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RESULTS OF RESEARCH ON INVENTORY UNCERTAINTY OF METHANE FUGITIVE EMISSION FROM COAL MINING SYSTEM

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WYNIKI BADAŃ NAD NIEPEWNOŚCIĄ INWENTARYZACJI EMISJI LOTNEJ METANU Z SYSTEMU WĘGLA KAMIENNEGO

Konwencja klimatyczna ONZ zobowiązuje jej sygnatariuszy do inwentaryzacji emisji gazów cieplarnianych, w tym między innymi emisji lotnej metanu z systemu węgla kamiennego. Realizując to zobowiązanie Polska oszacowała w oparciu o dane z 1992 r. tzw. „wskaźniki emisji" metanu z poszczególnych źródeł emisji. Zgodnie z zaleceniami IPCC/OECD wskaźniki te po wymnożeniu przez wydobycie węgla pozwalają w prosty sposób szacować emisję metanu. Od czasu ich opracowania w 1994 roku doszło jednak do znaczących zmian organizacyjno-technicznych w krajowym górnictwie węglowym. Nastąpił też znaczący rozwój wiedzy w zakresie geologii metanu pokładów węgla. Spowodowało to dezaktualizację wcześniej obliczonych krajowych wskaźników emisji. Szeroki zakres proponowanych badań niezbędnych do precyzyjnego określenia wielkości wskaźników emisji przedstawiono w artykule. W artykule zaleca się, by do czasu przeprowadzenia tych badań stosować poprawione wskaźniki emisji, które uwzględniają zmiany organizacyjne przemysłu węglowego. Oszacowana z ich użyciem emisja metanu z systemu węglowego wyniosła w 1999 roku 527,889 Gg.

Summary

United Nations Framework Convention on Climate Change obliges member countries to make an inventory of greenhouse gases emission and, among others, an inventory of fugitive emission from coal mining system. To comply with this obligation, basing on 1992 data, Poland has evaluated so-called "emission factors" for identified sources of methane emission. According to IPCC/OECD guidelines, the emission factors multiplied by coal output allow simple evaluation of methane emission. Since the time when the emission factors were evaluated in 1994, coal industry in Poland has undergone major organisational and technical changes. At the same time significant development of basic knowledge on geology of methane in coal-bearing strata have occurred. Both these facts make the emission factors evaluated earlier inaccurate. A wide range of research indispensable for accurate evaluation of new emission factors is described in the paper. It is also recommended in the paper that by the time the research results are known, the improved emission factors, which take into account organisational changes of mining industry should be used. Methane emission from coal mining system in 1999 evaluated using those emission factors equals 527,889 Gg.

INTRODUCTION

Methane is, after carbon dioxide, the second important greenhouse gas [1]. The system of coal mining is on the sixth place [7] among main sources of its emission. As the possibilities for reducing methane emission from coal mining system are better than from other sources, the system is more important than the place would suggest. The efforts are therefore undertaken to control this emission. One of elements of methane emission control is its inventory. According to the article 4 of the United Nations Framework Convention on Climate Change [27] the inventory should be done by particular countries using a comparable methodology. The principles of the methodology have been formulated during the Intergovernmental Panel for Climate Changes (IPCC) in Paris [6], and have been consequently modified according to the current state of the art. Basing on the formulated principles, the activities towards accuracy improvement of methane emission evaluation have also been undertaken in Poland. Based on the data from 1992 *Country Case Study...* [24] which was worked out in 1994 can serve as an example of such activities. The results of this study have been till now the basis for evaluation and reporting of methane fugitive emission from coal mining in Poland.

Many years have passed since the *Country Case Study...* was elaborated. In the meantime the Polish hard coal mining industry has changed considerably, as far as organisational and technical aspects are concerned. At the same time the increase of interest in greenhouse gases in general and in coalbed methane as a source of energy in particular, caused the significant development in the knowledge on this topic. These two main factors, as well as some more of lower significance, resulted in devaluation of the study results. For these reasons the attempts are done in this paper to evaluate the influence of the above mentioned factors on accuracy of methane emission evaluation. The analysis includes the methodological assumptions of *Country Case Study...*, the practice of its results using for the purpose of emission inventory as well as the influence of technical and organisational changes of hard coal mining industry on its results. Finally, suggestions are made concerning decrease uncertainty of emission evaluation and kind of research projects needed to make corrections to devaluated methodological assumptions of *Country Case Study...*

METHOD OF METHANE FUGITIVE EMISSION INVENTORY FROM COAL MINING SYSTEM RECOMMENED BY OECD

Polish inventory of methane emission from coal system is based on the methodological guidelines of the Intergovernmental Panel for Climate Changes/OECD [6], improved in 1996 [25]. The methodology assumes that the emission is evaluated separately for ventilation systems of mines, degassing systems and for post – mining activities. It is additionally recommended to include into the evaluation, where possible, the emission from spoil heaps of mining wastes and from closed down mines. Generally, the IPCC/OECD methodology assumes that the emission depends on coal production and the dependency is expressed by the emission factor, i.e. the volume of methane emitted per unit of coal output. OECD recommends the following formula for emission evaluation:

$$E = W_e Q_w \rho_{CH_4} \tag{1}$$

where:

E – emission from identified source, Gg,
W_e – emission factor, m^3/Mg,
Q_w – coal output, M Mg,
ρ_{CH_4} – the density of CH_4 at 20^oC and 1 atmosphere

$$(\sigma_{CH_4} = 0{,}67 \text{ Gg/M m}^3).$$

The values of Q_w and ρ_{CH_4} from the formula (1) can usually be defined with a good precision, whilst the value of emission factor W_e very often remains unknown. For this reason the IPCC/OECD methodology focuses on emission factors evaluation. According to IPCC guidelines the emission factors should be determined in the country of the inventory with maximum possible precision. Depending on the availability of existing data the following methods of emission evaluation are distinguished:

(a) Global average method, in which emission factors used are the one developed basing on the global average data,
(b) Country or basin specific method, in which the individual emission factors adequate for conditions of country or coal basin are established,
(c) Mine specific method, based generally on mines measurements of ventilation emission and emission from degassing systems.

POLISH METHODOLOGY OF EVALUATION OF METHANE EMISSION FROM COAL MINING SYSTEM

Country specific method is used for reporting methane emission in Poland. The emission factors used are the results of research done in 1994 [10, 24]. Although those results have already been published [8, 9, 19] for the comprehensiveness of further part of this paper it is necessary to remind them briefly.

For emission factors estimation from identified sources of methane emission from coal mining system the following data were used:

- measurements of methane content and desorption ratio of coal,
- coal outputs of individual mines,
- calculated amounts of methane: released by ventilation shafts, captured by degassing systems and utilised,
- results of studies on the coal material content in mining wastes,
- amount of wastes deposited at spoil heaps,
- depths of exploitation of each individual coal mine.

The set of data concerning the results of methane content and desorption ratio measurements was limited to the one determined for selected boreholes. The methane content data chosen for the analysis were, according to the best knowledge of that time, recalculated using the following formula to evaluate lost gas:

$$G_l = 0.33 G_p \qquad (2)$$

where:

G_l – lost methane, m^3/Mg,
G_p – unit volume of methane measured in the laboratory, m^3/Mg.

The data on coal output were taken from the mine resources balances (MRB), where output is calculated basing on the surface of exploited seams, average density of coal and average thickness of exploited part of each seam. The output of coal evaluated in this procedure is different from the one published in bulletins of State Hard Coal Restructuring Agency (PARG), in which the data show output of saleable coal containing pieces of waste rock. The ratio of output according to MRB (Q_{MRB}) to the output given by PARG (Q_{PARG}) for 1992 data was 0.866365:

$$Q_{MRB} = 0.866365 Q_{PARG} \tag{3}$$

The data concerning the amount of methane released by ventilation shafts and captured by degassing systems as well as utilisation of captured methane for each mine were the calculations done in mines basing on:

- measurements of methane concentration and velocity of air flow in ventilation shafts done periodically,
- measurements of capture and use of methane done by industrial measuring instruments and periodical measurements of methane concentration in captured gas mixture.

The data were recalculated from working to standard conditions (20°C, 1 atm.) on the assumption that the average temperature in ventilation shafts and outlets of degassing systems is 30°C.

The amount of mining wastes dumped in environment was evaluated for each coal basin on the basis of the environmental survey data. An average coal material content in wastes was assumed according to limited number of measurements published by Polish Geological Institute [27]. The data on depths of exploitation were gathered from each coal mine. It was assumed that the average depth of exploitation is the depth of each opening weighted by amount of output and the maximum depth was assumed the depth of the deepest heading.

The data were used for evaluation of emission factors. The following was assumed [19]:

(1) The amount of methane emitted by a mass unit of coal produced, in all processes of coal mining, is proportional to the average methane content of exploited coal seams.

(2) The average methane content of exploited coal is a function of the depth-dependent distribution of methane content and the depth of exploitation.

(3) The difference in the rates of methane release implies that during coal exploitation methane is released dynamically, whereas diffusion takes place after the mining process, from coal in post-mining processes and also from dispersed coal material in waste rock mined together with coal.

(4) The emission of methane from post-mining activities and from waste rock heaps is proportional to the residual methane content.

(5) The measurements of methane captured and used are precise enough, so the emission from this source should be reported using the results of measurements.

The assumptions mentioned above forced the method in which gathered data were used. At first, coal basins and their parts were divided into regions characterised by a similar gas and geological conditions. In each region the depth-dependent distribution of average methane content was evaluated. Then, the depth interval of the exploitation in each mine was compared with the appropriate depth-dependent distribution of the methane content. The minimum depth of exploitation (Z_{min}, m) was evaluated from the formula:

$$Z_{min} = Z_{max} - 2(Z_{max} - Z_{av}) \tag{4}$$

where:

Z_{max}, Z_{av} – the maximum (Z_{max}) and the average (Z_{av}) depth of exploitation, m.

As a result of comparisons mentioned above, the average methane content of exploited coal seams in each coal mine ($\overline{G}_k$, m^3/Mg) was evaluated and then used for analysis of correlation and regression with the specific emission (W_{ek}, m^3/Mg) achieved from the following formula:

$$W_{ek} = \frac{E_c}{Q_{wk}} \tag{5}$$

where:

E_c – measured total emission (a sum of ventilation emission and emission from degassing system), m^3/year,

Q_{wk} – coal output, Mg/year.

Many variants of correlation and regression between the methane content and the specific emission were analysed and finally two regression equations characterised by the least error of ventilation emission estimation were chosen. "The resulting regression equation has the form:

$$W_e = a_1\overline{G}_k + a_2\overline{G}_k^2 \tag{6}$$

where:

- for coal mines of specific emission $W_{ek} < 10$ m^3/Mg $a_1 = 3{,}776$ $a_2 = -0{,}605$,
- for coal mines of specific emission $W_{ek} \geq 10$ m^3/Mg $a_1 = 21{,}452$ $a_2 = -3{,}346$.

In further work the established equations were extrapolated to all coal mines" [8].

The values of emission factors W_e achieved for each mine were multiplied by coal output to estimate the emission from each coal mine. However for coal mines of average methane content lower than the residual methane content, the final emission was assumed to be twice lower than the one estimated. The amount of methane captured by degassing systems was subtracted from the evaluated emissions and the results were divided by coal outputs to get finally emission factors from ventilation system of each mine.

Keeping in mind the assumptions given in points 3 and 4 above, emission factors from post-mining activities (W_{ep}, m^3/Mg) were assumed to be equal to:

- residual methane content in those coal mines in which the average methane content of coal seams exploited was higher than the residual methane content,
- average methane content of coal seams exploited, if it was lower than the residual methane content.

Similarly, the emission factors from mining wastes (W_{eo}, m^3/Mg) were evaluated for each coal basin. They were assumed to be the average residual methane contents of coal in a given coal basin multiplied by the amount of coal material in mining wastes deposited in the environment and divided by the sum of the output of a given coal basin:

$$W_{eo} = \frac{S_o B \overline{G}_r}{100 Q_{wk}} \tag{7}$$

where:

S_o – amount of deposited mining wastes, Mg/year,

B – share of coal material in waste rock, % mass,

$\bar{G}_r$ – average residual methane content, m^3/Mg.

The share of coal material in waste rock was assumed, basing on [28], to be 15%.

Emission from degassing systems was not estimated but it was the one measured and reported by mines as a difference between the amount of methane captured and used.

PRACTICAL ASPECTS OF THE COUNTRY SPECIFIC METHOD APPLICATION

The country specific method of emission evaluation described above has become the basis for methane emission reporting and inventories since it was worked out. In practice in its application the methodology was slightly different from recommended by the authors [10]. The main differences were:

(1) The evaluation of the emission from degassing system was done using the emission factor for the 1992, instead of mines' data on emission. As the emission from degassing systems is strongly dependent on market conditions (prices, demand, effectiveness of transport, etc.), the use of the emission factor led to low reliability of the evaluation.

(2) The data on coal output used for reporting emission [13] were different from the ones published by PARG (saleable coal). Additionally, the data on saleable coal were not recalculated to output according to MRB, as recommended.

(3) The emissions from post-mining activities and from spoil heaps of mine wastes were evaluated for the country in total, instead of each mine and each basin, respectively.

Additionally there has not been taken into account the depreciation of the factors resulting from constant changes of exploitation depths in coal mines, development of the knowledge about gas conditions in coal deposits and occurring tendency to decrease the amount of mining wastes deposited in environment.

The negative tendencies mentioned above were accelerated by unusual and unpredictable in its scale organisational and technical changes of Polish coal mining industry, being the result of restructuring process. It is enough to say that out of 71 coal mines taken into consideration for evaluation of emission factors in 1992, by the end of 1997 – 10 stopped to produce coal entirely and in 1998 additional 9 coal mines were closed down. It is obvious that the restructuring process influenced very strongly the value of emission factors established for 1992 conditions.

EVALUATION OF METHANE EMISSION FOR 1999

The changes that took place in the coal mining industry in Poland during the last few years are of great importance for the structure of coal output from particular mines and in consequence, for the level of the country average emission factors. To show how the restructuring process has influenced the country average emission factors established for 1992, the evaluation of methane emission from identified sources of emission was done for 1999 using the emission factors established by L. Gawlik and I. Grzybek

[8] and shown in Table 1. For evaluation of emission from ventilation systems and from post-mining activities the mine specific emission factors were used and for evaluation of emission from spoil heaps – the basin specific emission factors.

To use properly the old emission factors established in conditions of 1992 for emission evaluation in 1999 it was necessary to track the organisational changes that occurred in coal mining between 1992 and 1999. The changes are shown in Table 2. As far as the changes in the emission factors that occurred between 1992 and 1999 are concerned, the mines that produced coal in 1999 can be divided into the following groups:

- The mines without major changes – for which the emission factors applied were the same as for 1992.
- The mines which merged and by 1999 one of the former mines was closed down – for which the emission factors applied were the ones for coal mine from 1992 that still produced coal.
- The merged mines with uniformed documentation of production in 1999 – for which the emission factors applied were the arithmetic average emission factor from 1992 of merged mines.
- The mines that produced coal from parts of deposits of previously closed mines – for which the emission factors applied were the ones from 1992 for already closed mines.
- The mines that stopped coal production were excluded from the analysis.

The described method of the proper emission factors identification was applied in the case of evaluation of ventilation emission and emission from post-mining activities. For evaluations of emission from spoil heaps the emission factors established for 1992 conditions were directly applied.

In *Country Case Study...* [24] it was recommended using the data on coal output (Q_w) of each particular coal mine according to mine resource balances (MRB). For such data the emission factors were established. Unfortunately, for 1999 such data were not available, because the traditional source of mine resource balances data (e.g. [2]) was not reliable as the data differed considerably in comparison to other published data on coal resources. Therefore, for evaluation of coal output, the data on saleable coal output were used (Q_{wn} – according to State Hard Coal Restructuring Agency) and were recalculated to output according to mine resource balances using the coefficient established for 1992 data (see equation 3). The recalculated data on coal output are shown in Table 3.

The data on captured (U) and used methane (Z) obtained from mines were applied directly to evaluate emission from degassing systems of mines (E_o), using the formula:

$$E_o = U - Z \tag{8}$$

The emission measured in working condition (30^{o}C) was recalculated into the one in standard conditions (20^{o}C).

The methane emissions from identified sources for 1999, evaluated using modified emission factors established for 1992 and the data received directly from mines are as follows:

- Ventilation emission 412.096 Gg,
- Emission from degassing systems 42.696 Gg,
- Emission from post-mining activities 65.580 Gg,
- Emission from spoil heaps 4.018 Gg.

Table 1. Emission factors from hard coal mining system established for 1992 conditions

BASIN	No. of mine*	Emission factor [m³/Mg] Ventilation systems	Post-mining activities	Spoil heaps
1.	1	4.995	1.686	0.064
	2	23.010	1.686	
	3	2.286	1.686	
	4	17.126	1.686	
	5	4.866	1.686	
	6	5.322	1.686	
	7	3.417	1.469	
	8	2.974	1.368	
	9	3.800	1.320	
	10	12.784	1.145	
	11	14.498	0.975	
	12	2.367	0.911	
	13	2.010	0.751	
	14	1.764	0.647	
	15	1.459	0.524	
	16	1.148	0.408	
	17	1.161	0.408	
	18	1.121	0.393	
	19	1.121	0.393	
	20	5.203	1.907	
	21	29.551	1.907	
	22	13.926	1.907	
	23	9.315	1.907	
	24	13.917	1.907	
	25	23.580	1.907	
	26	30.108	1.907	
	27	18.104	1.673	
	28	27.432	1.224	
	29	5.413	1.224	
	30	5.453	1.224	
	31	4.515	1.224	
	32	5.442	1.224	
	33	4.310	1.224	
	34	4.288	1.224	
	35	2.830	1.138	
	36	3.397	1.138	
1.	37	2.830	1.138	0.064
	38	2.562	1.003	
	39	10.041	0.992	
	40	1.959	0.729	
	41	2.315	0.716	
	42	1.786	0.715	
	43	2.073	0.632	
	44	2.073	0.632	
	45	1.386	0.547	
	46	1.456	0.523	
	47	1.381	0.493	
	48	1.195	0.421	
	49	1.020	0.355	
	50	0.912	0.316	
	51	0.855	0.295	
	52	0.579	0.212	
	53	0.273	0.091	
	54	0.273	0.091	
	55	0.123	0.044	
	56	0.132	0.044	
	57	0.132	0.044	
	58	0.131	0.043	
	59	0.107	0.036	
	60	0.098	0.032	
	61	0.095	0.032	
	62	0.094	0.032	
	63	0.084	0.028	
	64	0.049	0.014	
	65	0.029	0.009	
	66	0.000	0.000	
2.	67	28.088	1.224	0.212
	68	4.553	1.224	
	69	27.088	1.224	
	70	27.996	1.224	
3.	71	1.698	0.506	0.032

* No. of mine as in [8] – different than in other tables

Table 2. Comparison of organisational structures of coal mines in 1992 and 1999

List of mines as in 1992	Remarks	List of mines as in 1999
1	2	3
Andaluzja		ZG Brzeziny
Anna		Anna
Bobrek	Merged, exploitation stopped in Miechowice mine	ZG Bytom III
Miechowice		
Bogdanka		Bogdanka
Bolesław Śmiały		Bolesław Śmiały
Borynia		Borynia
Brzeszcze		Brzeszcze
Budryk		Budryk
Centrum	Merged, exploitation stopped in Szobmierki mine	Centrum
Szombierki		
Chwałowice	Merged, exploitation stopped in Rymer mine	Chwalowice
Rymer		
Czeczott		Czeczott
Dębieńsko		Dębieńsko
Gliwice		Gliwice
Halemba		Halemba
Jan Kanty		Jan Kanty
Janina		Janina
Jankowice		Jankowice
Jastrzębie	Merged, average emission factors as for 1992 assumed	Jas- Mos
Moszczenica		
Jaworzno		ZGE Jaworzno- Sobieski III
Jowisz	Closed, at a part of deposit ZG Wojkowice works	ZG Wojkowice
Julian		ZG Piekary
Katowice	Merged, average emission factors as for 1992 assumed	Katowice - Kleofas
Kleofas		
Kazimierz Juliusz		Kazimierz Juliusz
Knurów		Knurów
Krupiński		Krupiński
Makoszowy		Makoszowy
Marcel	Merged, average emission factors as for 1992 assumed	Marcel
1-Maja		
Murcki		Murcki
Mysłowice		Mysłowice
Niwka-Modrzejów		Niwka-Modrzejów
Nowa Ruda		Nowa Ruda
Nowy Wirek	Merged, exploitation stopped in Polska mine	Polska - Wirek
Polska		
Piast		Piast
Pniówek		Pniówek
Pokój	Merged, exploitation stopped in Wawel mine	Pokój
Wawel		
Powstanców Śląskich		ZG Bytom I
Pstrowski	Closed, at a part of deposit ZWSM Jadwiga works	ZWSM Jadwiga
Rozbark		ZG Bytom II

Table 2. (cont'd)

1	2	3
Rydułtowy		Rydułtowy
Siemianowice	Closed, at a part of deposit ZG Rozalia works	ZG Rozalia
Siersza		Siersza
Silesia		Silesia
Śląsk		Śląsk
Sośnica		Sośnica
Staszic		Staszic
Szczygłowice		Szczygłowice
Wesoła		Wesoła
Wieczorek		Wieczorek
Wujek		Wujek
Zabrze-Bielszowice		Bielszowice
Ziemowit		Ziemowit
Zofiówka		Zofiówka
Barbara-Chorzów	Stopped exploitation	
Grodziec	Stopped exploitation	
Morcinek	Stopped exploitation	
Paryż	Stopped exploitation	
Porąbka-Klimontów	Stopped exploitation	
Saturn	Stopped exploitation	
Sosnowiec	Stopped exploitation	
Thorez	Stopped exploitation	
Victoria	Stopped exploitation	
Walbrzych	Stopped exploitation	
Żory	Stopped exploitation	

Additionally, basing on direct measurements done in field, the emission from one of already closed down mines was evaluated to be: 3.499 Gg.

Then, the total emission from hard coal system equals 527.889 Gg.

Appropriate calculations of emissions from each particular emission sources are given in Tables 3–6.

The average emission factors from identified sources of emission in hard coal mining system that could be calculated basing on the above emissions established for 1999 conditions are:

- For ventilation emission – 6.502 m^3/Mg.
- For emission from degassing systems – 0.674 m^3/Mg.
- For emission from post-mining activities – 1.035 m^3/Mg.
- For emission from spoil heaps – 0.063 m^3/Mg.

Those emission factors are different from the country average emission factors established in *Country Case Study...* [24] – the ones used till now for the country inventory of CH_4 fugitive emission from hard coal mining (see Tab. 7). As their value was estimated by taking into account organisational changes of the Polish hard coal mining industry, they should be recognised as more reliable than the ones used up till now. In the case of using the emission factors established for 1992 conditions for evaluation of emission in 1999, the total emission would be underestimated by 2.7%. It is a result of underestimation of ventilation emission by 7.6% and degassing system emission by

Table 3. Evaluation of ventilation emission from hard coal mines in 1999

Mine	Output according to PARG [M Mg]	Output according to MRB (col. 2* 0.866365) [M Mg]	Emission factor [m^3/Mg]	Methane emission [M m^3]	Methane emission (col. 5 x 0.67) [Gg]
1	2	3	4	5	6
1	4,231	3,666	1,121	4,110	2,753
2	3,928	3,403	27,432	93,351	62,545
3	3,900	3,379	1,161	3,923	2,628
4	3,850	3,335	1,698	5,663	3,794
5	3,727	3,229	12,648	40,840	27,363
6	3,686	3,193	13,917	44,437	29,773
7	3,668	3,178	2,974	9,451	6,332
8	3,278	2,840	4,310	12,240	8,201
9	3,217	2,787	14,498	40,406	27,072
10	3,189	2,763	3,397	9,386	6,289
11	2,939	2,546	3,417	8,700	5,829
12	2,934	2,542	23,828	60,570	40,582
13	2,825	2,447	5,203	12,732	8,530
14	2,772	2,402	1,459	3,505	2,348
15	2,735	2,370	10,041	23,797	15,944
16	2,681	2,323	1,381	3,208	2,149
17	2,667	2,311	3,800	8,782	5,884
18	2,616	2,266	4,866	11,026	7,388
19	2,496	2,162	13,926	30,108	20,172
20	2,491	2,158	1,764	3,807	2,551
21	2,483	2,151	23,580	50,721	33,983
22	2,316	2,006	1,121	2,249	1,507
23	2,212	1,916	17,126	32,813	21,985
24	2,209	1,914	5,322	10,186	6,825
25	2,165	1,876	2,830	5,309	3,557
26	2,163	1,874	2,830	5,303	3,553
27	2,146	1,859	0,000	0,000	0,000
28	2,046	1,773	5,453	9,668	6,478
29	1,895	1,642	4,995	8,202	5,495
30	1,886	1,634	1,173	1,917	1,284
31	1,746	1,513	1,959	2,964	1,986
32	1,717	1,488	0,049	0,073	0,049
33	1,712	1,483	2,315	3,433	2,300
34	1,594	1,381	1,148	1,585	1,062
35	1,576	1,365	0,912	1,245	0,834
36	1,576	1,365	5,413	7,389	4,950
37	1,526	1,322	1,020	1,348	0,903
38	1,468	1,272	5,442	6,922	4,638
39	1,316	1,140	0,029	0,033	0,022
40	1,187	1,028	4,288	4,408	2,953
41	1,180	1,022	2,367	2,419	1,621
42	1,118	0,969	1,386	1,343	0,900
43	0,971	0.841	12,784	10,751	7,203
44	0,913	0,791	1,786	1,413	0,947
45	0,802	0,695	0,095	0,066	0,044
46	0,662	0,574	1,456	0,836	0,561
47	0,571	0,495	2,073	1,026	0,688
48	0,542	0,470	0,123	0,058	0,039
49	0,530	0,459	0,098	0,045	0,030
50	0,492	0,426	4,515	1,923	1,289
51	0,384	0,333	28,088	9,353	6,267
52	0,259	0,224	0,107	0,024	0,016
Total	109,193	94,601	6,502	615,068	412,096

Table 4. Evaluation of methane emission from post-mining processes of hard coal mining system in 1999

Mine	Output according to PARG [M Mg]	Output according to MRB (col. 2* 0.866365) [M Mg]	Emission factor [m³/Mg]	Methane emission [M m³]	Methane emission (col. 5 x 0.67) [Gg]
1	2	3	4	5	6
1	4,231	3,666	0,393	1,441	0,965
2	3,928	3,403	1,224	4,165	2,791
3	3,900	3,379	0,408	1,379	0,924
4	3,850	3,335	0,506	1,688	1,131
5	3,727	3,229	1,686	5,444	3,648
6	3,686	3,193	1,907	6,089	4,080
7	3,668	3,178	1,368	4,348	2,913
8	3,278	2,840	1,224	3,476	2,329
9	3,217	2,787	0,975	2,717	1,821
10	3,189	2,763	1,138	3,144	2,107
11	2,939	2,546	1,469	3,740	2,506
12	2,934	2,542	1,790	4,550	3,049
13	2,825	2,447	1,907	4,666	3,127
14	2,772	2,402	0,524	1,259	0,843
15	2,735	2,370	0,992	2,351	1,575
16	2,681	2,323	0,493	1,145	0.767
17	2,667	2,311	1,320	3,051	2,044
18	2,616	2,266	1,686	3,820	2,560
19	2,496	2,162	1,907	4,123	2,762
20	2,491	2,158	0,647	1,396	0,935
21	2.483	2,151	1,907	4,102	2.748
22	2,316	2,006	0,393	0,788	0,528
23	2,212	1,916	1,686	3,230	2,164
24	2.209	1,914	1,686	3,227	2,162
25	2,165	1,876	1,138	2,135	1,430
26	2,163	1,874	1,138	2,133	1,429
27	2,146	1,859	0,000	0,000	0,000
28	2,046	1,773	1,224	2,170	1,454
29	1,895	1,642	1,686	2,768	1,855
30	1,886	1,634	0,362	0,591	0,396
31	1,746	1,513	0,729	1,103	0,739
32	1,717	1,488	0,014	0,021	0,014
33	1,712	1,483	0,716	1,062	0,711
34	1.594	1,381	0,408	0,563	0.378
35	1,576	1,365	0.316	0,431	0,289
36	1,576	1,365	1,224	1,671	1,119
37	1,526	1,322	0,355	0,469	0,314
38	1,468	1,272	1,224	1,557	1,043
39	1,316	1,140	0,009	0,010	0,007
40	1,187	1,028	1,224	1,258	0,843
41	1.180	1,022	0,911	0,931	0,624
42	1,118	0,969	0,547	0,530	0,355
43	0,971	0,841	1,145	0,963	0,645
44	0,913	0,791	0,715	0,566	0,379
45	0,802	0,695	0,032	0,022	0,015
46	0.662	0,574	0,523	0,300	0,201
47	0,571	0,495	0,632	0,313	0,210
48	0,542	0,470	0,044	0,021	0,014
49	0,530	0,459	0,032	0,015	0,010
50	0,492	0,426	1,224	0,521	0,349
51	0,384	0,333	1,224	0,408	0,273
52	0,259	0,224	0,036	0,008	0.005
Total	109,193	94,601	1,035	97,880	65,580

Table 5. Evaluation of methane emission from degassing system of hard coal mines in 1999

Mine	Output according to PARG [M Mg]	Output according to MRB (col. 2* 0.866365) [M Mg]	Methane emission in		Methane emission (col. 5 x 0.67) [Gg]
			Working conditions [M m^3]	Standard conditions [M m^3]	
1	2	3	4	5	6
1	4,231	3,666			
2	3,928	3,403	4.000	3.868	2.592
3	3,900	3,379			
4	3,850	3,335			
5	3,727	3,229	8.700	8.413	5.637
6	3,686	3,193	18.700	18.083	12.116
7	3,668	3,178	5.100	4.932	3.304
8	3,278	2,840	7.800	7.543	5.054
9	3,217	2,787	6.600	6.382	4.276
10	3,189	2,763			
11	2,939	2,546			
12	2,934	2,542	0.400	0.387	0.259
13	2,825	2,447	0.800	0.774	0.518
14	2,772	2,402	5.200	5.028	3.369
15	2,735	2,370	5.300	5.125	3.434
16	2,681	2,323			
17	2,667	2,311			
18	2,616	2,266			
19	2,496	2,162	2.200	2.127	1.425
20	2,491	2,158			
21	2,483	2,151	1.000	0.967	0.648
22	2,316	2,006			
23	2,212	1,916	0.100	0.097	0.065
24	2,209	1,914			
25	2,165	1,876			
26	2,163	1,874			
27	2,146	1,859			
28	2,046	1,773			
29	1,895	1,642			
30	1,886	1,634			
31	1,746	1,513			
32	1,717	1,488			
33	1,712	1,483			
34	1,594	1,381			
35	1,576	1,365			
36	1,576	1,365			
37	1,526	1,322			
38	1,468	1,272			
39	1,316	1,140			
40	1,187	1,028			
41	1,180	1,022			
42	1,118	0,969			
43	0,971	0,841			
44	0,913	0,791			
45	0,802	0,695			
46	0,662	0,574			
47	0,571	0,495			
48	0,542	0,470			
49	0,530	0,459			
50	0,492	0,426			
51	0,384	0,333			
52	0,259	0,224			
Total	109,193	94,601	65.900	63.725	42.696

Table 6. Evaluation of methane emission from spoil heaps of hard coal mines in 1999

Basin	Output acc. to PARG [M Mg]	Output acc. to MRB (col. 2* 0.866365) [M Mg]	Emission factor [m³/Mg]	Methane emission [M m³]	Methane emission (col.5 x 0.67) [Gg]
1	2	3	4	5	6
1	104.958	90.932	0.064	5,820	3,899
2	0.384	0.333	0.212	0,071	0,047
3	3.850	3.336	0.032	0,107	0,072
Total	109.193	94.601	0.063	5,997	4,018

26.4% as well as overestimation emission from of post mining activities by 43.1% and emission from spoil heaps by 3.2% (Tab. 7). By the time the new research proposed in this paper is accomplished, the country inventory of the emission from hard coal mining system should be done using emission factors for 1999, with exclusion of the emission from degassing systems, which should be evaluated using the mines measurements.

Table 7. Difference in emission evaluation for 1999 using emission factors for 1992 (W_{i92}) and modified emission factors for 1999 (W_{i99})

Source of emission	W_{i92}*	W_{i99}	$A** = \frac{W_{i92}}{W_{i99}} - 1$ [%]	$U** = \frac{W_{i99}}{\sum W_{i99}}$	AU [%]
Ventilation systems	6.005	6.502	-7.6	0.786	-6.0
Degassing systems	0.496	0.674	-26.4	0.081	-2.1
Post-mining activities	1.481	1.035	43.1	0.125	5.4
Spoil heaps	0.065	0.063	3.2	0.008	0.0
Total	–	8.274	–	1.000	-2.7

* According to [8] – emission factor from degassing system has been calculated basing on the data given in this paper
** A – difference in the evaluation for each source of emission; U – share of each source emission in the total emission

COUNTRY SPECIFIC METHOD IN THE VIEW OF METHANE GEOLOGY DEVELOPMENT

As mentioned earlier, the increase of interest in methane as greenhouse gas and also as energy source led to the development of basic knowledge on geology of methane in coal-bearing strata. The progress can be seen both in better understanding of previously used research methods as well as in the development of new research methods. The detailed areas, which have been developed since the previous study and are significant for the paper topic, are:

- The reliability of methods used for measurements of the in-situ methane content.
- The variability of the depth-dependent distribution of the methane content field.
- The influence of the gas release during exploitation on the distribution of the average methane content of coal seams.
- The dependence of residual methane content on coal petrography.

As far as the reliability of methods used for measurements of methane content is concerned, the detailed review of the measurement methods applied in Poland since the 1950s was done. Three basic groups of methods have been distinguished [16, 17]:

(1) The group of methods that base on coal samples from side-walls of mining openings. The methods are called "hermetic containers methods" (MPH). The differentiation of those methods, if we forget about unsignificant differences in laboratory research procedures, lies in the methods of evaluation of gas losses during the sampling (see [11]).

(2) The group of the "two-phase vacuum degassing method" (MDFD), where the samples come from borehole cores of non exploited coal seams.

(3) The group of two similar methods called "direct borehole methods" (MBO). In those methods cuttings of coal from especially drilled short boreholes into intact part of coal seam are used for evaluation of the methane content. The gas losses are evaluated basing on empirical formulae (see [14, 16]).

The details of coal sampling as well as laboratory procedures and calculation methods were then compared using also data that could be found in the bibliography [3, 4, 5, 11, 12, 21, 22, 26]. Additionally, the methods of lost gas evaluation were statistically compared using the samples of borehole cores.

The conclusion of this wide analysis was that the best methods whose results are comparable with the ones applied abroad are the methods of the third group (MBO) [16]. Good results can also be obtained for the first (MPH) and the second (MDFD) groups if, for the evaluation of lost gas, the formula (2) is applied in the MPH method, while in the MDFD method the formula:

$$G_l = a\,G_p \tag{9}$$

where:

a – coefficient ranging 0.11 – 0.16, depending on the desorption characteristic of coal.

Results obtained using MBO methods are additionally reliable for each individual samples, while the results of MPH and MDFD methods can be used only as average values from a series of measurements.

In the view of the results of the analysis it could, therefore, be stated that the application of MDFD method in *Country Case Study...* [24] for evaluation of the average methane content was justified. Nevertheless, to evaluate the lost gas, the formula (2) was applied according to the best knowledge of that time, instead of the formula (9).

As far as the variability of the depth-dependent field of methane content is concerned, none major work has been conducted since *Country Case Study...* [24]. Nevertheless, coal mines have worked out many unpublished documentation that showed that the depth-dependent distribution of methane content field varies significantly from mine to mine, and sometimes from part to part of the same mine. It could therefore be stated that applying the average methane content distribution fields for evaluation of methane content in mines might cause a significant error of emission factors established for individual mines. Evaluation of the error is not possible within this paper, as it can be done only after a wide research project.

The next area, the influence of gas release during exploitation on the distribution of the average methane content of coal seams has been noticed to develop considerably. The evaluation methods of coal bearing strata degassing as a result of coal exploitation are based on models of coal degassing (O_d, %) developed earlier (see [23]) as a function of the distance from exploited seam:

$$O_d = f(d) \tag{10}$$

where:

d – the distance of degassed seam from exploited seam, m.

The formula (10) was adopted for so called "methodology of methane content field geometrisation based on dispersed data" [20]. The methodology assumes grouping irregularly distributed methane content measurements into vertical blocks of circular (or square) base of the radius established by auto-correlation of methane content and plotting for each block a depth-dependent methane content profile.

If we define degassing of coal as:

$$O_d = \frac{G_o - G_t}{G_o} \cdot 100 \tag{11}$$

where:

G_o – measured original methane content, m^3/Mg,

G_t – methane content in degassed seam, m^3/Mg,

and then transform the formula (11) to establish G_t, it is possible to take into account the quotient of exploited surface in a single block (S_e, m^2) to the total surface of the block (S, m^2) as an additional measure of degassing. Thus, methane content of degassed seam dependent on the share of coal exploitation in the total volume of the block, percentage of degassing, found by model (10) and measured original methane content, can be found from the formula:

$$G_t = \frac{S_e}{S} G_o \left(1 - 0{,}01 O_d\right) \tag{12}$$

Therefore, it is possible to take into account the influence of coal exploitation on depth-dependent methane content distribution, by calculating the average degassing of coal in specified depths of each block and then in an entire coal deposit.

The methodology applied in *Country Case Study...* [24] used the depth-dependent distributions of original methane content, without taking into account degassing of coal caused by exploitation. It probably was the next source of estimation errors of individual mine's emission factors. Similarly, as in the case of variability of the depth-dependent distribution of methane content field, evaluation of the error is not possible before an appropriate research is done.

The last of the mentioned areas is dependence of residual methane content on coal petrography. The residual methane content in Poland is usually evaluated using "analytical method". The method is based [18] on regression analysis of methane content and desorption ratio, that leads to establishing regression equation in the form:

$$G_o = a_0 + a_1 \Delta P_2 \tag{13}$$

where:

ΔP_2 – desorption ratio measured using desorbometer of DMC-2 type (for details see: [14]), mm H_2O,

It is also assumed, that:

$$G_r = a_0 \tag{14}$$

where:

G_r – residual methane content, m^3/Mg.

During the research that led to country specific method of methane emission evaluation, the analytical method was applied without taking into account the influence of petrographical characteristic of coal on its sorption properties. The research done later [15, 17] showed the significant dependence of evaluated residual methane content value from the coalification of coal, leading to modification of the analytical method. The modification consists in determining "partial" residual methane content (G_{ri}, m^3/Mg) for coals of similar volatile matter content (V_i^{daf},%), determining the regression equation between V_i^{daf} and G_{ri} in the form:

$$G_{ri} = b_1 + b_2 V_i^{daf} \tag{15}$$

where:

b_1, b_2 – equation coefficients,

and finally in evaluation of the residual methane content for those types of coal that dominate in the deposit.

The obtained results occurred to be comparable to measurements of residual methane content done by US Bureau of Mines as well as sorption isotherm methods [17].

In *Country Case Study...* [24] residual methane contents of coal were used directly for emission factor evaluation without taking into account the dependence of coalification on residual methane content. It led to an error in evaluation of emission factors. The error is difficult to establish without additional wider research. At this stage it can only be said that residual methane content values evaluated on the basis of modified analytical method vary from nearby null to above 3.5 m^3/Mg, while in *Country Case Study...* the following values were used: 1.224, 1.680 and 1.907 m^3/Mg.

The developments of the basic research on methane geology described above in a short form show that the results of *Country Case Study...* have depreciated and need to be updated. Nevertheless it has to be said, that the development did not shake any assumption or general methodology of *Country Case Study...* but made it possible to undertake works toward considerable improvement in methane emission accuracy.

OTHER CONDITIONS THAT INFLUENCE ACCURACY OF THE COUNTRY SPECIFIC METHOD

The characteristic of the country specific method shows that beside geological data for its development, other information, such as technical and technological data, was necessary. It would be useful to draw attention to the uncertainty in emission factors evaluation that is a result of such conditions.

The first one, used for evaluation of ventilation emission factors, is the method of emission measurements in mines. During the research for final publication of *Country Case Study...* it was stated [10] that the amount of methane vented by shafts was established using discrete measurements (at least once a month) of air velocity in ventilation shaft (v, m/sec) and methane concentration in the air (C_M, %). Knowing the cross section area of the shaft (P, m^2), the amount of methane (Q_{CBM}, m^3/sec) can be evaluated from the formula:

$$Q_{CBM} = \frac{v\,P\,C_M}{100} \tag{16}$$

The described state changed radically already in 1995, when on-line measurements of air velocity in ventilation shafts and on-line controls of methane concentration became obligatory. Quick review of those data, done for the purposes of this paper, showed that they fluctuated in time. For the reports done for safety purposes they are averaged and then put into the formula (16).

The change may dramatically influence the value of evaluated emission factors from ventilation system and should be deeply analysed from the point of view of the measurements errors of both methane concentration and velocity of air flow as well as the reliability of the way for those values averaging.

Similarly, in-deep analysis is needed to evaluate measurement accuracy of gas volumes in degassing systems and methane concentration in gas mixture as well as the method of their averaging for the purposes of emission inventory. The experience shows that methods of measurements and averaging differ from mine to mine (e.g.: differential manometers versus flow-meters, continuous versus discrete registration of data or they manual reading-out, etc.)

Another significant condition for emission evaluation from both ventilation and degassing systems is the temperature at which the measurements of air volume and air flow are done. In the inventory the emission should be given in standard conditions (20^{0}C). However, work conditions in ventilation shafts and degassing systems usually differ from the standard ones. The problem has not been explored till now and in *Country Case Study...* the temperature was assumed á priori. For this reason the results may be burdened with an error of unknown value.

Other conditions that influence the reliability of emission from spoil heaps are the amount of deposited wastes and share of coal material in the wastes. The method of emission evaluation from this emission source has been worked out using data on total amount of deposited wastes and on scarce data on coal material content. At the same time the applied methodology assumes that the emission from this source depends on residual methane content that changes from mine to mine. So, to improve the accuracy of emission evaluation it is necessary to analyse the data on deposition of wastes from each mine and to widen the database on coal material content in the wastes.

It seems that the last of the important mining conditions to be mentioned is an average depth of exploitation that is used for evaluation of the average methane content of exploited seams. The average depth of exploitation is not a standard data. It is evaluated only if needed. In consequence, the methodology and precision of its evaluation differs depending on the person responsible. Some people evaluate it very precisely, according to methodological rules. Others use approximated data and simplified procedure. It causes emission estimation error that is difficult for evaluation. The error is even higher as in the formula (4) for exploitation interval the maximum depth was assumed to be the depth of the deepest heading. As it was later found out in practice the emission from headings is usually lower than from longwalls. It seems then that in further works on emission factors estimation it would be well advised to change the methodology of the depth interval evaluation by exchanging the depth of the deepest heading with the depth of the deepest longwall.

CONCLUSIONS AND RECOMMENDATIONS FOR IMPROVEMENT OF UNCERTAINTY FOR METHANE EMISSION EVALUATION

Basing on the preliminary analysis of currently applied methodology of methane emission evaluation from hard coal mining, the results of new research concerning geology of gas deposits in coal-bearing strata as well as observations of technical and organisational changes in hard coal mining industry, it can be stated that the emission factors being currently applied for evaluation of emission from identified sources of emission in coal system, have become outdated. It has led to the increase of evaluation errors. In particular, the modification of the emission factors established for the 1992 conditions made it possible to find out that in the case of using unmodified emission factors for emission evaluation in 1999 the emission would be underestimated by 2.7%. Relatively low underestimation of the total emission from hard coal system is a result of relatively high errors of emission estimation from each particular source of emission, i.e. 7.6% underestimation of ventilation emission, 26.4% underestimation of degassing system emission, 43.1% overestimation of emission from post-mining activities and 3.2% overestimation of emission from spoil heaps. It is therefore recommended to use the modified emission factors for the further works on emission inventory. Recommended emission factors are: 6.502 m^3/Mg – for ventilation emission, 1.035 m^3/Mg – for emission from post-mining activities and 0.063 m^3/Mg – for emission from spoil heaps. The emission from degassing systems should be evaluated using the mines' measurements.

The emission from hard coal mining system evaluated for 1999 using modified emission factors equals 527.889 Gg, out of which 3.499 Gg is the emission from newly identified source of emission i.e. closed down mine.

In the view of recent developments in basic studies on geology of gas deposits in coal-bearing strata, it occurs that some of assumptions and methodology applied for evaluation of emission factor in *Country Case Study...* [24] are not very precise. It concerns in the first place the reliability of average methane content and residual methane content assessed for each coal mine, which have been used for evaluation of emission factors. Without a wide range of research, suggested below, it is not possible to evaluate quantitatively the influence of those factors on emission value reported in the inventory. Similarly, without a special research it is not possible to establish uncertainty of the emission evaluation resulting from the technical and technological data. Therefore, in spite of recommended modification of the emission factors it seems that the new research project is needed. Within this project the following tasks should be undertaken:

- Re-division of coal mines into groups according to their geological and gas conditions.
- Verification and widening of the range of gas data used for evaluation of methane content distribution.
- Re-assessment of the shape of methane content distributions for each of coal mines basing on verified data to compare them with the location of mining workings.
- Study on the influence of the previous exploitation of coal on the distribution of methane content.
- More precise evaluation of the content of coal substance in dumped mining wastes.
- Evaluation of residual methane content in the context of coalification with the aim to assess, in a more accurate way, emission factors from post-mining activities and from spoil heaps.
- Assessment of the methane emission from mines being closed down basing on the field measurements.
- Assessment of measurement errors of methane emission from degassing systems and from ventilation shafts.

It is also recommended that the complex analysis of legal regulations are undertaken to explore how it is possible to use them for gathering the information indispensable for emission inventory with a stress put on probable corrections needed. This could be a part of suggested research project. An achievement of the possibility for evaluating methane emission by the mines specific method should be the final result of the research project.

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