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ESTIMATION AND FORECASTING OF CARBON DIOXIDE EMISSIONS FROM COAL-FIRED THERMAL POWER PLANTS IN UKRAINE

Purpose. Development and verification of a method for calculating and forecasting CO_2 emissions from coal combustion at thermal power plants based on proximate analysis data. Calculation of gross and specific CO_2 emissions per unit of output energy and mass of coal consumed at Ukrainian thermal power plants (TPPs).

Methodology. Methods of mathematical statistics were used for processing the data of ultimate and proximate analysis of 170 samples of *A, L, G*, and *LFG* coal ranks with low heat value on operating state (Q_i^r) in the range of 17.2 to 31.0 MJ/kg and ash content on dry state (A^d) in the range of 3.8 to 38.0 % to determine relationships between carbon emission factors (k_c), calorific value, and ash content.

Findings. The values of emission factors (k_{CO_2}) and gross CO_2 emissions for mixtures of coals of grades *A* and *L*, *G* and *LFG* at Ukrainian TPPs in 2017–2021 were calculated. For 2021, the average value of k_{CO_2} for coals of grades *G* and LFG was 94,128 g/GJ, and for coals of grades *A* and *L* it was 104,987 g/GJ. Gross CO_2 emissions at Ukrainian TPPs have been in the range of 38–49 million tons in recent years, and their annual reduction is due to a decrease in energy production and fuel consumption at TPPs, primarily of grades *A* and *L*.

Originality. Empirical dependencies k_c for steam coal of different ranks are determined in the form of $k_c = a + bQ_i^r + cA^d$. The coefficients *a*, *b*, and *c* are determined for grades *A, L, G*, and *LFG* and their mixtures. The relationship between the carbon content in coal and the low heat value for coal is linear: $C^r = K \cdot Q_i^r$, where *K* is a coefficient depending on the coal grade. The values of *K* are determined for coal of grades *A, L, G*, and *LFG.*

Practical value. Verification of the created method shows that the calculation error is less than 1.0 %. This is in line with the requirements of the Monitoring Procedure and Directive 2003/87/EC. In 2021, the specific CO_2 emission per unit of output energy at TPPs in Ukraine was 1,084 g/kWh for all ranks of steam coal. The values of specific CO_2 emissions per unit mass of consumed coal were 1.94 t/t for coals of all grades, 1.91 t/t for grades G and LFG, and 2.21 t/t for grades *A* and *L*. The official annual reports of the Ministry of Energy of Ukraine contain information on the amount of produced electricity, consumed coal, and forecast balances of electricity production at TPPs, therefore, the values of specific emissions established by us are convenient to use for estimating and forecasting carbon dioxide emissions.

Keywords: *emissions, carbon dioxide, calculation method, coal, carbon content, emission factor, thermal power plant*

Introduction. On September 16, 2014, Ukraine signed and ratified the Association Agreement between Ukraine, on the one hand, and the European Union (EU), the European Atomic Energy Community and their member states, on the other hand, which fully entered into force on September 1, 2017. The Association Agreement provides for the gradual approximation of Ukrainian legislation to the EU policy and legislation in the field of environmental protection, including in the sector of climate change and preservation of the ozone layer. It also plans to implement a number of provisions of Directive 2003/87/EC by the European Parliament and the Council on the implementation of a system of greenhouse gas (GHG) emission quota trading, including the creation of a system for monitoring, reporting, and verifying greenhouse gases (MRV) from fossil fuel combustion plants, as well as public consultation procedures on this issue. In addition, on April 22, 2016, Ukraine signed the Paris Agreement on Combating Climate Change for 2021–2030 as part of the United Nations Framework Convention on Climate Change. It was ratified on July,13, 2016 by Law of Ukraine No. 0105 “On Ratification of the Paris Agreement on Combating Climate Change”. The Paris Agreement regulates the process of monitoring emissions of greenhouse gases – CO_2, CH_4, N_2O, SF_6 and NF_3.

The main regulatory act of the EU governing the rules for calculating GHG emissions is Commission Regulation (EU) No. 601/2012 on monitoring and reporting of greenhouse gas emissions in accordance with Directive 2003/87/EC. The calculation methodology was developed by the Intergovernmental Panel on Climate Change Guidelines (IPCC) [1]. The Law of Ukraine “On Principles of Monitoring, Reporting and Verification of Greenhouse Gas Emissions” dated December 12, 2019 No. 377-IX is aimed at fulfilling Ukraine’s obligations under the Association Agreement and the Paris Agreement. This law is a framework law, it defines the legal and organizational basis for the functioning of the MRV system. The methods for calculating GHG are outlined in the “Procedure for Monitoring and Reporting on Greenhouse Gas Emissions” approved by Resolution No. 960 of the Cabinet of Ministers of Ukraine dated September 23, 2020 [2]. According to the Resolution of the Cabinet of Ministers of Ukraine No. 880 of 09.23.2020 “On approval of the list of activities, as a result of which GHG emissions are subject to MRV”, GHG emissions at Ukrainian thermal power plants (TPPs) are subject to monitoring, reporting and verification.

One of the biggest sources of GHG emissions is burning of organic fuel, including at thermal power plants. In 1990–2019, Ukrainian TPPs accounted for 19–13 % of national industrial GHG emissions [3, 4]. Greenhouse gases produced by burning organic fuels are CO_2, CH_4 and N_2O. In 2017–2018, carbon dioxide made 99.5 % of the total amount of GHG at the TPPs [4, 5]; therefore, the assessment and forecasting of GHG emissions, primarily CO_2, is of interest for both experts and the public.

Literature review. Information on carbon dioxide emissions at thermal power plants can be obtained either with the help of satellite data [6] or by permanent measurement of its concentration and volume flow rate of flue gases [7] or by calculation methods [8, 9].

Permanent continuous measurements require appropriate measuring equipment, which is not available at TPPs in Ukraine nowadays. It is possible to calculate carbon dioxide emissions at thermal power plants according to the methodology developed by the IPCC [1] and outlined in the Monitoring Procedure [2], which is based on applying the carbon dioxide emission factor and the degree of carbon oxidation of the fuel in the boiler

$$E_{CO_2} = 10^{-6} k_{CO_2} \cdot B \cdot Q_i^r \cdot \varepsilon_C, \quad (1)$$

where E_{CO_2} is CO_2 emission, thousand t; k_{CO_2} is the carbon dioxide emission factor, g/GJ; B is fossil fuel consumption (coal or natural gas or fuel oil) over a certain period of time, for example, per year, thousand *t* or thousand m^3; Q_i^r is the lower heating value of the fuel (LHV), MJ/kg or MJ/m^3; ε_C is oxidation state of carbon from fuel, share.

The oxidation state of carbon ε_C in coal can be calculated using the formulas given in articles [10, 11]

$$\varepsilon_C = 1 - \frac{q_4}{C^r} \cdot \frac{Q_i^r}{Q_C}; \quad (2)$$

$$\varepsilon_C = 1/(1 - q_4/100),$$

where q_4 is heat loss due to mechanical incomplete combustion of fuel (Unburned Carbon), %; Q_C is the heat of combustion of carbon to CO_2, which equals 32.68 MJ/kg.

According to [1], the oxidation states of carbon ε_C in fuel oil and natural gas are assumed to be equal to 1.

The emission factor characterizes the amount of matter emitted by a combustion plant into the atmosphere together with flue gases, relative to the unit of energy released during fuel combustion. The CO_2 emission factor is the specific emission value, its amount is determined by the individual characteristics of the organic fuel. The value k_{CO_2} is either chosen by default or calculated according to the elemental composition of the corresponding fuel, determined on the basis of laboratory tests. The default values k_{CO_2} for different types of fossil fuels are given in Table 1 [1, 2]. To do the calculations, the IPCC recommends using an emission factor unique for the country or region, which reflects the specifics of the fuel consumed. Directive 2003/87/EC also requires the use of k_{CO_2} determined by the elemental composition of coal. Table 1 also shows the values of these factors for thermal coal of Ukraine [12], Great Britain and Germany [13], South Korea [14], Indonesia [15], and the United States [16]. The values of these factors for anthracite for different sources compared to the IPCC values have a discrepancy within 12.9 %, for hard coal – within 3.7 %, for natural gas – within 0.7 %, for fuel oil – within 5 %. Significant discrepancies in determining CO_2 emissions calculated by the IPCC coefficients and those determined by the elemental composition of coal are also recorded in other studies [17].

According to the Monitoring Procedure, Ukrainian thermal power plants belong to combustion plants of category B, whose volume of greenhouse gas emissions exceeds 500 thousand tons of CO_2 equivalent per year. Coal at Ukrainian TPPs belongs to a "significant" material flow, since the amount of CO_2 emissions generated during its combustion is over 90 % of the total amount of carbon dioxide [5]. For category B combustion plants, when calculating CO_2 emissions generated during the burning of "significant" material flows, such methods should be used that allow obtaining results with an error of less than 2.5 %. Fuel oil and gas are classified as "insignificant" and "minimal" material flows, since the volumes of CO_2 emissions generated during their combustion are less than 10 and 2 % of the total volume of CO_2, respectively. To calculate them, calculation errors of less than 5.0 and 7.5 % are allowed, respectively, which are achieved when using the default emission factors given in Table 1. Therefore, the issue of creating methods for calculating CO_2 emissions generated during coal combustion is of interest, which would take into account the elemental composition of coal and allow obtaining a result with an error of less than 2.5 %.

In the literature, there are methods in which the carbon emission factor k_C is used to calculate carbon dioxide emissions generated in coal combustion plants; the factor is the ratio of the carbon content of coal to its lower calorific value. The CO_2 emission factor can be written as [3, 15]

$$k_{CO_2} = \frac{44}{12} \cdot \frac{C^r}{100} \cdot \frac{10^6}{Q_i^r};$$

$$k_{CO_2} = 3.67 k_C, \quad (3)$$

where k_C is the carbon emission factor $k_C = \frac{C^r}{100} \cdot \frac{10^6}{Q_i^r}$ (4), g/GJ; C^r is the mass content of carbon in the fuel on the operating state of the fuel, %.

To calculate carbon dioxide emissions, article [18] suggests using the generalized value C^{daf} (carbon content in coal per dry ash-free mass) for different coal grades according to the "Certificates of genetic, technological and quality characteristics". The certificates were developed for 4-year periods for each manufacturer and type of coal product by "UkrNDI vuhlezbahachennia" institute. As for C^r, it is calculated according to the standard formula

$$C^r = C^{daf} \cdot \left(1 - \frac{W_t^r}{100} - \frac{A^r}{100}\right),$$

where W_t^r, A^r are moisture and ash content on the working condition of the fuel according to the reporting form 3-tech-TES, %.

It is this technique that was used to calculate CO_2 emissions at TPPs in Ukraine in 2016–2019 when preparing the Annual Reports on the national GHG inventory. The article [18] shows the average C^{daf} values for different grades of Ukrainian thermal coal for 1990–2015, but it does not indicate where to find information on C^{daf} of coal supplied to TPPs of Ukraine starting from 2016. The values of the carbon content

Table 1

CO_2 emission factor by default and calculated according to the elemental composition of the fuel determined on the basis of laboratory tests

Type of fuel	IPCC, the procedure for monitoring [1, 2]		Ukraine for 2019 [12]		South Korea [14]		Indonesia [15]		US [16]	Great Britain [13]	Germany [13]
	k_{CO_2}, g/GJ	Q_i^r, MJ/kg	k_{CO_2}, g/GJ	Q_i^r, MJ/kg	k_{CO_2}, g/GJ	Q_i^r, MJ/kg	k_{CO_2}, g/GJ	Q_i^r, MJ/kg	k_{CO_2}, g/GJ	k_{CO_2}, g/GJ	k_{CO_2}, g/GJ
Anthracite	98,300	26.7	94,500	22.0	111,100	n/d	n/d	n/d	98,900	95,900	96,800
Hard coal	96,100	18.9	94,500	22.0	95,600	19.7	97,700	21.9	92,000	95,900	96,800
Natural gas	56,100	48.0	55,900	47.9	n/d	n/d	n/d	n/d	n/d	55,700–55,900	
Fuel oil	77,400	40.4	77,300	40.2	n/d	n/d	n/d	n/d	n/d	79,000–81,300	

in coal per dry ash-free mass for different grades of coal fluctuate somewhat; thus, for bituminous coal grade *G* in 2002–2015, *Cdaf* values were in the range of 79–81 %, for sub-bituminous coal of grade *LFG* – 77–80 %, for semi-anthracite of grade *L* – 89–92 %. In addition, the article does not indicate the error of calculations using this method.

In the article [8], calculation of carbon dioxide emissions in the energy sector of China was performed by determining the specific emissions of CO_2 per unit of supplied electricity, g/kWh. A similar approach was used in the article [3], where specific emissions of CO_2 per unit of supplied energy and consumed coal for TPPs of Ukraine were determined for the 2014–2018 period. These parameters are convenient to use to forecast CO_2 emissions at TPPs as well, since the official annual reports of the Ministry of Energy on the operation of the energy complex of Ukraine contain information on forecast balances of electricity generation at TPPs.

Purpose. The literature analysis performed shows that for the calculation of carbon dioxide emission factors and carbon emission factors k_C, information is required on the mass content of carbon C^r and the lower calorific value Q_i^r for the operating state of the fuel. However, in practice, TPPs are supplied with batches of coal accompanied only by a proximate analysis which provides information on a lower heat of combustion of fuel and ash content. Thus, the purpose of the work is:

1) to develop and verify a method for calculating and forecasting CO_2 emissions generated during coal combustion, based on the proximate analysis data, which would allow obtaining a result with an error of less than 2.5 %;

2) to establish the value of k_{C_2} for different grades of thermal coal supplied to TPPs of Ukraine in recent years according to the method obtained;

3) to perform calculations of gross emissions and establish specific emissions of CO_2 per unit of the energy supplied and per unit of mass of the coal consumed at these TPPs.

Methods. To develop a method for calculating and forecasting carbon dioxide emissions, 170 samples of thermal coal of grades *A*, *L*, *G* and *LFG* with a lower heat of combustion Q_i^r on the operating state in the range from 17.2 to 31.0 MJ/kg and ash content A^d on the dry state in the range from 3.8 to 38.0 %. The mentioned method was developed on the basis of certificates of genetic, technological and quality characteristics for coal and coal products (hereinafter – Certificates), drawn up and approved by the state enterprise "UkrNDIvuhlezbahachennia" (Ukrainian Scientific and Research Institute of Coals Cleaning). The Certificates contain information on the coal grade, its elemental composition, in particular, organic carbon on a dry ash-free state (combustible mass, daf) C^{daf}, organic hydrogen H^{daf}, nitrogen and oxygen $(N + O)^{daf}$, total sulfur on a dry (*d*) state S_t^d, pyritic sulfur S_p^d, sulfate sulfur S_s^d, organic sulfur S_o^{daf}, lower heat of combustion on operating state (*r*) Q_i^r, total moisture W_t^r, ash content A^d, volatile yield V^{daf}, and so on. The content of nitrogen and oxygen was determined by the residual method: $N^{daf} + O^{daf} = 100 - (C^{daf} + H^{daf} + S_o^{daf})$. To divide their sum into separate components, a statistical method was applied using the data from a handbook by V. S. Vdovchenko (1991), Energy fuel of the USSR (fossil coal, combustible shale, fuel oil and combustible natural gas). A total of 73 samples of coal of different grades were analysed. Table 2 shows the calculated ratios between the values of nitrogen and oxygen content for different grades of coal. These ratios for different grades of coal were used to calculate N^r and O^r for each sample.

Table 2

Ratio of oxygen and nitrogen content

Coal grade	O^r, %	N^r, %
Anthracite A	67	33
Lean coal L (semi-anthracite)	55	45
Gas coal G (bituminous)	87	13
Long-flame-gas coal LFG (bituminous)	88	12

For each of the coal samples, its elemental composition was determined according to the Certificates. The values of k_{CO_2} and k_C were calculated as for the elemental composition of each of the coal samples. The values obtained were generalized for different coal grades and their mixtures. The research was conducted on mixtures of coal grades *A*, *L* and *G*, *LFG* because in recent years, these are thermal coal mixtures that have been consumed at Ukraine's TPPs [11].

Results. ***Carbon content in coal.*** According to the ultimate analysis data, the average C^r values were determined for Ukrainian thermal coal of grades *A, L, G*, and *LFG*. In Table 3, apart from the established average *Cr* values, their root mean square deviations and relative errors are given.

The determined average C^r values can be only used for estimation calculations of carbon emission factors, since these values within one grade vary between 4.1–6.8 %. The use of a fixed C^r value for the coal grade for calculations gives an error of 7–9 %.

To calculate the calorific value of coal Q_i, MJ/kg, we can use the well-known formula by Mendeleev

$$Q_i^r = 4.19(81C^r + 300H^r - 26(O^r - S^r) - \\ - 6(9H^r + W^r)) \cdot 10^{-3}, \quad (4)$$

or Knievel's formula

$$Q_i^r = 4.19(81.05C^r + 316.4H^r - 29.9O^r + 23.9S^r - \\ - 3.5A^r - 6(9H^r + W^r)) \cdot 10^{-3}. \quad (5)$$

The analysis of formulas (4–5) shows that there is a relationship between the combustion heat and the carbon content in coal of different grades, and that the contribution of the carbon combustion heat to the fuel combustion heat is the largest. Fig. 1 shows this relationship for coal grades *A*, *L*, and *G*, as an example.

Figs. 2, 3 show the relationship between combustion heat and carbon content in coal mixtures of different grades.

It was established that for coal grades *A, L, G, LFG* and their mixtures, the relationship between the carbon content of coal and the combustion heat is linear: $C^r = K \cdot Q_i^r$, where *K* is a coefficient that depends on the coal grade. Table 4 shows the established empirical relationship for coal grades *A, L, G, LFG*, and their mixtures. The table also presents the ranges of combustion heat and ash content of coal for which these dependencies were obtained.

For coal grades *A*, *L*, the relative error of using the obtained dependencies was ≤ 0.9 %. For coal grades of the bituminous (gas) group, the error made ≤ 1.9 %, and for mixtures *A*, *L* and *G, LFG* – less than 4.0 and 2.0 %, respectively. The obtained empirical dependences for determining the carbon content for coal mixtures of grades *A* and *L* can be used for estimation calculations only.

Carbon emission factors for Ukrainian thermal coal. At the previous stages of the research, it was established that for coal

Table 3

Average values of carbon content in coal of different grades

Parameter	Coal grades			
	A	*L*	*G*	*LFG*
Average values C^r, %	79.88	67.22	56.24	53.27
Root mean square deviation, %	±6.78	±4.12	±5.17	±4.76
Relative error, %	8.49	6.93	9.20	8.94

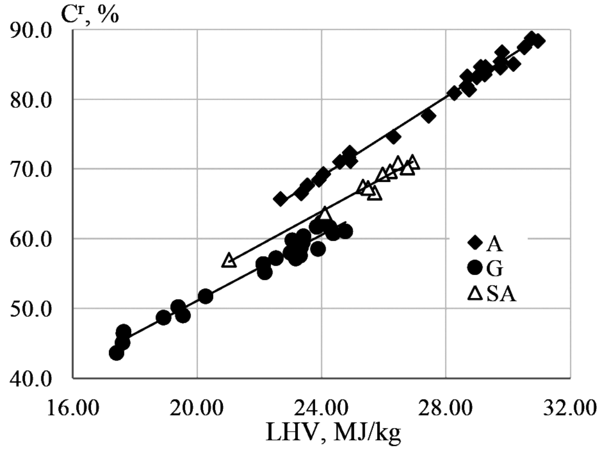

Fig. 1. Dependence of carbon content for coal of different grades on combustion heat

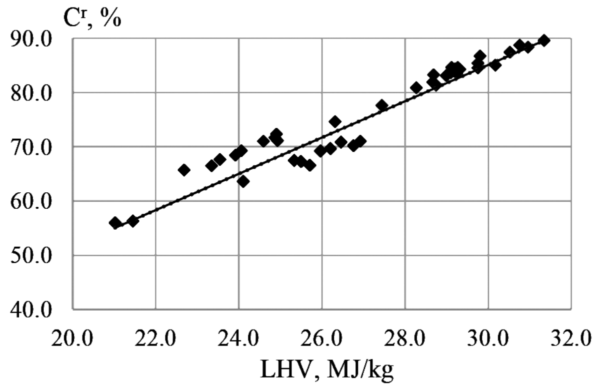

Fig. 2. Dependence of carbon content for mixture of coal of grades A and L on combustion heat

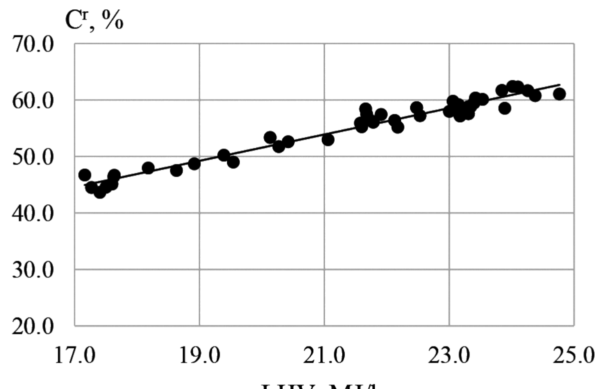

Fig. 3. Dependence of carbon content for mixture of coal of grades G and LFG on combustion heat

grades *A, G* and *LG*, the dependence of carbon emission factors k_C on the combustion heat of coal Q_i^r, MJ/kg, is of a linear nature

$$k_C = A + B \cdot Q_i^r,$$

where *A* and *B* are the factors which depend on the coal grade [5]. Dependencies for calculating the carbon emission factor for coal of grade *L* and for a mixture of coal of grades *A* and *L* have not been established.

Mendeleev's (4) for calculating the combustion heat of coal does not take into account the effect of ash content. Our studies showed that the Q_i^r values calculated by Mendeleev's formula for coal of different grades with an ash content A^d up to 23 % coincide with their values from the Certificates with an accuracy of about 1 %. For the ash content A^d of coal in the range of 23–38 %, a better correlation between the calculated and experimental results is provided by the use of Knievel's (5), which takes into account the ash content of coal. That is, to develop empirical dependencies for calculation of k_C, it is reasonable to consider the ash content of coal, in addition to the combustion heat. Taking this into account, we recorded the dependence of the carbon emission factor for a certain coal grade in the form

Table 4

Empirical relationships between the carbon content in coal and combustion heat

Coal grade	Q_i^r range, MJ/kg	A^d range, %	Obtained dependence for C^r, %	Relative error less than, %
A	22.7–31.0	3.8–25.2	$C^r = 2.87 \cdot Q_i^r \pm 0.66$	0.82
L	21.0–26.9	17.7–25.4	$C^r = 2.65 \cdot Q_i^r \pm 0.61$	0.90
A, L	21.0–31.0	3.8–25.4	$C^r = 2.77 \cdot Q_i^r \pm 2.94$	4.0
G	17.4–24.8	19.4–37.9	$C^r = 2.54 \cdot Q_i^r \pm 1.06$	1.88
LFG	17.2–23.8	18.5–38.0	$C^r = 2.60 \cdot Q_i^r \pm 0.92$	1.72
G, LFG	17.2–24.8	18.5–38.0	$C^r = 2.56 \cdot Q_i^r \pm 1.25$	2.0

$$k_C = a + bQ_i^r + cA^d.$$

Since the number of Certificates for each coal grade is greater than the number of unknown factors *a*, *b*, *c*, the method of least squares was used to determine their values, that is, the minimum of the function was found

$$S = \sum_{j=1}^{N} (k_{Cj} - a - bQ_{ij}^r - cA_j^d)^2, \quad (6)$$

where *N* is the number of Certificates for different coal grades and/or different quality (for example, for the range of ash content) of the coal of a certain grade, *j* is the number of Certificate.

To find this minimum, a system of three equations is to be solved

$$\frac{\partial S}{\partial a} = 0; \quad \frac{\partial S}{\partial b} = 0; \quad \frac{\partial S}{\partial c} = 0. \quad (7)$$

We substitute function (6) into equation (7) and obtain

$$\begin{cases} \frac{\partial S}{\partial a} = \sum_{j=1}^{N} 2(k_{Cj} - a - bQ_{ij}^r - cA_j^d)(-1) = 0 \\ \frac{\partial S}{\partial b} = \sum_{i=1}^{N} 2(k_{cCj} - a - bQ_{ij}^r - cA_j^d)(-Q_{ij}^r) = 0, \\ \frac{\partial S}{\partial c} = \sum_{i=1}^{N} 2(k_{Cj} - a - bQ_{ij}^r - cA_j^d)(-A_j^d) = 0 \end{cases}$$

or after converting the equation

$$\begin{cases} Na + \sum_{j=1}^{N} bQ_{ij}^r + \sum_{j=1}^{N} cA_j^d = \sum_{j=1}^{N} k_{Cj} \\ \sum_{j=1}^{N} aQ_{ij}^r + \sum_{j=1}^{N} bQ_{ij}^r + \sum_{j=1}^{N} Q_{ij}^r A_j^d = \sum_{j=1}^{N} k_{Cj} Q_{ij}^r \\ \sum_{j=1}^{N} aA_j^d + \sum_{j=1}^{N} bA_j^d Q_{ij}^r + \sum_{j=1}^{N} cA_j^d = \sum_{j=1}^{N} k_{Cj} A_j^d \end{cases}. \quad (8)$$

Solving the system (8) gives the optimal values of the sought factors *a, b* and *c*. The search for this solution was implemented in a Fortran computer program developed by the authors. The results of the calculations are summarized in Table 5. In recent years, Ukraine's TPPs have been supplied with coal of different ash content, from 22 to 36 %. Table 5 shows the obtained empirical dependences for different ranges of ash content.

Verification of the developed calculation method. Table 6 provides information from the Certificates regarding Q_i^r, C^r

Table 5

Empirical dependences for calculating k_C, g/GJ in coal based on the proximate analysis data

Coal grade	The number of experiments	A^d, % range	A^d, % average value	Relationships obtained	Relative error is less than, %
A	33	3.8–32.2	12.6	$k_C = 42{,}949 - 445 \cdot Q_i^r - 164 \cdot A^d \pm 347$	1.2
	12	17.9–32.2	22.3	$k_C = 48{,}827 - 654 \cdot Q_i^r - 202 \cdot A^d \cdot 400$	1.4
L	11	17.7–34.3	22.3	$k_C = 31{,}179 - 130 \cdot Q_i^r - 67 \cdot A^d \pm 17$	0.6
	10	17.7–25.4	21.1	$k_C = 32{,}768 - 159 \cdot Q_i^r - 107 \cdot A^d \pm 153$	0.6
A, *L*	70	3.8–38.5	19.0	$k_C = 56{,}436 - 872 \cdot Q_i^r - 330 \cdot A^d \pm 694$	2.5
	25	17.7–34.3	22.1	$k_C = 61{,}710 - 1117 \cdot Q_i^r - 287 \cdot A^d \pm 585$	2.1
G	35	19.4–37.9	24.8	$k_C = 32{,}522 - 246 \cdot Q_i^r - 53 \cdot A^d \pm 435$	1.7
LFG	20	18.5–38.0	26.2	$k_C = 43{,}657 - 602 \cdot Q_i^r - 193 \cdot A^d \pm 551$	2.1
G, LFG	100	7.2–44.3	25.6	$k_C = 38{,}147 - 432 \cdot Q_i^r - 126 \cdot A^d \pm 566$	2.2
	80	20.1–40.0	26.1	$k_C = 36{,}964 - 393 \cdot Q_i^r - 114 \cdot A^d \pm 520$	2.0
	60	20.1–28.9	22.8	$k_C = 38{,}461 - 422 \cdot Q_i^r - 151 \cdot A^d \pm 530$	2.0
	20	28.9–40.0	35.7	$k_C = 32{,}380 - 290 \cdot Q_i^r - 40 \cdot A^d \pm 441$	1.7

Table 6

Comparison of calculations of carbon content and carbon emission factor to the data of the Certificates for coal of different coal enterprises

Coal enterprises	Coal grade	Certificate data			Calculation				
		Q_i^r, MJ/kg	C^r, %	A^d, %	C^r, % Table 4	δ*, %	k_C, g/GJ f. (6)	k_C, g/GJ Table 5	δ**, %
Mine Komendantska of DTEK Rovenkyantratsyt LLC	*A*	24.06	69.30	20.8	69.06	0.11	28,796	28,830	0.12
CCF Rovenkivska of DTEK Rovenkyantratsyt LLC	*A*	29.10	83.70	7.8	83.52	0.03	28,751	28,719	0.11
	A	22.68	65.70	25.2	65.10	0.91	28,976	28,722	0.88
CCF Vakhrushevska of DTEK Rovenkyantratsyt LLC	*A*	28.99	83.20	8.0	83.21	0.01	28,680	28,736	0.19
	A	24.87	71.70	19.7	71.38	0.22	28,834	28,651	0.63
CCF Vakhrushevska of DTEK Rovenkyantratsyt LLC	*A*	23,35	66.50	24.2	67.00	0.51	28,497	28,591	0.33
CCF Tsentrospilka of DTEK Sverdlovantratsyt LLC	*A*	23.92	68.50	21.2	68.65	0.07	28,626	28,828	0.71
	A	23.55	67.70	21.8	67.58	0.02	28,743	28,895	0.53
Donprombiznes LLC	*L*	26.21	66.69	18.2	69.44	0.35	26,594	26,654	0.22
Mospine Coal-Treatment Enterprise LLC	*L*	25.97	69.25	19.1	68.81	0.63	26,668	26,596	0.27
Mine Rassvet-1 LLC	*L*	25.33	67.51	19.8	67.14	0.56	26,648	26,621	0.10
DTEK “Komsomolets Donbasu” OJSC	*L*	25.50	67.31	23.4	67.57	0.39	26,398	26,210	0.72
CCF Vuhlehirska PJSC	*L*	24.11	63.65	24.5	63.89	0.37	26,402	26,313	0.34
Mine Yuvileina of Pershotravenske Mine Enterprise of DTEK Dobropilliavuhillia LLC	*G*	20.27	51.77	34.5	51.49	0.54	25,538	25,707	0.66
CCCF Selidivska LLC	*G*	23.15	59.20	20.2	59.03	0.29	25,575	25,757	0.71
CCF Komsomolska OJSC	*G*	24.26	61.68	21.9	61.86	0.28	25,429	25,394	0.14
CCF Rosiia OJSC	*G*	23.40	59.50	20.9	59.66	0.26	25,433	25,659	0.89
CCF Komsomolska OJSC	*LFG*	21.78	56.10	24.9	56.6	0.19	25,756	25,707	0.95
CCF Ukraina OJSC	*LFG*	22.48	58.70	21.9	58,4	0.88	26,098	25,868	0.38
CCF Selidivska LLC	*LFG*	21.91	57.50	21.4	57	0.31	26,226	26,307	0.86
Kapustin Mine LLC	*LFG*	21.76	56.30	23.5	56.6	0.51	25,859	25,990	0.55

* Relative error of C^r calculations compared to experimental data from the Certificates C^r.

** Relative error of k_C calculations based on the elemental composition of coal from the Certificates according to formula (4) and according to the proximate analysis data using the established empirical dependencies given in Table 5.

CCF is Coal Cleaning Factory

and A^d coal from various coal enterprises of Ukraine. The table also shows the calculated C^r values based on the proximate analysis data using the established empirical relationships given in Table 4. The error of C^r calculations compared to the experimental data from the Certificates made ≤0.91 %.

Table 6 shows the k_C values calculated according to the elemental composition of coal according to formula (5) and according to the proximate analysis data based on the established empirical dependences given in Table 5. The error of calculations using the empirical dependencies was ≤0.95 %, which meets the requirements of the Monitoring Procedure and Directive 2003/87/EC.

Carbon dioxide Emissions at TPPs of Ukraine in recent years. According to the established dependencies of the carbon emission factors based on the data of the proximate analysis of coal (Table 5), as well as according to (3) for carbon dioxide emission factors, f (2) for carbon oxidation states, and (1) for emissions, there were performed calculations of k_C, k_{CO_2}, ε_C and CO_2 emissions generated by burning coal, natural gas, and fuel oil for power units of TPPs of Ukraine in 2017–2021. The C^r values calculated according to the established empirical dependences given in Table 4 were substituted into the (2). To calculate total CO_2 emissions at the TPPs, the following formula was used

$$E_{CO_2} = E_{CO_2}^{coal} + E_{CO_2}^{fuel\ oil} + E_{CO_2}^{gas}, \quad (16)$$

where E_{CO_2} is CO_2 emission which is generated during fuel combustion at TPPs per year, thousand t; $E_{CO_2}^{coal}$ is CO_2 emission which is generated when burning coal; $E_{CO_2}^{fuel\ oil}$ is CO_2 emission which is generated when burning fuel oil; $E_{CO_2}^{gas}$ is CO_2 emission which is generated when burning natural gas.

For calculations, information on the quality and costs of coal, natural gas and fuel oil consumed at TPPs and q_4 from the TPP's official reporting forms 3-Tech were used. The applied emission factor values of CO_2 for natural gas and fuel oil from the Monitoring Procedure are given in Table 1. Tables 7 and 8 show the results of these calculations for 2021, as an example. Table 8 provides information on the consumption of organic fuel and the combustion heat of fuel oil and natural gas.

Average values of carbon dioxide emission factors for mixtures of coal grades *A*, *L* and *G*, *LFG* at Ukrainian TPPs have been established. The k_{CO_2} values for Ukraine's TPPs which burn coal of grades *G* and *LFG* in 2021 ranged from 92,876 to 95,298 g/GJ, depending on the quality of the coal. The average k_{CO_2} value was 94,128 g/GJ, that is, the calculated k_{CO_2} values for thermal power plants, taking into account the quality of coal, differ from the established average value within 1.35 % and are less than the value given in [1, 2] (Table 1) by 1.75 %. The established k_{CO_2} value for coal of grades *A* and *L* is 6.37 % higher than the value given in [1, 2]. For 2017–2020, the values of the established factors are given in Table 9.

Fig. 4 summarizes the results of calculations for the period of 2017–2021. In recent years, gross emissions of CO_2 at Ukrainian TPPs were at the level of 38–49 million tons, while their annual reduction is observed due to a decrease in energy production and fuel consumption, primarily that of grades *A* and *L* [11].

Assessment of specific emissions of carbon dioxide was also performed, namely, specific emissions related to the energy supplied, g/kWh, and to the coal consumed, t/t of coal (Table 8). Specific emissions of CO_2 per unit of the supplied energy were in the range of 1,142–1,065 g/kWh. The decrease

Table 7

Results of calculations of carbon emission factors, CO_2 emission factors and degrees of carbon oxidation of coal for TPPs in Ukraine in 2021

TPP	Coal grade	Q_i^r, MJ/kg	A^d, %	k_C, g/GJ	k_{CO_2}, g/GJ	q_4, %	ε_C, share
				Table 5	f. (5)		f. (2)
Burshtynska	*G*, *LFG*	21.49	24.72	25,700	94,232	0.95	0.989
Vuhlehirska	*G*, *LFG*	22.04	25.15	25,435	93,262	0.24	0.997
Dobrotvirska, including		21.91	22.84	25,751	94,421	–	–
st. Nos. 7–8	*G*, *LFG*	21.80	22.69	25,808	94,630	1.76	0.979
4×50 MWt		22.17	22.63	25,672	94,130	1.83	0.978
Zaporizka	*G*, *LFG*	20.91	25.99	25,784	94,540	0.7	0.992
Zmiivska, including		21,99	25.67	25,396	93,118	–	–
st. Nos.1–4	*G*, *LFG*	21.91	25.93	25,398	93,126	2.21	0.974
st. Nos.5–6		22.02	25.57	25,394	93,112	0.75	0.991
st. Nos. 7–10		21.94	25.52	25,431	93,246	2.69	0.968
Kryvorizka	*L*,	22.47	22.04	26,782	98,199	3.88	0.955
	G, *LFG*			25,652	94,057		
Kurakhivska, including		17.80	35.78	25,787	94,554	–	–
st. Nos. 3–7	*G*, *LFG*	17.80	35.82	25,786	94,547	3.01	0.964
st. Nos. 8–9		17.79	35.70	25,792	94,569	253	0.970
Ladyzhynska	*G*, *LFG*	20.51	27.68	25,750	94,415	0.53	0.994
Luhanska	*A*, *L*	22.82	22.98	29,624	108,620	6.23	0.931
Prydniprovska	*G*, *LFG*	21.00	23.88	25,990	95,298	0.51	0.994
Slovianska	*G*, *LFG*	20.13	30.28	25,599	92,876	4.19	0.954
Trypilska	*G*, *LFG*	21.38	26.59	25,530	93,608	1.98	0.976
Average value	*A*, *L*	22.82	26.60	28,633	104,987	–	0.946
	G, *LFG*	19.61	27.51	25,671	94,128	–	0.989

Table 8

Results of calculating gross and specific CO_2 emissions at TPPs of Ukraine in 2021

TPP	Coal grade	B^{coal}, thsnd. t	Fuel oil		Natural gas		CO_2 emissions, thsnd. t				Specific CO_2 emissions	
			$B^{fuel\ oil}$, thsnd. t	Q_i^r, MJ/kg	B^{gas}, mln. m^3	Q_i^r, MJ/m^3	$E_{CO_2}^{coal}$	$E_{CO_2}^{fuel\ oil}$	$E_{CO_2}^{gas}$	E_{CO_2}	g/kWh	t/t coal
Burshtynska	*G, LFG*	4,110.9	0	40.67	44.2	34.54	8,230.5	0	85.7	8,316.2	1,127	2.0
Vuhlehirska	*G, LFG*	1,558.3	1.8	39.04	37.8	34.01	3,193.8	5.5	72.1	3,271.4	1,019	2.0
Dobrotvirska, including		945,1	0	–	7.5	34.60	1,914.5	0	14.6	1,929.1	1,084	2.0
st. Nos. 7–8	*G, LFG*	692.4	0	–	3.5	34.62	1,398.6	0	6.8	1,405.4	1,022	2.0
4×50 MWt		252.7	0	–	4.0	34.57	515.9	0	7.8	523.7	1,296	2.0
Zaporizka	*G, LFG*	2,158.3	0	–	41.8	34.55	4,230.7	0	81.0	4,311.7	1,037	2.0
Zmiivska, including		1,080.3	3.5	28.39	64.3	33.62	2,179.1	7.7	121.3	2,308.1	1,080	2.0
st. Nos. 1–4	*G, LFG*	312.3	2.3	28.37	41.2	33.62	620.4	5.1	77.7	703.2	1,096	2.0
st. Nos. *5–6*		728.9	1.2	28.44	22.5	33.61	1,481.2	2.6	42.5	1,526.3	1,075	2.0
st. Nos. 7–10		39.1	0	–	0.6	33.62	77.5	0	1.0	78.5	1,042	2.0
Kryvorizka	*L, G, LFG*	1,002.8	0	–	30.4	34.16	2,086.6	0	58.1	2,144.7	1,109	2.1
Kurakhivska, including		3,119,5	18.0	38.82	8.6	34.43	5,069.8	54.2	16.6	5,140.6	1,119	1.6
st. Nos. 3–7	*G, LFG*	2,148.0	13.0	38.79	4.5	34.43	3,484.5	39.1	8.7	3,532.3	1,147	1.6
st. Nos. 8–9		971.5	15.0	38.87	4.1	34.42	1,585.3	15.1	7.9	1,608.3	1,064	1.6
Ladyzhynska	*G, LFG*	1,620.3	0	–	12.7	34.36	3,117.4	0	24.6	3,142.0	1,103	1.9
Luhanska	*A, L*	937.2	11.1	41.19	–	0	2,163.2	35.5	0	2,198.7	1,207	2.3
Prydniprovska	*G, LFG*	612.0	0	–	2.7	33.70	1,217.2	0	5.1	1,222.3	1,063	2.0
Slovianska	*A, L*	909.9	1.1	29.89	16.7	34.61	1,616.3	2.7	32.5	1,651.5	1,122	1,8
Trypilska	*G, LFG*	997.1	4.0	35.36	56.2	34.13	1,948.5	10.9	107.5	2,066.9	1,084	2.0
Total or average value (percentage of the total)	all grades	19,051.7	39.5	37.96	322.9	34.18	36,967.6 (98.1 %)	116.5 (0.3 %)	619.1 (1.6 %)	37,703.2	1,096	1.94
	A, L	1,639.1	11.1	41.2	21.2	34.20	3,623.8	35.5	40.7	3,700.1	1,165	2.21
	G, LFG	17,412.6	28.5	37.08	301.7	30.14	33,343.8	81.0	578.4	34,003.1	1,089	1.91

in these values in 2019 and 2020 is associated with a decrease in the consumption of grade A and L coal and an increase in the total share of natural gas and fuel oil from 2 to 4–6 % in the TPP fuel balance in these years [11]. It should be noted that at modern coal-fired thermal power plants of America, China, Japan, and European countries, which operate with supercritical steam parameters (such as thermal power plants of Ukraine, steam pressure 240–260 bar), this figure is 860–1,000 g/kWh, and those operating with ultra-supercritical steam parameters (more than 280 bar) make 760–840 g/kWh [8, 19–21]. However, in most cases, they work at base load, while coal-fired power units of TPPs of Ukraine are applied in the Integrated Power System of Ukraine as manoeuvrable power.

The values of specific CO_2 emissions per ton of the coal consumed are 1.94 t/t for steam coal (all grades), 1.91 t/t for coal of grades *G, LFG,* and 2.12 t/t for *A, L* grades, which correlates with higher k_{CO_2} values for coal of these grades. The official annual reports of the Ministry of Energy of Ukraine contain information on the amount of generated electricity and consumed coal as well as forecast balances of electricity production at TPPs; therefore, the established specific emission values are convenient to use for estimating and forecasting carbon dioxide emissions at thermal power plants.

Conclusions.

1. A method for calculating and forecasting CO_2 emissions generated during coal combustion has been developed, based on the proximate analysis data, which allows obtaining results with an error of ≤2.5 %. It was established that for coal of

Table 9

Average value k_{CO_2}, g/GJ for TPP of Ukraine, 2017–2020, for different coal grades

Coal grade	Years			
	2017	2018	2019	2020
A, L	103,020	105,914	104,121	103,531
G, LFG	94,134	94,142	96,543	94,134

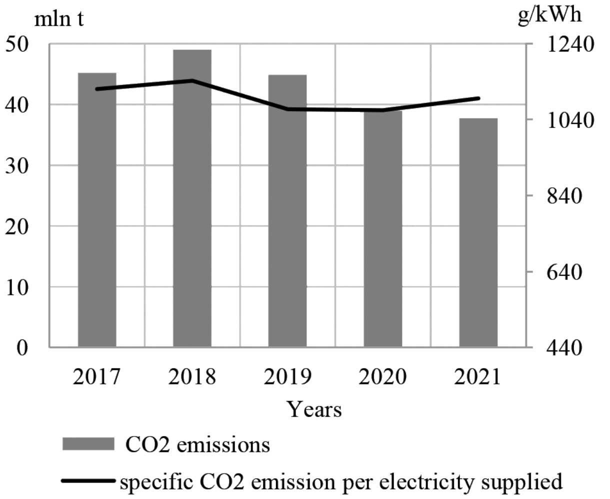

Fig. 4. Gross and specific emissions of CO_2 *at TPPs of Ukraine in recent years*

grades *A*, *L*, *G*, *LFG* and their mixtures, the relationship between the carbon content of coal and the combustion heat is of a linear nature: $C^r = K \cdot Q_i^r$, where *K* is a coefficient that depends on the coal grade. For coal grades *A, L,* the relative error of applying the obtained empirical dependences is ≤0.9 %, for grades *G, LFG* it is ≤1.9%, for mixtures *G, LFG* – 2.0 %. Empirical relationships of the type $k_c = a + bQ_i^r + cA^d$ were established for calculating carbon emission factors for coal of grades *A, L, G, LFG* and their mixtures. Verification of the method shows that the calculation error for highly metamorphosed coal is less than 1.0 %, which meets the requirements of the Monitoring Procedure and Directive 2003/87/EC.

2. Based on the obtained empirical relationships, the value of carbon dioxide emission factors was calculated for mixtures of coal of grades *A, L* and *G, LFG* at Ukrainian TPPs in the period of 2017–2021. For 2021, the average k_{CO_2} values for coal grades *G, LFG* were 94,128 g/GJ, while for coal grades *A, L* they made 104,987 g/GJ.

3. The developed method allows calculating carbon dioxide emissions at TPPs considering the information on the grade, consumption and proximate analysis of coal. CO_2 emissions calculated by the authors as for Ukrainian TPPs in recent years amounted to 38–49 million tons, with their annual reduction being observed, which is associated with a decrease in energy production and fuel consumption, primarily that of grades *A* and *L*.

4. It was established that at Ukrainian TPPs for all grades of thermal coal, the specific emissions of CO_2 per unit of the energy supplied in 2021 amounted to 1,084 g/kWh, while those per ton of the coal consumed made 1.94 t/t. For coal grades *G, LFG*, the specific CO_2 emissions made 1,089 g/kWh and 1.91 t/t, and for *A, L* – 1,165 g/kWh and 2.21 t/t. It is expedient to use the established specific values of emissions to estimate and forecast carbon dioxide emissions.

References.

1. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., ..., & Federici, S. (Eds) (2019). *IPCC 2019, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* IPCC, Switzerland. Retrieved from https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol2.html.

2. Verkhovna Rada of Ukraine. Legislation of Ukraine (n.d.) *On approval of the Procedure for Monitoring and Reporting on Greenhouse Gas Emissions. Resolution of the Cabinet of Ministers of Ukraine of September 23, 2020 No. 960.* Retrieved from https://zakon.rada.gov.ua/laws/show/9602020%D0%BF#n407.

3. Volchyn, I. A., & Haponych, L. S. (2018). Carbon dioxide emissions at the Ukrainian pulverized-coal thermal power plants. *Scientific Works of NUFT, 24*(6), 131-142. https://doi.org/10.24263/2225-2924-2018-24-6-17.

4. Ministry of Ecology and Natural Resources of Ukraine (n.d.) (2021). *Annual National Inventory Report for Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol.* Retrieved from https://menr.gov.ua/files/docs/Zmina_klimaty/Kadastr_2021/Ukraine_NIR_2021_draft.pdf.

5. Volchyn, I., & Haponych, L. (2019). Emissions of Greenhouse Gases from Ukrainian Thermal Power Plants. *Energy Technologies & Resource Saving*, (4), 3-12. https://doi.org/10.33070/etars.4.2019.01.

6. Hu, Y., & Shi, Y. (2021). Estimating CO_2 Emissions from Large Scale Coal-Fired Power Plants Using OCO-2 Observations and Emission Inventories. *Atmosphere*, *12*, 811. https://doi.org/10.3390/atmos12070811.

7. Quick, J. C. (2014). Carbon dioxide emission tallies for 210 U.S. coal-fired power plants: A comparison of two accounting methods. *Journal of the Air & Waste Management Association*, *64*(1), 73-79. https://doi.org/10.1080/10962247.2013.833146.

8. Ma, C.-M., & Ge, Q.-S. (2014). Method for calculating CO_2 emissions from the power sector at the provincial level in China. *Adv. Clim. Change Res*. *5*(2). https://doi.org/10.3724/SP.J.1248.2014.092.

9. Pan, K., Zhu, H., Chang, Z., Wu, K., Shan, Y., & Liu, Z. (2013). Estimation Of Coal-Related CO_2 Emissions: The Case Of China. *Energy & Environment*, *24*(7/8), 1309-1321. https://doi.org/10.1260/0958-305X.24.7-8.1309.

10. Volchyn, I. A., & Haponych, L. S. (2014). Estimate of the sulfur dioxide concentration at thermal power plants fired by Donetsk coal. *Power Technology and Engineering*, *3*(48), 218-221. https://doi.org/10.1007/s10749-014-0511-0.

11. Volchyn, I., Haponych, L., & Bizek, V. (2021). Emissions of sulfur dioxide and dust at coal power plants of Ukraine. *Environmental Problems, 6*(3), 145-153. https://doi.org/10.23939/ep2021.03.145.

12. Ministry of Environmental Protection and Natural Resources of Ukraine (2021). *Coefficients of emissions of greenhouse gases and lower calorific values (NTZ) of fuel types per unit mass used in the "National inventory of anthropogenic emissions from sources and absorption by sinks of greenhouse gases in Ukraine for 1990-2019"*. Retrieved from https://mepr.gov.ua/news/37927.html.

13. Juhrich, K. (2016). CO_2 *emission factors for fossil fuels, Climate Change.* Retrieved from https://www.umweltbundesamt.de/en/publikationen/co2-emission-factors-for-fossil-fuels.

14. Lee, J., Im, G., Yoo, J.-H., Lee, S., & Jeon, E.-C. (2015). Development of Greenhouse Gas (CO_2) Emission Factor for Korean Coal Briquettes. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *37*(13), 1415-1423. https://doi.org/10.1080/15567036.2011.610868.

15. Damayanti, R., & Khaerunissa, H. (2018). Carbon dioxide emission factor estimation from Indonesian coal. *Indonesian Mining Journal*, *21*(1), 45-58. https://doi.org/10.30556/imj.Vol21.No1.2018.687.

16. Quick, J. C. (2010). Carbon dioxide emission factors for U.S. coal by origin and destination. *Environ Sci Technol*, *44*(7), 2709-2714. https://doi.org/10.1021/es9027259.

17. Quick, J. C., & Marland, E. (2019). Systematic error and uncertain carbon dioxide emissions from U.S. power plants. *Journal of the Air & Waste Management Association*, *69*(5), 646-658. https://doi.org/10.1080/10962247.2019.1578702.

18. Chernyavskyy, M. V., Moiseyenko, O. V., & Monastyryova, T. M. (2017). History and prospects of coal use at TPPs of Ukraine in view of the goal of reducing greenhouse gas emissions. *XIII International Scientific – Practical Conference "Coal thermal energy: ways of reconstruction and development"*, (pp. 21-27). Kyiv: CETI of NAS of Ukraine. Retrieved from http://ceti-nasu.org.ua/upload/iblock/88c/88c6f0401fd1d30ba8dfad28c02675ad.pdf.

19. Phillips, J. N., & Wheeldon, J. M. (2010). Economic Analysis of Advanced Ultra-Supercritical Pulverized Coal Power Plants: A Cost-Effective CO_2 Emission Reduction Option. *Proceedings from the Sixth International Conference "Advances in Materials Technology for Fossil Power Plants". Santa Fe, New Mexico, USA*. Retrieved from https://www.asminternational.org/documents/10192/3298473/05319G_Sample_BuyNow.pdf/99adedbd-fc0e-4ff7-a650-5e2ad0210103.

20. Mohammed, S. J., & Mansoori, G. A. (2017). A Unique View on Carbon Dioxide Emissions around the World. *Global Journal of Earth Science and Engineering*, *4*(1), 8-17. https://doi.org/10.15377/2409-5710.2017.04.01.2

21. Gouw, J. A., Parrish, D. D., Frost, G. J., & Trainer, M. (2014). Reduced emissions of CO_2, NO_x, and SO_2 from U.S. power plants owing to switch from coal to natural gas with combined cycle technology. *Earth's Future. Bognor Regis*, *2*(2), 75-82. https://doi.org/10.1002/2013EF000196.

Оцінка та прогнозування викидів діоксиду вуглецю на вугільних теплових електростанціях України

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Мета. Розроблення, верифікація методу розрахунку та прогнозування викидів CO_2, що утворюється при спалюванні вугілля на ТЕС, за даними технічного аналізу. Виконання розрахунку валових і питомих викидів CO_2 на одиницю відпущеної енергії та маси спожитого вугілля на українських ТЕС.

Методика. При обробці даних елементного й технічного аналізу 170 зразків вугілля марок А, П, Г, ДГ із нижчою робочою теплотою згоряння (Q_i^r) у діапазоні від 17,2 до 31,0 МДж/кг і зольністю на сухий стан (A^d) у діапазоні від 3,8 до 38,0 %, для встановлення залежностей між коефіцієнтами викиду вуглецю (k_c), теплотою згоряння й зольністю, використані методи математичної статистики.

Результати. Розраховані значення коефіцієнтів викидів (k_{CO_2}) і валових викидів CO_2 для сумішей вугілля марок А, П та Г, ДГ на українських ТЕС у 2017–2021 рр. Для 2021 р. середні значення k_{CO_2} для марок вугілля Г, ДГ становили 94128 г/ГДж, а для марок вугілля А, П – 104 987 г/ГДж. Валові викиди CO_2 на українських ТЕС в останні роки були в діапазоні 38–49 млн т., а їхнє щорічне скорочення пов'язане зі зменшенням виробництва енергії та споживання палива на ТЕС, у першу чергу марок А та П.

Наукова новизна. Встановлені емпіричні залежності k_c для енергетичного вугілля різних марок виду $k_c = a + bQ_i^r + cA^d$. Знайдені коефіцієнти *а*, *в* та *с* для марок А, П, Г, ДГ та їх сумішей. Залежність між вмістом вуглецю у вугіллі й теплотою згорання має лінійний характер: $C^r = K \cdot Q_i^r$, де *K* – коефіцієнт, що залежить від марки вугілля. Встановлені значення *K* для вугілля марок А, П, Г, ДГ.

Практична значимість. Верифікація запропонованого методу показує, що похибка розрахунків становить менше 1,0 %. Це відповідає вимогам Порядку здійснення моніторингу та Директиви 2003/87/ЄС. Питомі викиди CO_2 на одиницю відпущеної енергії на ТЕС України для всіх марок енергетичного вугілля у 2021 р. становили 1084 г/кВтгод. Значення питомих викидів CO_2 на одиницю маси спожитого вугілля для вугілля всіх марок становили 1,94 т./т., для марок Г, ДГ – 1,91 т./т., а для марок А, П – 2,21 т./т. Офіційні щорічні звіти Міністерства енергетики України містять інформацію про кількість виробленої електроенергії, спожитого вугілля та прогнозні баланси виробництва електроенергії на ТЕС, тому встановлені нами питомі величини викидів зручно використовувати для оцінки та прогнозування викидів діоксиду вуглецю.

Ключові слова: *викиди*, *діоксид вуглецю, метод розрахунку, вугілля, вміст вуглецю, коефіцієнт викиду, теплоелектростанція*

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