with CO_2 (9.1 $\pm$ 0.9 years, total atmospheric lifetime) [20,21]. At the molecular level, this gas is a much more potent driver of climate change (with a global warming potential over a 100-year period 28 times higher than that of carbon dioxide and 86 times higher over a 20-year period) [22]. Methane is a much more poisonous gas than carbon dioxide. It makes warming happen much faster.

Since the beginning of the industrial revolution, an increase in atmospheric methane concentrations has been noted in global reports. Increases in atmospheric methane concentrations have increased as economies have grown. Although atmospheric methane levels increased more slowly in the 1990s than in the 1980s (methane concentrations were below 1780 ppb for several years at the turn of the 20th century), atmospheric CH_4 concentrations rose again around 2007. According to data published by the US National Oceanic and Atmospheric Administration (NOAA) [23], there is more and more methane in the atmosphere. Only a few hundred years ago, the background concentration of methane (CH_4) in the Earth's atmosphere was around 700 ppb (parts per billion), and in 1920, it was still below 1000 ppb [22]. On a global scale, the increasing trends in methane emissions over the last few years are a cause for concern [15]. In recent years, methane production has increased most sharply in Africa and the Middle East; China; and South Asia and Oceania. Each of these three regions emitted 10–15 million tonnes more methane per year between 2000 and 2017. They were immediately followed by the United States, which emitted about 4.5 million tonnes more methane each year [16]. In 2021 (after the pandemic), methane concentrations reached a record high of 1889 ppb (parts per billion)—11 ppb more than the year before [24,25]. According to the NOAA report, methane concentrations in September 2022 were 1915.44 ppb and in September 2023, 1927.35 ppb [14]. The NOAA website provides a table (Table 1 in our article) with the annual increase in globally averaged atmospheric methane.

Table 1. Annual increase in globally averaged atmospheric methane [16].

Year	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Growth (ppb)	12.87	12.20	12.89	11.43	10.68	11.20	8.66	14.07	2.39	3.87
Uncertainty (ppb)	0.84	0.84	0.72	0.73	0.47	0.57	0.49	0.56	0.47	0.63
Year	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Growth (ppb)	7.24	3.83	2.48	6.36	12.12	2.38	−1.45	−0.72	3.24	4.84
Uncertainty (ppb)	0.62	0.52	0.42	0.69	0.64	0.61	0.53	0.45	0.56	0.60
Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Growth (ppb)	−4.84	0.32	1.91	7.85	6.51	4.71	5.21	4.92	4.98	5.64
Uncertainty (ppb)	0.42	0.43	0.51	0.64	0.44	0.56	0.70	0.59	0.46	0.57
Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	
Growth (ppb)	12.78	10.00	7.03	6.88	8.76	9.67	15.13	17.98	13.22	
Uncertainty (ppb)	0.43	0.72	0.64	0.75	0.62	0.65	0.45	0.45	0.77	

Source: [16].

Additional information on Table 1: The Global Monitoring Division of NOAA's Earth System Research Laboratory has measured methane since 1983 at a globally distributed network of air sampling sites [26]. A global average is constructed by first smoothing the data for each site as a function of time, and then, smoothed values for each site are plotted as a function of latitude for 48 equal time steps per year. Global means are calculated from the latitude plot at each time step [27].

High atmospheric methane concentrations pose a very serious threat to global efforts to keep warming below 1.5–2 °C. The global warming impact of 1 tonne of atmospheric methane over a 20-year horizon is comparable to the footprint of more than 80 tonnes of CO_2. Methane is also responsible for at least 25% of the increase in the Earth's temperature since the beginning of the industrial revolution [28–30].

Approximately 60 per cent of global methane emissions are anthropogenic, the largest sources of which, based on estimates, are fossil fuel production and use (one-quarter to one-third); waste (about one-quarter); and agriculture (about half of total methane emissions), particularly agriculture associated with intensive production [31]. According to IEA data [16], the source structure of methane emissions in 2021 was as follows: (1) natural from wetlands (more than 190 Mt methane/contents), (2) agriculture (about 140 Mt) (3) energy (about 135 Mt including oil, gas, coal), (4) waste (73 Mt), (5) other (about 40 MT), and (6) biomass burning (less than 10 Mt).

The rapid increase in atmospheric methane concentrations in recent years has worried the world, and the problem of methane was put on the agenda of the COP26 summit. The Global Methane Pledge is a multi-country pact to reduce methane emissions by 30% by 2030 from 2020 levels. Over 100 countries (representing 50% of anthropogenic methane emissions) recently signed up for the Global Methane Pledge (globalmethanepledge.org), and there is extensive potential for mitigation [32–34]. These countries agree that moves towards decarbonization must (should) run in parallel with moves towards de-methanization. The term 'de-methanization' may not yet be as popular as decarbonization, but it too will accelerate in the coming years. The Intergovernmental Panel on Climate Change (IPCC) notes that in order for the world to meet the global goal of limiting temperature increase by 1.5 °C (or even 2 °C) by 2050, there must be sharp reductions in methane emissions by 2030 [35]. In September 2021, the European Union and the United States announced the Global Methane Commitment, which is a political commitment to reduce global methane emissions in all methane-emitting sectors by at least 30% (relative to 2020 levels) by 2030, at the United Nations Climate Change Conference (COP 26) in Glasgow in November 2021. The Global Methane Commitment includes a move towards the use of the best available inventory methods to quantify methane emissions with a focus on high emission sources. The International Panel (IPCC) recommends reducing its emissions as one of the best ways to tackle global warming in the coming years. Methane (CH_4) emissions not only are a factor in global warming but also negatively affect human health—particularly respiratory diseases. Methane also contributes to the formation of ozone, which is a potent air pollutant. Methane is an important precursor of tropospheric ozone production and is responsible for 50% of the increase in tropospheric ozone levels [36]. Ozone is not only a greenhouse gas but also a major component of photochemical smog (UNEP, 2011) [37]. It contributes to one million premature deaths from respiratory diseases worldwide each year [37,38]. The role of methane as a lever to achieve climate goals is an active topic [25–27,33,39].

Reducing atmospheric emissions of methane is a priority strategic direction today, all the more so because predictions for atmospheric emissions of this gas are poor. Allen et al. [40] showed that by 2050, global average atmospheric methane concentrations will decrease by 26%, resulting in a 9.7% decrease in surface ozone concentrations and a 0.39 ± 0.05 K decrease in temperature compared to SSP3-7.0. Shindell et al. [32] examined a 30% reduction in methane concentrations from a specific day to present day (2015) using an ensemble of models. They attributed a global, population-weighted decrease in ozone exposure of 2–2.5 ppb and a temperature decrease of 0.18 ± 0.02 K to the methane change.

However, a global policy to reduce methane emissions must take into account the specificities of methane emissions in different countries. Poland, which is the subject of the research in this article, is a country where more than 90% of harmful methane emissions come from coal mines [41].

When analyzing the structure of methane emission sources in Poland and the EU, it can be seen that in Poland, the main emitters of methane are mines. So much of Poland's methane emissions come from coal mining, much higher in relation to the European Union as a whole, where the share of emissions from fossil fuel extraction is 38% [29]. Ember (2020) points out that in Poland, about 70% of methane emissions comes from the mining industry (hard coal, oil, and gas mining) [28,29]. In the total makeup of greenhouse gases in Poland, the share of methane is 10.7% [19].

After the pandemic (2021), Polish coal mines emitted more than 420,000 tonnes of methane, 28% more than a decade ago. Between 2013 and 2021, methane emissions from active coal mines in Poland remained stable at 450,000–525,000 tonnes per year [29]. Despite the fact that between 2010 and 2022, the amount of annual hard coal production in Poland fell by more than 20 million tonnes, or 28%, methane emissions increased by 26% over the same period—to 426,000 tonnes in 2021 [29]. This situation is due to the fact that, despite the steady decline in hard coal mining in Poland, coking coal mining has remained stable—around 12 million tonnes. In 2021, coking coal extraction in Poland amounted to 12.6 million tonnes and accounted for 23% of total hard coal extraction in that year [19]. As coking coal is a critical raw material of the European Union from 2020 (European Commission), restrictions on methane emissions from these deposits have not been planned. However, work is currently underway in Poland to detail how methane emissions are reported. The problem lies in a good estimation of how much methane there is per 1 tonne of thermal coal mined and how much per 1 tonne of coking coal. In Poland, it is assumed that more than 60% of methane emissions come from mines, with both thermal and coking coal in their deposits. At the same time, the attribution of methane emissions to the extraction of a specific type of coal is important because of the new requirements set out in the EU policy on methane emission reduction. However, as these provide the methane emission charges for 2027 only from mined thermal coal, this lack of differentiation makes it impossible today to assess the impact of the regulation as a whole. An important aspect of the new regulation is that emissions will be billed per operator (coal company) and not per mine. However, it will still be difficult to account for methane emissions accurately. There is a gap in Poland at the level of conscious state policy to reduce methane emissions. The social and environmental costs of methane emissions are not reflected either in the Polish environmental fee system or in the EU ETS emissions pricing mechanism. The environmental fee in Poland in 2023 was only 34 gr per tonne of methane emissions and was only revalued in line with inflation [29]. The government program on ending the exploitation of the most emitting coal deposits is therefore of key importance for reducing methane emissions from Polish mines. This is due to the fact that Poland has committed to reducing its emissions by 30% by 2030, as part of the Global Methane Pledge. It is assumed that as part of the planned transformation process in the Silesian Voivodship in Poland, further mines will be liquidated by 2030. By 2030, hard coal production will fall by 7.1 million tonnes per year—from 30 million tonnes per year in 2021 to 23 million tonnes per year by 2030. The reduction in coal production will represent 62% of the planned national reduction in coal production by 2030 according to Polish policy (the government program KPEiK) and will contribute to a reduction in the share of coal in electricity generation [29,42,43]. The decommissioning of mines is also expected to contribute to the reduction in methane emissions into the atmosphere. However, the amount of methane per extraction level is important. The mines selected for decommissioning currently emit 62.4 million m^3/year of methane. The closure of more mines is planned for after 2030, and it will be gradual (up to 2049), which will translate into a reduction in hard coal production and, as a result, will additionally contribute to a decrease in the production of raw material and methane emissions (Table 2).

Table 2. Schedule of liquidation of thermal power plants and mines in Poland.

Type of Plants	Thermal Power Plant			Hard Coal Mines					Lignite Coal Mines
year	2030	2035	2036	to 2030	to 2035	to 2040	to 2045	to 2049	2036
number	3	1	1	2	2	4	2	4	21

Source: [44].

The release of gas from coal occurs not only in the process of mining but also during processing, during transportation or storage, as well as after mine closure. Methane escapes into the atmosphere from active underground coal mines in two different ways:

- Through de-methanation systems;
- Through ventilation shafts.

In Polish mining, the key sources of methane emissions from mines are unclear installations (35%), ventilation shafts (22%), and the methane from methane installations (43%) [19].

It is assumed that Polish mines will increasingly switch to a reserve-peak operation system during decommissioning periods (until 2049). However, this is not always possible due to the safety of plant operation and the requirements of mining and geological law. On the other hand, due to the destabilization 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. In 2018, the Program for the hard coal mining sector in Poland was adopted, which covers the period until 2030. The goal of the Program is to improve the situation of the hard coal mining sector and make efficient use of its resources. Implementation of the Program is monitored in annual cycles. In 2022, the Program was updated, taking into account the assumptions of PEP2040 [45] and the provisions of the Social Agreement on the Transformation of the Coal Mining Sector and Selected Transformation Processes of the Silesian Voivodeship, which set out the planned dates for coal mine shutdowns. As amended, the Program pursues an additional objective of equitable transformation, taking into account activities aimed at winding down the mining sector and mechanisms to support this process. According to the indications of the Program, the termination of thermal coal mining from hard coal mines should take place by 2049 [46,47].

Methane emissions into the atmosphere will continue to be a problem during the transition. To reduce these emissions, the emitter (mine) should use captured methane. It should also do this for its own energy economy. A solution is also to sell the methane on the open market [48]. Ways of managing methane-rich mine gases from mine de-methanation in Polish conditions are described in [49–51]. Currently, methane from many mines in Poland is lost due to release into the atmosphere. A second source of methane may also be mines that are no longer in operation. Preliminary analyses conducted by PIG-PIB have shown that it is inefficient to extract methane from the Lower Silesian Mining Basin, but it is possible to extract it from the recently abandoned deposits of the Upper Silesian Mining Basin, according to ongoing analyses. As part of the ongoing work, a method for its extraction has also been developed. Therefore, the capture of methane from closed mines can—and should—complement the national energy mix. The capture of methane from mines in Poland is, next to the decarbonization of steelworks, a key industrial problem in the radical climate policy [52,53]. In Poland, the extraction of methane from decommissioned coal mines has so far been marginal. It is carried out in only two deposits, and the annual volume of extraction is about 5 million cubic meters (data for 2020), which is 1 per mille of national gas extraction and about 1.7% of methane captured during coal mining [54]. It has been assumed that the most important criterion indicating the possibility of extracting methane from a discontinued deposit is the total amount of methane emissions (methane yield) recorded during coal mining [55,56]. In the case of closed mines, the amount of methane decreases from year to year. According to estimates by the Central Mining Institute, during the first year, the amount of methane emissions from a single longwall drops to less than 20% of the average methane yield of that longwall from the period of its operation [54]. After a few years, the amount of methane emitted is only a few percent of the initial volume of emissions, and after a dozen years (estimated to be about 15 years), emissions virtually disappear [54–56].

The process of capturing methane involves employing advanced technologies to trap and extract the gas before it is released into the atmosphere [57–59]. One method involves the installation of methane capture systems directly within coal mines. These systems utilize a combination of ventilation and gas extraction techniques to capture methane emissions at their source [60–63]. By implementing these technologies, coal mining operations can minimize their environmental impact and simultaneously harness methane as a valuable energy resource [64,65].

The captured methane can be utilized for various purposes, such as power generation or as a feedstock for industrial processes [66]. This not only reduces the reliance on traditional fossil fuels but also provides an economic incentive for coal mining companies to adopt methane capture technologies [67].

Also, capturing methane from coal mines aligns with global efforts to transition towards cleaner and more sustainable energy sources [68]. Governments, environmental organizations, and industries are increasingly recognizing the importance of reducing methane emissions to combat climate change. Implementing methane capture technologies in coal mines represents a tangible and effective step towards achieving these environmental goals [69–72].

In addition to environmental benefits, the reduction in methane emissions enhances safety within coal mines [73]. Methane is not only a potent greenhouse gas but also poses a significant explosion risk in underground coal mines. By capturing and utilizing methane, the likelihood of accidental releases leading to explosions is mitigated, promoting a safer working environment for miners [74].

In Table 3, there is a juxtaposition of the main advantages of using methane from coal mines.

Table 3. Advantages of using methane from coal mines.

Advantage	Description
Mitigation of Greenhouse Gas Emissions	Prevents its release into the atmosphere, reducing the greenhouse effect and mitigating climate change.
Utilization as a Clean Energy Source	Allows for its use in power generation or as a feedstock for industrial processes, contributing to cleaner energy production.
Economic Incentives for Coal Mining Companies	Provides an economic incentive for coal mining companies to adopt methane capture technologies by offering a valuable energy resource.
Alignment with Global Sustainability Goals	Supports international efforts to reduce methane emissions and the transition towards more sustainable and environmentally friendly practices.
Enhanced Safety in Coal Mines	Reduces the risk of methane-related explosions in underground coal mines, promoting a safer working environment for miners.
Responsible Resource Extraction and Management	Demonstrates a commitment to responsible mining practices by addressing environmental concerns associated with coal extraction.
Environmental Stewardship	Contributes to environmental conservation by preventing the release of methane, a potent greenhouse gas, into the atmosphere.
Reduction in Carbon Footprint	Significantly lowers the carbon footprint of coal mining operations, aligning with global efforts to combat climate change.
Renewable Energy Resource	Allows for it to serve as a renewable energy resource, reducing dependence on non-renewable fossil fuels for energy production.
Economic Diversification for Coal Industry	Offers economic diversification for the coal industry by turning methane emissions into a valuable energy commodity.
Green Energy Portfolio Enhancement	Enhances the green energy portfolio of coal mining companies, promoting a positive image and attracting environmentally conscious stakeholders.
Compliance with Environmental Regulations	Meets and exceeds regulatory requirements for reducing methane emissions, ensuring adherence to environmental standards.
Technological Innovation and Development	Drives the development and implementation of advanced technologies for methane capture, fostering innovation within the mining industry.
Global Leadership in Sustainable Practices	Positions coal mining companies as leaders in sustainable practices, contributing to a positive reputation within the global market.
Community Relations and Social Responsibility	Demonstrates social responsibility by addressing environmental concerns, improving community relations, and fostering a positive relationship with local stakeholders.
Long-term Viability of Coal Industry	Enhances the long-term viability of the coal industry by integrating environmentally friendly practices, adapting to changing energy trends.

Source: Authors own work based on [54–57,68,70–85].

Capturing methane from coal mines, while offering significant environmental benefits, is not without its challenges. One prominent issue is the substantial initial investment costs associated with the installation of methane capture systems [86]. Coal mining operations face financial constraints when implementing these technologies, hindering widespread adoption. To address this, governments can play a pivotal role by providing financial incentives and subsidies, thereby alleviating the financial burden and making methane capture more economically feasible for mining companies [87].

Operational and maintenance expenses pose an ongoing challenge for coal mining operations that have implemented methane capture systems. The sustained operation of these systems requires consistent financial resources, necessitating long-term financial planning to manage these costs effectively. Without proper planning, the economic viability of methane capture projects may be compromised over time [88]. Technological challenges further impede the successful implementation of methane capture initiatives. Developing and implementing effective capture technologies requires substantial research and development investment to overcome technical hurdles. Increased funding in this area can lead to the creation of more efficient and cost-effective methane capture technologies, fostering technological advancements within the mining industry [57,89].

The variability in methane emissions from coal mines presents another challenge. Designing capture systems that are consistently effective across different mining conditions proves to be a complex task. Adaptive system designs are essential in addressing this variability, ensuring the systems can adapt to the changing emission levels encountered in different mining scenarios [58,90,91]. Land use and infrastructure constraints can hinder the implementation of methane capture systems, often leading to resistance and logistical challenges. Government infrastructure support becomes crucial in overcoming these obstacles, facilitating the necessary modifications and ensuring a smoother integration of methane capture technologies into existing coal mining operations [92]. Collaboration through partnerships and funding initiatives with industry stakeholders, research institutions, and environmental organizations becomes essential to share the financial load and overcome resource competition [58,93]. Regulatory compliance and reporting burden can also impede progress. Simplifying and streamlining regulatory processes are necessary to reduce the administrative burden on coal mining companies, ensuring they can meet regulatory requirements for methane capture without undue strain [57].

Also, the perception of continued fossil fuel use and potential economic viability concerns in the short term may deter investment in methane capture projects. Integrating these projects with broader renewable energy initiatives can enhance their economic viability and contribute to a more sustainable energy portfolio, making them more appealing in the short term [57,58]. Public resistance and perception issues within local communities pose a final challenge. Proactive stakeholder engagement, clear communication about the benefits of methane capture, and addressing concerns are crucial in overcoming resistance and gaining community support for these projects [64,91,92].

In Table 4, there is an analysis of the main problems connected to using methane from coal mines.

Incentives and funding programs provided by the EU also play a role in encouraging the adoption of methane capture technologies. Financial support for research and development, as well as subsidies for companies investing in cleaner technologies, further facilitate the integration of methane capture systems in coal mining operations [57–59,88,91]. For good preparation of a strategy for methane management from Polish mines, a comprehensive analysis of the current status of emissions of this gas from mines is necessary. This article will present data analyses to illustrate the directions of activities in this field to date.

Table 4. Problems of using methane from coal mines.

Problem	Description	Methods of Overcoming
Initial Investment Costs	The installation of methane capture systems requires a substantial upfront investment, which can be a financial challenge for coal mining operations.	Government incentives and subsidies: governments can provide financial incentives and subsidies to alleviate the initial investment burden, making methane capture more economically viable for coal mining companies.
Operational and Maintenance Expenses	Ongoing operational and maintenance costs associated with maintaining methane capture systems may strain financial resources over time.	Long-term financial planning: implementing long-term financial planning can help coal mining companies manage operational and maintenance costs effectively, ensuring the sustained operation of methane capture systems.
Technological Challenges	Developing and implementing effective methane capture technologies can pose technical challenges, leading to delays and potential setbacks.	Research and development investment: increased investment in research and development can address technological challenges, fostering the development of more efficient and cost-effective methane capture technologies.
Variability in Methane Emissions	Methane emissions from coal mines can vary, making it challenging to design capture systems that are consistently effective across different conditions.	Adaptive system designs: designing methane capture systems with adaptability to varying emissions can enhance effectiveness across different mining conditions, ensuring a more consistent performance.
Land Use and Infrastructure Constraints	Implementing methane capture systems may require significant land use and infrastructure modifications, facing resistance and logistical challenges.	Government infrastructure support: government support for infrastructure modifications can facilitate the implementation of methane capture systems, addressing land use and infrastructure constraints.
Competition for Limited Resources	Coal mining companies may face competition for limited resources, diverting attention and funding away from methane capture initiatives.	Collaborative funding and partnerships: establishing partnerships and collaborative funding initiatives with industry stakeholders, research institutions, and environmental organizations can help share the financial load and overcome resource competition.
Regulatory Compliance and Reporting Burden	Meeting regulatory requirements for methane capture may impose additional administrative burdens, leading to compliance challenges.	Streamlined regulatory processes: simplifying and streamlining regulatory processes can reduce the administrative burden on coal mining companies, encouraging compliance with methane capture requirements.
Economic Viability in the Short Term	The economic viability of methane capture projects may be questioned in the short term, potentially hindering widespread adoption.	Integration with renewable energy initiatives: integrating methane capture projects with broader renewable energy initiatives can enhance the economic viability and contribute to a more sustainable energy portfolio, making them more attractive in the short term.
Perception of Continued Fossil Fuel Use	Critics argue that investing in methane capture may perpetuate the use of fossil fuels, diverting focus from renewable energy alternatives.	Public awareness campaigns and education: conducting public awareness campaigns and education initiatives can address misconceptions, emphasizing the transitional nature of methane capture and its contribution to cleaner fossil fuel use.
Public Resistance and Perception Issues	Local communities and the public may resist methane capture projects due to concerns about safety, aesthetics, or perceptions of environmental impact.	Stakeholder engagement and communication: proactive engagement with local communities, clear communication about the benefits, and addressing concerns can help overcome resistance and gain community support for methane capture projects.

Source: Authors own work based on [57–64,69,86–92].

3. Study Method

It should be noted that the nature of this analysis is primarily a review. However, based on an analysis of the historical data over a period of more than 20 years, hypotheses can be formulated to show that limiting methane emissions from Polish thermal coal mines is not a straightforward subject and the solutions proposed so far are not unambiguous. Its aim is to analyze the data on methane production levels and the use of methane released from Polish hard coal mines for the years 2008–2022 from the perspective of building a decarbonization strategy for the Polish mining industry. Therefore, the authors would like to draw attention to the strategic position of this gas within the policy of decarbonization and diversification of market offerings. The management of methane from existing and closed hard coal mines in Poland should be one of the goals of strategic plans for mining companies, especially in relation to EU policy and accounting for emissions of this greenhouse gas. Therefore, the authors chose a three-area strategic analysis as the method [92]. The strategic analysis [94,95] was conducted for three areas, i.e., the interior of Polish hard coal mines, the close environment, and the macro environment (Figure 1).

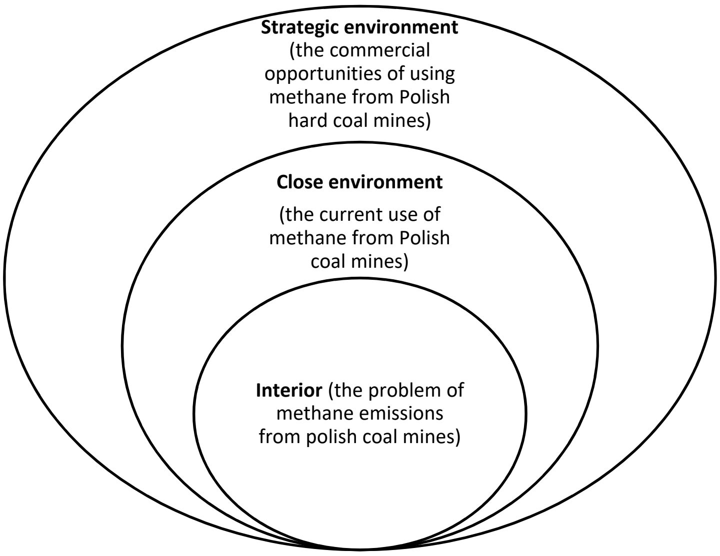

Figure 1. Methodology—three-area strategic analysis of the use of methane from coal mines in Poland. Source: individual study.

The research hypotheses (RH) were formulated on the basis of the source data and literature research conducted:

RH_1. *Reducing the volume of extraction does not significantly reduce methane emissions per tonne of thermal coal.*

RH_2. *The level of methane capture from hard coal mines is still dictated in particular by safety considerations and is not adapted to EU climate legislation.*

RH_3. *Capturing methane from Polish coal mines should be a long-term goal in the development and innovation strategies of these companies.*

The three-area strategic analysis applied allows the problem of methane emissions from Polish coal mines to be looked at from different points of view and to prove or deny the hypotheses assumed.

The interior of hard coal mines in Poland was analyzed to understand the problem of methane emissions from coal mines. The situation in the close environment was analyzed to understand the methods used to utilize methane from actively decommissioned coal mines. Then, from a strategy-building perspective (third level), the possible methods to improve methane management in response to the Regulation of the European Parliament and of the Council on the reduction in methane emissions in the energy sector and amending Regulation (EU) 2019/94 were discussed.

A set of official data published annually by the State Mining Authority in Katowice (WUG) was selected for the analysis. The division into methane emissions from thermal and coking coals is difficult, as it is still captured on an estimated basis. As mentioned in Section 2, it can be assumed that it accounts for 60% of all emitted gas. To simplify the analysis, we decided to assume that the trends and proportionality of the captures remain the same for methane from thermal coal deposits as for mining as a whole. For the purpose of inference in the applied strategic analysis, such an approach will make it possible to show the trends of change and to determine the current state of methane management from Polish mines. The results of the analyses are presented in graphical form. According to the authors, the use of complex statistical analyses not only is unnecessary but also would not contribute anything to the inference process. After analyzing the preliminary database from WUG, it was decided that the time period adopted would not be the whole of 2008–2022, but primarily 2014–2022. The justification and presentation of the results are included in next section.

4. Results of the Analysis

4.1. The Problem of Methane Emissions from Coal Mines in Poland

As is well known, the fuel–energy situation in the world is difficult, especially due to the war in Ukraine, the post COVID-19 situation, and the turbulence on fuel markets. At the same time, the European Union's climate policy is very demanding, strongly one-sided, and costly for many economies. This is due to legal regulations and financial burdens (e.g., EU ETS). The Polish hard coal mining industry not only faces quality and price requirements in relation to the needs of the Polish energy sector but also, as an emitter of the greenhouse gas methane, is subject to the rules of the EU climate policy in its assumptions of zero emissions by 2025. The amount of methane emitted from the Polish coal mines is mainly due to the characteristics of Polish deposits and the mining method used in Polish mines. Thus, the question of the analysis was as follows:

QR: *Does limiting the amount of hard coal mining have a direct impact on the amount of methane emissions into the air?*

From the point of view of emission charges, it is not so much the volume of thermal coal extraction that is important, but the amount of methane per 1 tonne of extraction. Coking coal, which is on the EU's list of critical raw materials, is not affected by the restrictions at this point.

Figure 2, based on data obtained from the WUG, presents the quantity of absolute methane emissions from 2008 to 2022, and is followed by Figure 3, which presents the variation in coal extraction to absolute methane emissions from 2008 to 2022.

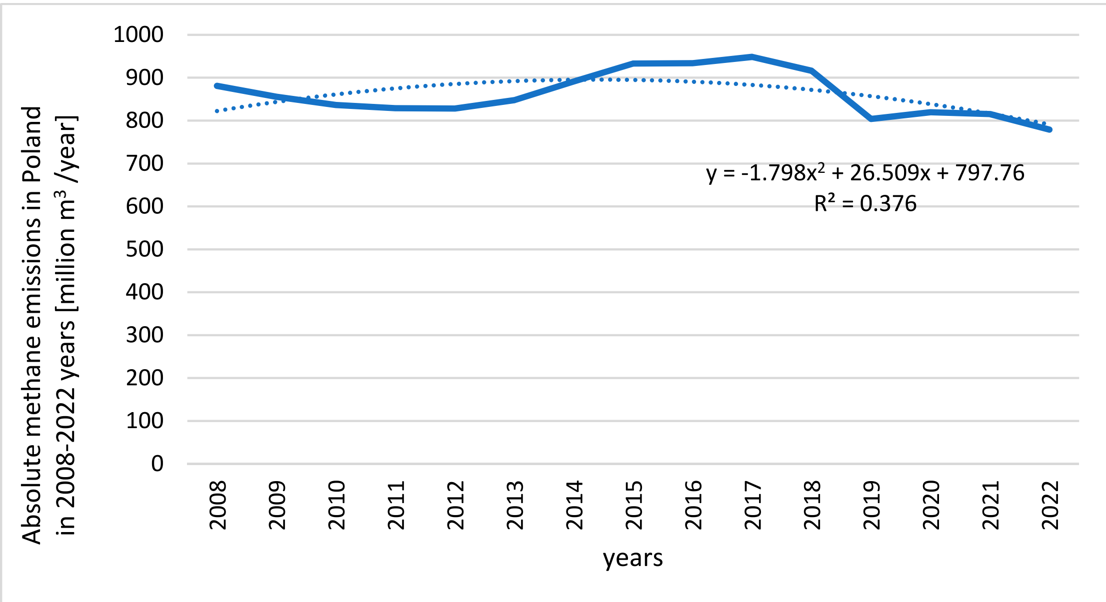

Figure 2. Absolute methane emissions in Poland in the years 2008–2022 [million m^3/year]. Source: individual study based on the data of WUG.

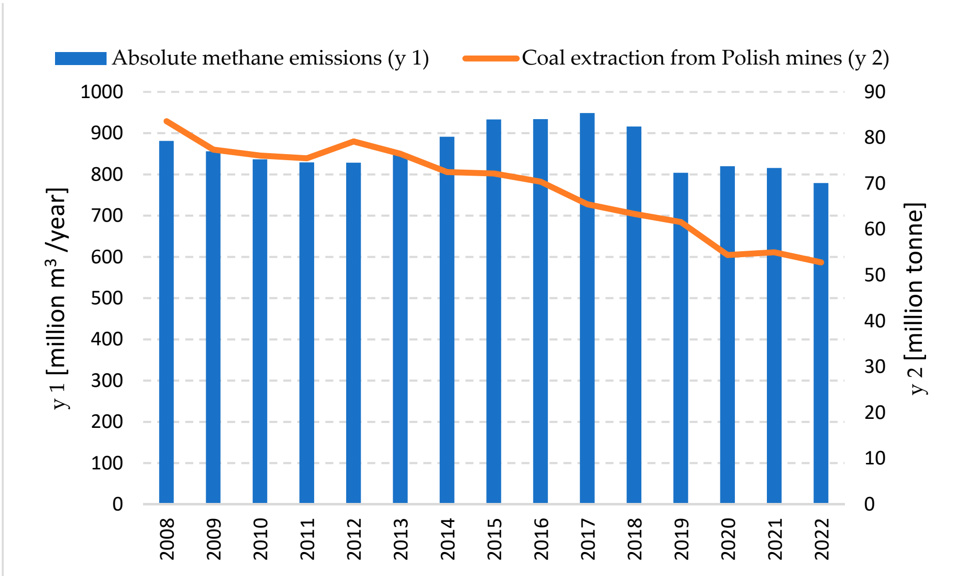

Figure 3. Variability in coal extraction volumes to absolute methane emissions in Poland in the years 2008–2022. Source: individual study based on the data of WUG.

As can be observed, the volume of absolute methane emissions in the years 2008–2022 is slightly decreasing. Coefficient m, the slope as a function of trend, is negative (Formula (1)):

$$y = -1.798x^2 + 26.509x + 797.76, \tag{1}$$

However, when analyzing this development against the background of extraction volumes for the period in the years 2008–2022 (Figure 3), it can be seen that hard coal extraction volumes in Poland are gradually declining, with absolute methane emissions continuing to oscillate between 778.9 [million m^3/year] in 2022 and 948.5 [million m^3/year] in 2017.

The analysis of the quantity of methane captured between 2008 and 2022 is presented in Figure 4.

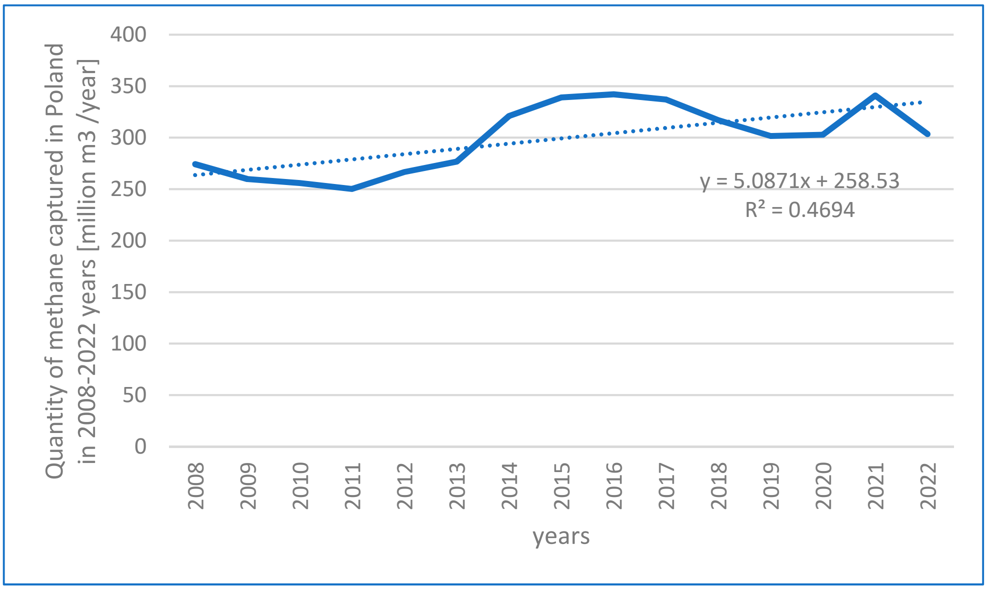

Figure 4. Quantity of methane captured in Poland in the years 2008–2022 [million m^3/year]. Source: individual study based on the data of WUG.

The trend for the quantity of methane captured between 2008 and 2022 was determined using Excel spreadsheet tools and has the form of (2):

$$y = 5.0871x + 258.53 \tag{2}$$

Analysing the available data from the WUG, it was noted that the cut-off year for further analysis should be 2014 (Figure 5). When we narrowed the scope of the assessment of the quantity of methane captured to the years 2014–2022, the trend function changed its characteristics and had the form of (3):

$$y = -2.9717x + 337.63 \tag{3}$$

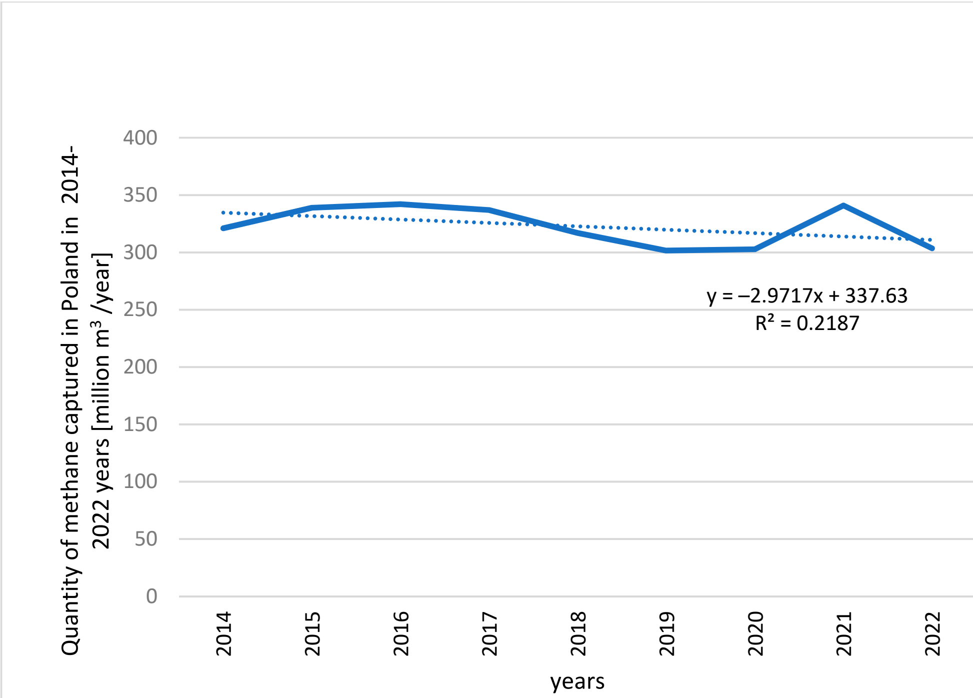

Figure 5. Quantity of methane captured in Poland in the years 2014–2022 [million m^3/year]. Source: individual study based on the data of WUG.

The slope m indicator thus changed to a negative sign. This means that, in the long term, it can be said that the amount of methane captured will increase. Unfortunately, this is most likely due to several factors: the number of mines working; the amount of coal extraction; and, above all, the level of methane in the exploited deposits. Since 2014, we have seen a relatively stabilized situation. Although m has a negative sign and unfortunately worsens our methane capture results, looking at the characteristics of the curve in Figure 5, it can be cautiously concluded that the level of methane capture from Polish coal mines is at a fairly stable level and is over 300 [million m^3/year]. Until 2013, the level was below this value.

As can be concluded from Figure 6, there is no clear correlation between coal extraction volumes and the quantity of methane captured. This finding is important for building a future methane management strategy in line with the EU climate policy.

When analyzing the level of de-methanation resulting from the absolute value of methane and the quantity of methane captured, first, the range of years 2008–2022 was analyzed (Figure 7). The analysis period was then shortened to the years from 2014 to 2022 (Figure 8). In both cases, slight upward trends of $m_1 = 0.7046$ and $m_2 = 0.5150$ were observed. However, taking into account the previous analyses, it has to be said that such a result does not allow for the formulation of the conclusion that the level of methane capture from Polish mines is improving. Thus, improvements to these results are ongoing and are the subject of much research work.

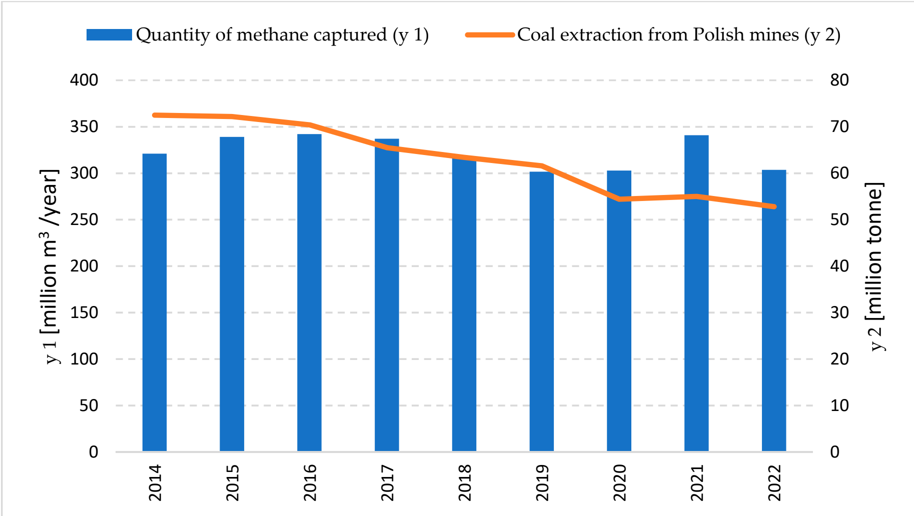

Figure 6. Variability in coal extraction volumes to quantity of methane captured in Poland in the years 2014–2022. Source: individual study based on the data of WUG.

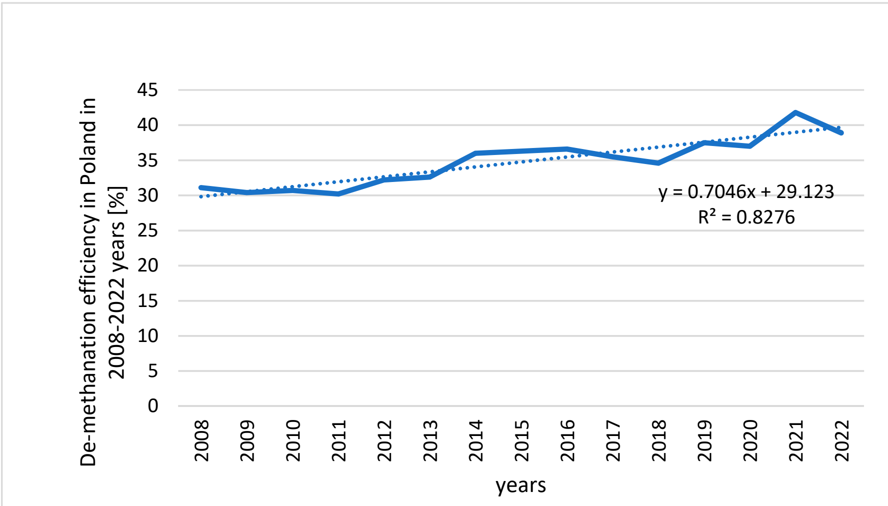

Figure 7. De-methanation efficiency in Poland in the years 2008–2022 [%]. Source: individual study based on the data of WUG.

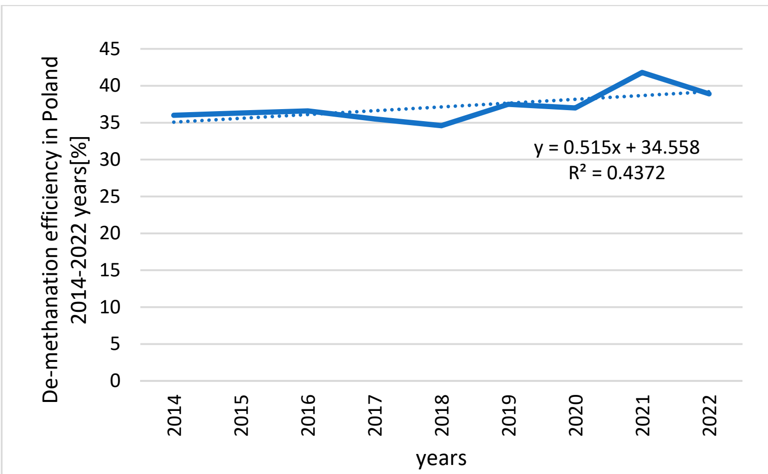

Figure 8. De-methanation efficiency in Poland the years 2014–2022 [%]. Source: individual study based on the data of WUG.

4.2. The Current Use of Methane from Coal Mines in Poland

Currently, the extraction of methane from mines is driven by safety regulations. However, as a result of changes in regulations resulting from the implementation of the Green Deal, methane must be looked at as an additional product from mines. Therefore, research is being conducted on extracting methane from mine air or mine de-methanation systems. Figure 9 presents the variation in the amount of use of captured methane in the Polish coal mines for absolute methane. As before, only data from 2014–2022 were analyzed. Currently, only about 25% of the methane emitted from Polish mines is used and this trend has no significant increase, m = 0.0053 (Figure 10). This situation requires decisive action on the part of mining companies if they are to prepare for the implementation of the EU climate policy.

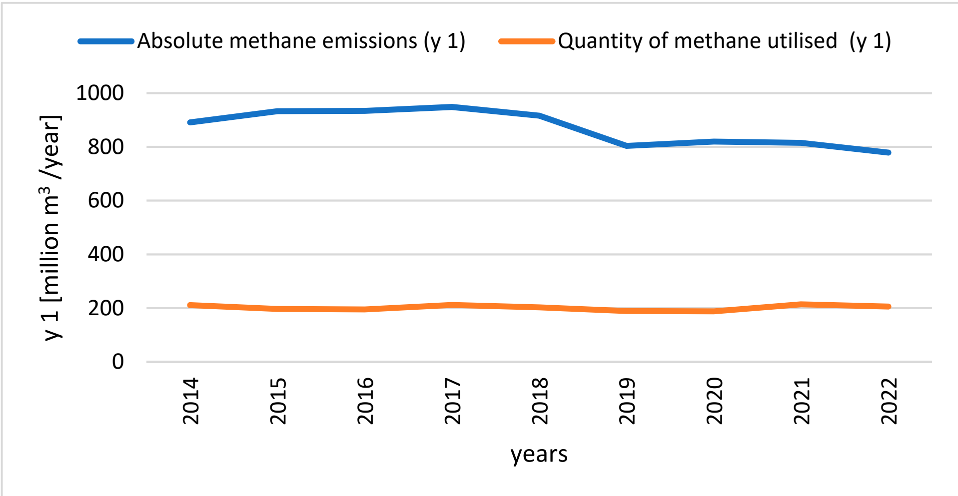

Figure 9. Absolute methane emissions and quantity of methane utilized in Poland in the years 2014–2022 [million m^3/year]. Source: individual study based on the data of WUG.

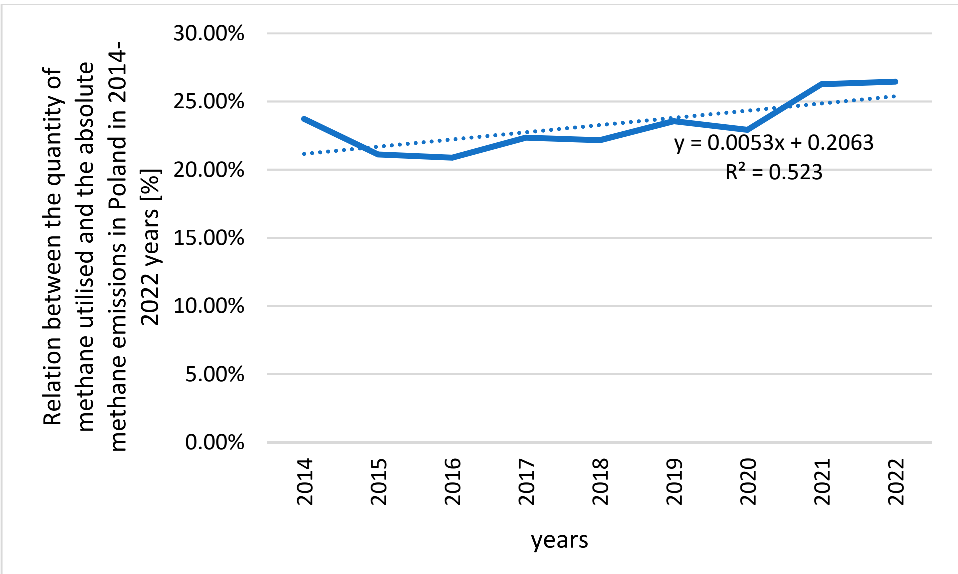

Figure 10. Relation between utilized and absolute methane emissions in Poland in the years 2014–2022 [%]. Source: individual study based on the data of WUG.

Officially, the efficiency of captured methane utilization is determined for reporting reasons (Figure 11), but this value is determined only from the value of captured methane and the level of its utilization. According to the authors, it is more appropriate to consider the efficiency of captured methane utilization to the value of absolute methane in terms of the tasks of the decarbonization policy of the Polish energy industry.

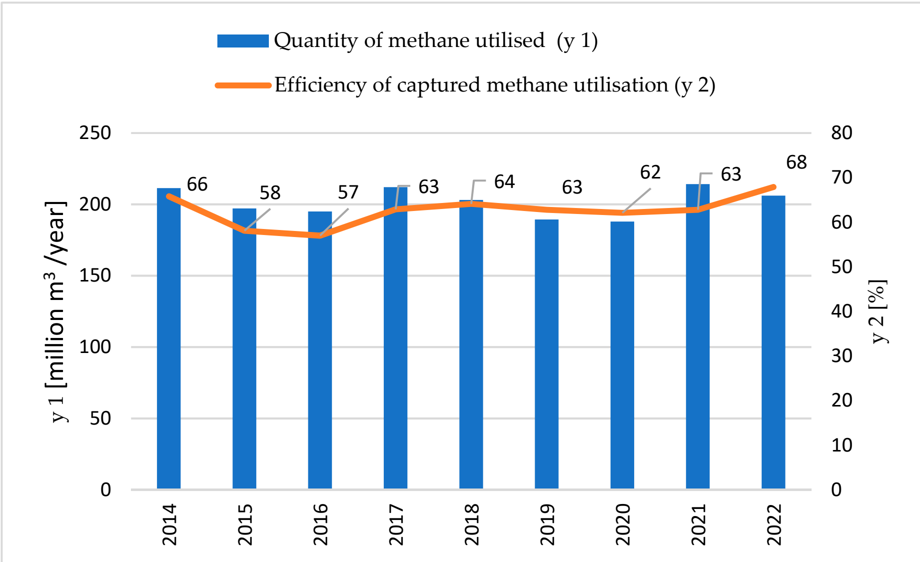

Figure 11. Variability in quantity of methane utilized and efficiency of captured methane utilization based the Polish database. Source: individual study based on the data of WUG.

The authors of this paper (analysis) compared the absolute methane emissions to the number of active longwalls (Figure 12). Although the Pearson correlation coefficient for these data was r = 0.761, it cannot be assumed that a reduction in the number of active longwalls will lead to a reduction in methane emissions in Polish mines.

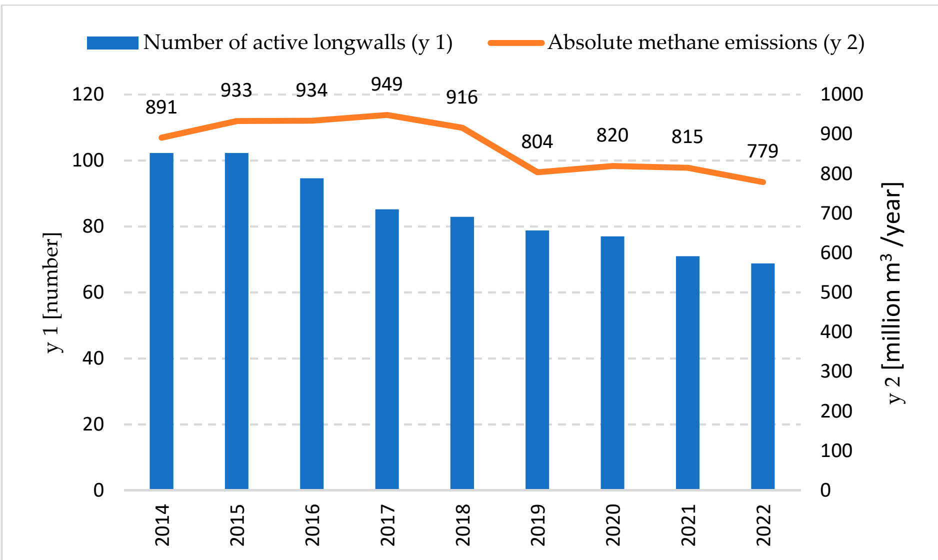

Figure 12. Variability in absolute methane emissions to number of active longwalls based on the Polish database. Source: individual study based on the data of WUG.

Analyzing the relative methane emissions first from 2008 to 2022 and then from 2014 to 2022, it was noted that the trend of this value is unchanged (m_1 = 0.3564 and m_2 = 0.2933)—Figures 13 and 14. Unfortunately, it is upward. This is not a good result in the context of per-tonne charges for methane emissions from Polish mines. The increase in relative methane emissions is due to mining at increasing depths and entering new seams with higher methane contents.

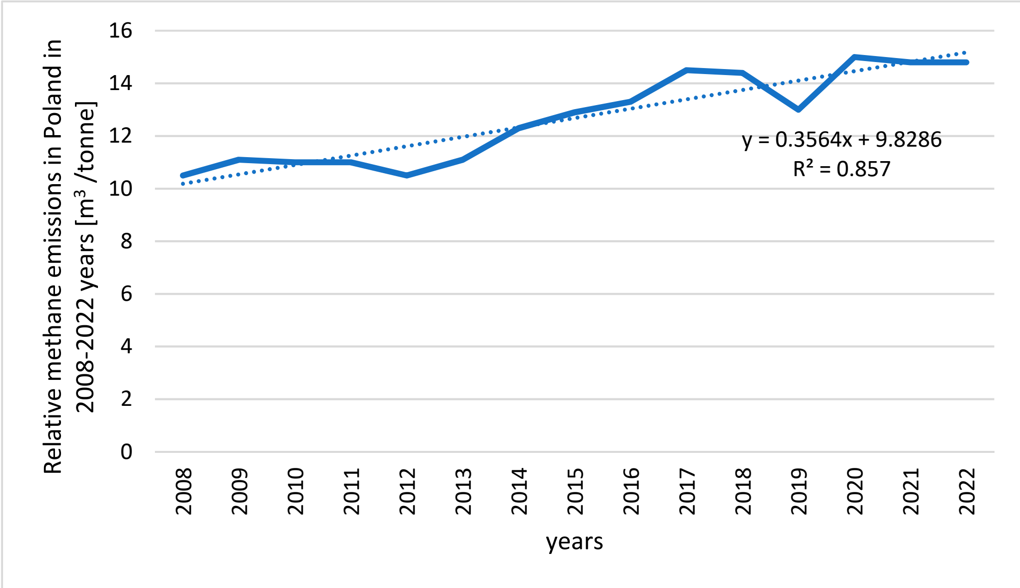

Figure 13. Relative methane emissions in Poland in the years 2008–2022 [m^3/tonne]. Source: individual study based on the data of WUG.

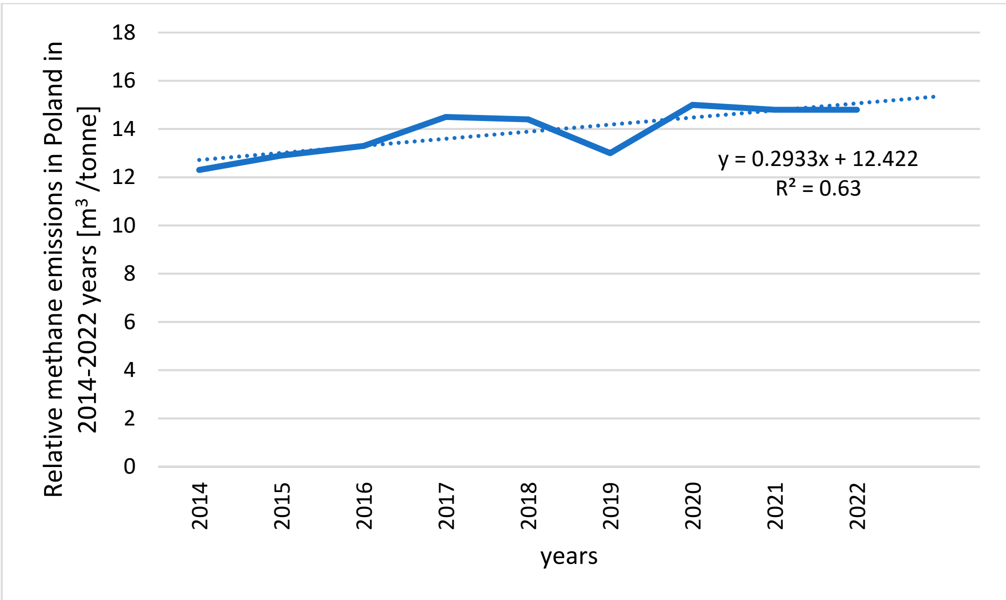

Figure 14. Relative methane emissions in Poland in the years 2014–2022 [m^3/tonne]. Source: individual study based on the data of WUG.

Therefore, the large reserves of coal bed methane in active and decommissioned Polish mines represent an economic and environmental opportunity for mining companies. This opportunity should be exploited through appropriate investment and state policies supporting the development of energy installations based on extracted methane. Unfortunately, a prerequisite for this is the development of investments in more efficient extraction of methane from ventilation air and de-methanation installations.

4.3. Commercial Opportunities of Using Methane from Polish Hard Coal Mines

JSW SA is already taking a number of measures to build a climate-friendly enterprise. Since 2018, the Budryk Mine has been implementing a 300 million project entitled Economic Use of Methane. It aims to reduce its carbon footprint and obtain energy for its own needs. As part of these measures, the installation of further de-methanisation gas engines at the

Budryk and Knurów-Szczygłowice mines continued in 2020, which, when completed, will reduce methane emissions by a total of approximately 1.3 million Mg CO_2 e.

Unfortunately, as demonstrated earlier, the efficiency of de-methanation is low. Therefore, mine de-methanation technologies need to be modernized. Modern drilling rigs that enable long and directional drilling must be introduced. It should be noted here that the nature of methane fixation in Polish deposits makes it difficult to apply solutions from other countries. The methane in Polish deposits is basically released only when the head is excavated. Therefore, de-methanation technologies dedicated to Polish deposits should be applied. The purpose of methane extraction also needs to be looked at differently. Currently, de-methanation is carried out to ensure the safety of coal mining, and not for energy, environmental, or economic purposes.

Mine de-methanation gas is mainly a mixture of air and methane with a concentration of 30% to 75% and a calorific value of 15 MJ/kg to 37.5 MJ/kg. The efficiency of methane utilization could be increased by building surface and underground reservoirs. This would improve the situation resulting from uneven methane capture during de-methanation.

Investing in the construction of gas engines will not only allow the extraction of own energy, but the heat from the flue gas and cooling can also be used for municipal purposes. If investments are made in the construction of switchgear and electrical grids to enable power to be taken out of the mine, electricity would become a new product of the mining company.

The second issue is the use of methane from mine air released into the atmosphere. Methane concentrations discharged through mine exhaust shafts are low and variable over time, ranging from 0.00% to 0.50–0.3% on average.

Depending on the density of methane in the mine air (VAM—Ventilation Air Methane), it can

- Be added (auxiliary) to power plants where the high combustion temperature is provided by another primary fuel;
- Be used in installations where VAM is the primary, or even the only, fuel [96,97].

Currently, in the literature on VAM utilization, most attention is paid to reversible reactors. Noteworthy is the innovative method developed by a team of scientists from the Institute of Chemical Engineering of the Polish Academy of Sciences in Gliwice for the utilization of methane from the ventilation air of coal mines. The TFRR (Thermal Flow Reversal Reactor) technology developed by the team does not generate toxic gases such as nitrogen oxides or carbon monoxide [53]. Under EU regulations, thermal coal mines will have to use such solutions.

The third issue is the extraction of methane from decommissioned mines. The GZW area is by far the most promising in terms of extracting methane. Several licenses have already been granted for the exploration, prospecting, and exploitation of methane from coal seams. An example of how this is already being applied is the use of methane from the "Morcinek" deposit.

5. Discussion

The analysis presented in this paper provides valuable insights into the challenges and opportunities associated with capturing methane from coal mines, particularly in the context of the European Union's (EU) climate policy objectives. One of the key findings is the substantial initial investment required for methane capture systems in coal mining operations. This paper suggests that government incentives and subsidies can play a crucial role in alleviating this financial burden, making methane capture economically viable for mining companies.

Operational and maintenance expenses are identified as ongoing challenges, requiring long-term financial planning for effective management. Additionally, this paper highlights the significance of addressing technological challenges through increased research and development investment to create more efficient and cost-effective methane capture technologies.

The variability in methane emissions from coal mines is acknowledged, emphasizing the need for adaptive system designs to ensure consistent effectiveness across different mining conditions [57,58]. Furthermore, land use and infrastructure constraints are identified as impediments, necessitating government infrastructure support for smoother integration of methane capture technologies [59].

Resource competition among coal mining companies and regulatory compliance burdens are discussed as potential obstacles, with collaboration and streamlined regulatory processes proposed as solutions [65]. This paper also emphasizes the importance of integrating methane capture projects with broader renewable energy initiatives for enhanced economic viability.

The study method involved a three-area strategic analysis, covering the interior of Polish hard coal mines, the close environment, and the macro environment. The results of the analysis indicate a gradual decline in absolute methane emissions from 2008 to 2022, despite varying coal extraction volumes. The quantity of methane captured has shown a positive trend, reaching a relatively stable level of over 300 million m^3/year since 2014.

The efficiency of methane capture, represented by de-methanation efficiency, exhibits a slight upward trend, indicating potential improvements. However, this paper notes that ongoing research is necessary to enhance these results further.

The current use of methane from the Polish coal mines is primarily driven by safety regulations, with about 25% of emitted methane utilized. The efficiency of methane utilization remains relatively constant, highlighting the need for more decisive actions to align with EU climate policy objectives.

The commercial opportunities of using methane from Polish hard coal mines are discussed, with JSW SA cited as an example of taking measures to build a climate-friendly enterprise. This paper suggests modernizing mine de-methanation technologies, introducing efficient drilling rigs, and exploring surface and underground reservoirs to increase methane utilization.

Improving methane utilization requires a multifaceted approach encompassing technological innovation, regulatory support, and strategic investment [98]. Enhancing the efficiency of de-methanation technologies is paramount. This could involve modernizing existing methods and introducing innovative techniques tailored to the unique characteristics of Polish coal deposits. Additionally, investing in advanced drilling rigs capable of long and directional drilling can facilitate more effective methane extraction [99]. Surface and underground reservoirs should be explored to optimize methane storage and distribution, ensuring consistent utilization [100].

There is a need to reframe the purpose of methane extraction from a safety-driven measure to an energy and environmental opportunity. This shift in perspective can incentivize mining companies to invest in methane capture systems and prioritize methane utilization [101]. Government incentives and subsidies can play a crucial role in making methane capture economically viable for mining operations. Also, expanding the infrastructure for methane utilization is essential [102]. This includes the construction of gas engines and electrical grids within mines to harness methane for energy production. Heat generated from flue gas and cooling processes can be repurposed for municipal use, contributing to energy efficiency and reducing environmental impact [103].

Innovative approaches to utilizing methane from mine air, such as reversible reactors or thermal flow reversal reactor technology, should be explored [104]. These solutions offer environmentally friendly alternatives while complying with EU regulations. It should be mentioned that fostering collaboration between stakeholders, including mining companies, government agencies, research institutions, and the private sector, is crucial [105,106]. By working together, these entities can pool resources, share expertise, and drive innovation in methane utilization. This collaborative effort is essential for realizing the economic and environmental potential of methane from Polish coal mines [101–104,107].

The findings of this paper shed light on the multifaceted challenges and potential avenues for mitigating methane emissions from coal mines, with a particular emphasis on the European Union's climate policy objectives [8–11,91,92]. The identified issues align with existing theoretical frameworks related to environmental sustainability, technology adoption, and policy implementation.

This paper underscores the substantial initial investment costs associated with methane capture systems in coal mining operations. This financial hurdle resonates with economic theories highlighting barriers to the adoption of environmentally friendly technologies [61]. The proposed solution involving government incentives and subsidies draws from theories of policy intervention to address market failures, promoting the adoption of sustainable practices.

Operational and maintenance expenses, recognized as ongoing challenges, reflect the importance of long-term financial planning. This aligns with theories emphasizing the need for businesses to incorporate environmental considerations into their strategic planning for sustainable operations [14,108,109]. The suggestion of increased research and development investment to tackle technological challenges resonates with innovation theories, acknowledging the role of technology in overcoming barriers to sustainable practices.

The acknowledgement of variability in methane emissions from coal mines underscores the complexities of designing effective capture systems. The proposed adaptive system designs align with ecological theories emphasizing the importance of resilience and adaptability in addressing environmental challenges [93,110]. Additionally, this paper's emphasis on government infrastructure support reflects the theories related to the role of institutions in facilitating sustainable practices.

Resource competition among coal mining companies, regulatory compliance burdens, and potential economic viability concerns are discussed in the context of broader environmental policies [81–95]. Collaborative funding initiatives and streamlined regulatory processes, proposed as solutions, draw from theories related to collaborative governance and policy design for sustainability. From the macro-economic level, this cooperation moves to the sectoral level, as mines are strongly linked to metallurgy, and methane can be used in metallurgy, heat, and energy management [111,112]. CO_2 emissions are a key negative aspect of steelworks in Poland, as more than 50% of steel is produced using high CO_2 emission technology [113,114].

This paper's discussion of integrating methane capture projects with broader renewable energy initiatives reflects a strategic approach grounded in theories of sustainability transitions [115,116]. This aligns with the recognition that a comprehensive shift toward cleaner energy requires the integration of various technologies and practices [117,118].

The analysis of absolute methane emissions, quantities of methane captured, and de-methanation efficiency trends provides empirical evidence supporting the theoretical frameworks discussed. The decline in absolute methane emissions, despite varying extraction volumes, aligns with theories of efficiency gains in resource use [119,120]. The positive trend in the quantity of methane captured, coupled with a relatively stable de-methanation efficiency since 2014, suggests ongoing efforts to improve methane capture technologies.

6. Conclusions

This paper provides a comprehensive analysis of the challenges, opportunities, and strategies associated with capturing methane from the Polish coal mines, with a focus on aligning with the European Union's climate policy. The identified challenges, ranging from initial investment costs to technological complexities and public perceptions, underscore the multifaceted nature of implementing methane capture initiatives in the coal mining industry.

This study emphasizes the critical role of government support, both in terms of financial incentives and streamlined regulatory processes, to alleviate the economic burden on coal mining companies and facilitate the integration of methane capture technologies. Collaboration through partnerships, funding initiatives, and stakeholder engagement emerges as a crucial approach to overcoming resource competition and ensuring the long-term success of methane capture projects.

The main scientific value of this paper lies in its comprehensive examination of the challenges associated with capturing methane from coal mines and its alignment with the climate policy objectives of the European Union. By delving into issues such as initial investment costs, operational challenges, technological hurdles, and regulatory complexities, this paper provides a nuanced understanding of the multifaceted nature of methane capture initiatives within the coal mining industry.

The identification of these challenges is complemented by a thoughtful analysis of potential solutions, grounded in both practical considerations and theoretical frameworks. The integration of economic, ecological, and governance theories adds depth to the proposed strategies for addressing obstacles to widespread adoption of methane capture systems.

A comprehensive analysis of both the source data over the period 1988–2023 and the literature data carried out made it possible not only to prove complex hypotheses but also show directions for building future strategies to reduce methane emissions per tonne of thermal coal from Polish mines.

While this paper provides a comprehensive analysis of the challenges and opportunities associated with capturing methane from coal mines, it is important to acknowledge certain limitations in its scope and methodology. This study predominantly focuses on the European context, specifically emphasizing the European Union's climate policy objectives. This geographical specificity may limit the generalizability of the findings to other regions with different regulatory frameworks, economic conditions, and technological landscapes. Consequently, this paper may not fully capture the diverse challenges faced by coal mining operations in other parts of the world. The empirical analysis, particularly the examination of trends in absolute methane emissions, quantities of methane captured, and de-methanation efficiency, relies on data from coal mines in Poland. The applicability of these findings to mines in other countries might be constrained by variations in mining practices, geological conditions, and the extent of technological adoption.

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