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EMISSIONS OF SULFUR DIOXIDE AND DUST AT COAL POWER PLANTS OF UKRAINE

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Abstract. We developed an algorithm for the estimation of harmful emissions depending on the amount of supplied electricity and heat at coal-fired TPP. By this algorithm, we calculated the emissions of SO_2 and dust at Ukrainian TPP in 2017 and 2018. The values of SO_2 concentrations in dry flue gases at Ukrainian TPP in 2017 and 2018 depending on fuel brand, sulfur content, and method of slag removal in the boiler were in the range of 1520–5900 mg/Nm^3, and the general gross emissions of SO_2 were about 620 thousand t. The specific emissions of SO_2 were at a level of 14–15 g/kWh of supplied electric energy as compared with 1.2 g/kWh – the level for coal-fired plants of EU countries. At Ukrainian TPP, about 100 thousand t of dust were thrown away. The dust concentrations in flue gases at Ukrainian TPP were equal to 300–1800 mg/Nm^3. The values of specific dust emissions per 1 kWh of supplied electricity constituted 0.8–5.1 g against 0.2 g/kWh characteristic of present-day coal-fired TPP of EU countries. The level of gross emissions of SO_2 and dust at the TPP of Ukraine did not exceed the maximum possible according to the National Emission Reduction Plan of Pollutants from Large Combustion Plants.

Keywords: thermal power plant, flue gas, harmful emissions, sulfur dioxide, dust, emission limit value.

1. Introduction

Approval of the National Plan for Reducing Pollutants Emissions from Large Combustion Plants (hereinafter – the NERP) by the Ukrainian Government (National Emissions Reduction Plan …, 2017) requires combustion plant operators of Ukraine not to exceed the limit values of gross emissions of pollutants for the country for each year of the plan – from 2018 until 2028 for the SO_2 and dust and from 2018 to 2033 for the NOx. Technological standards of permissible emissions of the SO_2 and dust for the NERP activity period are defined in the order of the Ministry of Environment Protection of Ukraine of February 16, 2018, No. 62 (Technological standards..., 2018).

Until 31.12.2028, the limit values of SO_2 concentration in the flue gas of existing pulverized coal boilers shall not exceed 3400 mg/Nm^3 for anthracite, 4500 mg/Nm^3 for lean coal, and 5100 mg/Nm^3 for other hard coal and lignite. For the combustion of solid fuel in the circulating fluidized bed boiler, the limit value of SO_2 emission in the dry flue gas is 400 mg/Nm^3. Dust emission limit values in the dry flue gas for dry bottom boilers with an existing electrostatic precipitator (ESP) should not exceed 1000 mg/Nm^3, for wet bottom boilers with existing ESP with collected electrode length less than 12 m it is 1000 mg/Nm^3, and with electrode length 12 m and more it is 400 mg/Nm^3. The pollutants emissions from the last year of the NERP action are based on emission limit values from Directive 2010/75/EU on industrial emissions (Eur-lex, 2010). From 01.01.2029, the outlet concentrations of SO_2 in the flue gas should not exceed 200 mg/Nm^3, and dust – 20 mg/Nm^3.

The task of estimating the expected emission of pollutants for each year of TPP operation is relevant for both professionals and the public. The concentration of

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pollutant emissions in the flue gas and their gross emissions can be calculated according to official methods adopted in the EU and Ukraine (Vykydy zabrudniuiuchykh rechovyn..., 2002; Graham et al., 2007; Graham et al., 2012) due to information on fuel consumption (coal, natural gas and fuel oil) at thermal power plants, low heat value *LHV*, MJ/kg, and fuel elemental composition. The composition of coal (as received) is moisture W^r, ash A^r, carbon C^r, hydrogen H^r, oxygen O^r, sulfur S^r, and nitrogen N^r. For calculations of SO_2 emissions, it is also possible to use calculation methods based on empirical dependences according to ultimate (technical) analysis (Volchyn, Haponych, 2014; Volchyn, Haponych, 2016). It should be noted that such methods are not available for dust and nitrogen oxides.

The complete information on the brands of coal supplied to TPPs, their consumption, elemental composition and heat of combustion is usually not available. The official annual reports of the Ministry of Energy and Environmental Protection of Ukraine on the operation of the power industry sector contain information on the amount of electricity and heat produced at thermal power plants and forecast balances of electricity production. Therefore, our target was to develop a new algorithm for predicting the emission of pollutants generated by coal combustion at thermal power plants, depending on the amount of produced (released) electricity (MWh) or heat (Gcal) for each year of operation. In addition, we aimed to calculate the values of gross emissions and concentrations of SO_2 and dust at Ukrainian TPPs according to the developed algorithm, and compare the obtained values with those calculated by the standard method (Vykydy zabrudniuiuchykh rechovyn..., 2002) and the available operational data of TPPs.

In recent years, the Ukrainian thermal power plants have consumed 25–30 million tons of coal per year. In the fuel balance of TPPs, the share of coal is predominating, in 2018 it was 98.3 %, the shares of natural gas and fuel oil were 1.4 % and 0.3 %, respectively. Authors have developed an algorithm for estimating the expected emission of pollutants generated during the combustion of coal at thermal power plants.

2. Method description

The annual gross emission of pollutant *E*, t, is determined by the product of its average concentration *c*, mg/Nm^3, and the annual volume of dry flue gas V_{DFG}, Nm^3, by normal conditions (temperature 0 °C and pressure 101.35 kPa) and by standard oxygen content (for solid fuel – 6 %):

$$E = 10^{-9} \times c \times V_{DFG}. \quad (1)$$

The amount of dry flue gas V_{DFG}, m^3/a, is determined by the amount of burned fuel *G*, t/a, and the specific volume of dry flue gas v_{DFG}, Nm^3/kg

$$V_{DFG} = 10^3 \times G \times v_{DFG}. \quad (2)$$

The specific volume of the dry flue gas is determined by the content in the fuel of carbon *C*, hydrogen *H*, sulfur *S*, oxygen *O*, nitrogen *N*, ash *A* and moisture *W*. These parameters of the elemental composition are specified in fuel certificates issued by special certified laboratories using equipment that absent in chemical laboratories of thermal power plants.

In (Volchyn, Haponych, 2014; Volchyn, Haponych, 2016) it was proposed to consider the correlation between the lower heat value (LHV) of fuel, MJ/kg, which is determined at the TPP by the technical analysis, and the specific volume of dry flue gas (v_{DFG}). Based on the analysis of more than 100 certificates for coal products from mines and coal enriching plants of the Donetsk coal basin for samples of coal brand A, SA, G, DG, D for Ukrainian coal, v_{DFG} values were calculated, which can be related to the LHV of the fuel by the empirical dependence:

$$v_{DFG} = k \times LHV, \quad (3)$$

where *k* is the coefficient of proportionality, m^3/MJ.

Different coefficients of the *k* were proposed: for gas coal group (brand G, DG) is 0.357 and anthracite and semianthracite (brand A, SA) is 0.368 (Volchyn, Haponych, 2019). The value of the *k* for coal of the anthracite group is higher due to the low content of hydrogen in it, the combustion of which produces water vapor, which is not included in the dry flue gas.

Due to the incompleteness of high-temperature oxidation (combustion) of fuel carbon, there is a decrease in the specific volume of dry flue gas:

$$v_{DFG} = k \times Q_i^r \times \varepsilon_C = k_1 \times Q_i^r, \quad (4)$$

where ε_C is the oxidation degree of carbon of fuel; k_1 is the modified coefficient of proportionality, m^3/MJ.

The oxidation degree of carbon of fuel is determined by the share of heat loss of fuel q_4 due to mechanical incomplete combustion associated with the presence of unburned carbon (*UBC*) in the ash, according to the formula (Vykydy zabrudniuiuchykh rechovyn..., 2002):

$$\varepsilon_C = 1 - (q_4/C^r) \times (LHV/CHV) \quad (5)$$

where *CHV* is the heat of combustion of carbon to CO_2, which is equal to 32.68 MJ/kg.

According to previous studies (Volchyn, Haponych, 2016) ε_C with an accuracy of about 0.6 % can be determined by the formula:

$$\varepsilon_C = 1 - q_4/100 \quad (6)$$

Taking into account the actual values of heat loss due to mechanical incomplete combustion of fuel q4 at TPPs of Ukraine in 2017–2018 gave the following values of modified proportionality coefficients: for boilers running on anthracite and semianthracite it is 0.3463 Nm^3/MJ with a standard deviation of 0.0072 Nm^3/MJ, the error is 1.7 %; for boilers operating on gas coal it is 0.3537 Nm^3/MJ with a standard deviation of 0.0022 Nm^3/MJ, the error is 0.6 % (Volchyn, Haponych, 2014). The value of the average modified proportionality coefficient for coal is 0.3490 Nm^3/MJ with a standard deviation of 0.0072 Nm^3/MJ, the error is 1.2 %.

The amount of fuel consumed in boiler *G* is proportional to the amount of released electricity or heat. As the coefficients of proportionality can be taken the specific consumption of coal equivalent per unit of released electricity b_e, g/kWh, or the specific consumption of coal equivalent per unit of realized heat b_t, kg/Gcal. Then the amount of consumed coal equivalent $G_{ce(e)}$, t, for the supply of electricity in the amount of P, kWh, can be calculated by the formula:

$$G_{ce(e)} = P \times b_e \times 10^{-6} \quad (7)$$

The amount of consumed coal equivalent $G_{ce(t)}$, t, for the release of thermal energy in the amount of *W*, Gcal, is calculated by the formula:

$$G_{ce(t)} = W \times b_t \times 10^{-3} \quad (8)$$

To switch to natural fuel consumption, it should be considered that the heat value of coal equivalent (*CEHV*) is 29.3 MJ/kg or 7000 kcal/kg.

Then when supplying electricity, the amount of fuel consumed is determined by the formula:

$$G_{ce(e)} = 10–6 \times P \times b_e \times CEHV/LHV \quad (9)$$

The amount of gross emission of pollutants during the release of electricity E_e, t, can be calculated by the formula:

$$E_e = 10^{-12} \times c \times k_1 \times P \times b_e \times CEHV \quad (10)$$

where *c* is the average concentration of pollutants in the dry flue gas, mg/Nm^3.

The specific emission of pollutants per unit of electricity e_e, g/kWh, can be determined by the formula:

$$e_e = 10^{-6} \times c \times k_1 \times b_e \times CEHV \quad (11)$$

If data are available only on the amount of electricity produced P_{br}, the amount of electricity released *P* will be 87–90 % of P_{br}.

In the case of heat release, the amount of fuel and the number of pollutant emissions are determined by the formulas:

$$G_{ce(t)} = 10^{-3} \times W \times b_t \times CEHV/LHV, \quad (12)$$

$$E_t = 10^{-9} \times c \times k_1 \times W \times b_t \times CEHV \quad (13)$$

Thus, the amount of pollutant emission does not directly depend on the low heat value of the fuel. Fuel quality affects the value of specific consumption of coal equivalent.

The information on the concentrations of sulfur dioxide in the flue gas is required to calculate the gross SO_2 emissions at TPPs. This concentration depends on the coal brand, the low heat value, fuel ash content, sulfur content, type of slag removal from the boiler (type of boiler) and the presence of desulfurization plants at TPPs (Graham et al., 2007). Ukrainian coal thermal power plants are mainly equipped the boilers with liquid slag removal (wet bottom boilers – WBB), in which the efficiency of intra-furnace sulfur binding is 5.0 % (see Table 1). No desulfurization plant has been built at thermal power plants in Ukraine.

Authors recommend calculating the SO_2 concentrations in flue gas cSO_2, mg/Nm^3, according to the following empirical dependences for different types of slag removal for two groups of Ukrainian coal–brands A, SA and brands G, D, DG (Volchyn, Haponych, 2016):

– dry bottom boilers (DBB):

for coal brands A and SA

$$c_{SO2} = S^d \times (1400 + 24 \times Ad) \pm 40, \quad (14)$$

for coal brands G and DG

$$c_{SO2} = S^d \times (1350 + 31 \times Ad) \pm 60; \quad (15)$$

– wet bottom boilers (WBB):

for coal brands A and SA

$$c_{SO2} = S^d \times (1500 + 25 \times A^d) \pm 40, \quad (16)$$

for coal brands G, D and DG

$$c_{SO2} = S^d \times (1450 + 32 \times A^d) \pm 70. \quad (17)$$

The developed algorithm for calculating harmful emissions can be used to estimate the maximum allowable emissions of pollutants. For this purpose, the average concentrations can be taken as the emission limit values (the technological standards) defined in the order of the Ministry of Environment dated 16.02.2018 No. 62 (Technological standards..., 2018).

3. The main material and scientific results

3.1. Gross and specific emissions of sulfur dioxide at the power plants of Ukraine

Today, thermal power plants on fossil fuels form the basis of Ukraine's energy (Malovanyy et al., 2019; Mitin et al., 2021). As of January 1, 2019, the total installed capacity of TPPs of power-generating companies (PGCs) of Ukraine was 21.6 GW or 43.5 % of the capacity of the United Power System of Ukraine. Coal thermal power plants in 2018 generated about 30.0 % of the total amount of electricity. In addition, to reduce the deficit of anthracite at TPPs of the PGCs in 2017–2019, power units that worked on anthracite and semianthracite were reequipped for the combustion of coal of the gas group. 10 power units with a total installed capacity of 2.1 GW were retrofitted for the combustion of coal brand G and DG, namely power units No. 2, 5, 6 at Zmiivska TPP, No. 7-10 at Prydniprovska TPP, No. 3, 4 at Trypilska TPP and No. 1 at Kryvorizka TPP. At the beginning of 2018, Kryvorizka TPP introduced the joint combustion of coal brands A and D in the ratio of 70/30.

In recent years, the consumption of anthracite in Ukraine has decreased significantly–from 9.2 million tons in 2016 to 3.6 million tons in 2019, including due to the replacement of domestic coal of the gas group.

According to the algorithm developed by the authors to estimate the emission of pollutants, calculations of SO_2 emissions at Ukrainian TPPs in 2017–2018 were performed. Table 1 provides information on the type of boilers, brand of coal, technical analysis of coal composition (low heat value, ash content A^d as dry, sulfur content S^d as dry, %) and the obtained values of sulfur dioxide concentrations c_{SO2}, mg/Nm^3 (formulas (14)–(17)) taking into account the degree of oxidation of carbon of the fuel (Table 2, formulas (5), (6)) in dry flue gas of TPPs of Ukraine in 2017 and 2018.

The values of SO_2 concentrations in the dry flue gas at TPPs of Ukraine in 2017 and 2018, depending on the fuel brand, sulfur content and boiler type (WBB or DBB) were in the range of 1520–5900 mg/nm^3.

Tables 2 and 3 show the results of calculations of gross emissions of sulfur dioxide E_{SO_2},, thousand t/y, at TPPs of Ukraine in 2017 and 2018 according to the algorithm, proposed by the authors, depending on the amount of electricity and heat released into the grid, and the standard method that is based on the use of information on consumption and elemental composition of coal [(Vykydy zabrudniuiuchykh rechovyn..., 2002). For comparison, the operational data of TPPs are also presented (Ministry of Energy of Ukraine, 2020).

It is shown that the results of calculations of SO_2 emissions according to the proposed algorithm coincide well with those calculated by the standard method and the operational data of TPPs.

The results of the authors' calculations of total gross emissions and average specific emissions of sulfur dioxide at Ukrainian TPPs in 2006–2018 are presented in Fig. 1.

Table 1

Data on the project fuel, technical analysis of coal composition and values of average SO_2 concentration in the dry flue gas of Ukrainian coal thermal power plants in 2017 and 2018

Thermal power plant	Boiler type	Coal brand	2017				2018 рік			
			LHV, MJ/kg	A^d, %	S^d, %	c_{SO_2}, mg/nm^3	LHV, MJ/kg	A^d, %	S^d, %	c_{SO_2}, mg/nm^3
Slovianska	WBB	A, SA	24.3	19.5	0.8	1603	23.0	23.7	1.1	2217
Vuhlehirska	WBB	G, DG	21.9	23.8	2.7	5890	22.2	23.4	2.5	5471
Trypilska	WBB	A, SA G, DG	21.7	25.9	1.4	3083	22.3	25.1	1.7	3829
Zmiivska	WBB	A, SA, G, DG	22.5	23.6	2.2	4790	21.9	24.3	2.4	5262
Kryvorizka	WBB	SA A, SA, G	23.4	23.2	1.5	3019	23.8	20.9	0.7	1521
Prydniprovska	WBB	A, SA, G, DG	23.3	21.3	1.4	2927	21.8	23.1	1.3	2761
Zaporizka	WBB	G, DG	20.9	26.5	1.5	3472	21.0	25.9	1.4	3069
Burshtynska	WBB	G, DG	21.1	24.3	1.5	3367	21.5	23.6	1.5	3356
Dobrotvirska	DBB	G, DG	21.2	26.8	1.8	3925	22,0	23.0	1.7	3492
Ladyzhynska	WBB	G, DG	20.8	25.2	1.6	3700	20.9	24.5	1.6	3609
Kurakhivska	DBB	G, DG	18.1	36.7	1.5	3809	18.7	35.9	1.6	3910
Luhanska	WBB	A, SA	23.8	20.2	1.4	2846	23.5	19.9	0.8	1529
Average values										
for all coal brands			21.1	26.4	1.6		21.3	25.8	1.4	
for A + SA brands			23.6	21.7	1.4		23.3	22.1	1.0	
for G + DG brands			20.5	27.7	1.7		20.9	26.6	1.7	

Table 2

Results of calculations of gross sulfur dioxide emissions at Ukrainian TPPs in 2017 according to the proposed algorithm, standard methodology and operational data of TPPs

Thermal power plant	E_{SO_2}, thousand t/y	E_{SO_2}, thousand t/y	δ*, %	E_{SO_2}, thousand t/y	δ**, %	Specific emission, g/kWh
	proposed algorithm	[4]		TPP data		
Slovianska	14.4	14.5	0.98	13.9	3.18	6.84
Vuhlehirska	89.1	86.9	2.56	87.5	1.82	23.04
Trypilska	11.1	11.3	2.30	11.7	5.36	15.37
Zmiivska	25.0	25.1	0.41	22.7	9.88	22.02
Kryvorizka	31.0	31.0	0.04	31.1	0.32	13.26
Prydniprovska	16.9	16.8	0.67	16.0	5.59	14.77
Zaporizka	74.0	72.8	1.64	72.6	1.99	12.43
Burshtynska	113.9	112.4	1.38	113.8	0.14	14.26
Dobrotvirska	39.9	39.8	0.32	38.6	3.56	16.70
Ladyzhynska	72.2	70.8	1.93	71.0	1.65	14.96
Kurakhivska	96.8	99.3	2.54	99.3	2.51	16.29
Luhanska	29.9	30.9	3.23	30.1	0.65	13.26
TOTAL	614.2	611.6		608.3		
Average value			0.38		0.97	15.10

* Relative difference between the results of calculations according to the proposed algorithm and the standard method (Vykydy zabrudniuiuchykh rechovyn..., 2002).

** Relative difference between the results of calculations according to the proposed algorithm and the operational data of TPP.

Table 3

Results of calculations of gross sulfur dioxide emissions at Ukrainian TPPs in 2018 according to the proposed algorithm, standard methodology and operational data of TPPs

Thermal power plant	E_{SO_2}, thous. t/y	E_{SO_2}, thous. t/y	δ*, %	E_{SO_2}, thous. t/y	δ**, %	Specific emission, g/kWh
	proposed algorithm	[4]		TPP data		
Slovianska	29.1	29.8	1.96	29.75	2.1	9.26
Vuhlehirska	87.5	85.7	2.20	85.6	2.3	22.25
Trypilska	33.8	33.5	0.76	33,6	0.6	16.81
Zmiivska	43.3	43.1	0.28	NA***	–	22.97
Kryvorizka	14.7	14.3	1.88	NA	–	6.58
Prydniprovska	19.4	19.2	0.82	NA	–	12.73
Zaporizka	66.0	64.8	1.85	NA	–	11.15
Burshtynska	131.0	129.0	1.44	NA	–	14.93
Dobrotvirska	33.9	33.5	1.25	NA	–	14.94
Ladyzhynska	54.2	53.6	1.18	NA	–	15.02
Kurakhivska	96.3	95.9	0.41	NA	–	16.54
Luhanska	13.7	14.0	1.52	13,5	1,7	6.97
TOTAL	622.9	616.4		NA	–	
Average value			1.0			14.45

* Relative difference between the results of calculations according to the proposed algorithm and the standard method (Vykydy zabrudniuiuchykh rechovyn..., 2002).

** Relative difference between the results of calculations according to the proposed algorithm and the operational data of TPP

*** NA – not available.

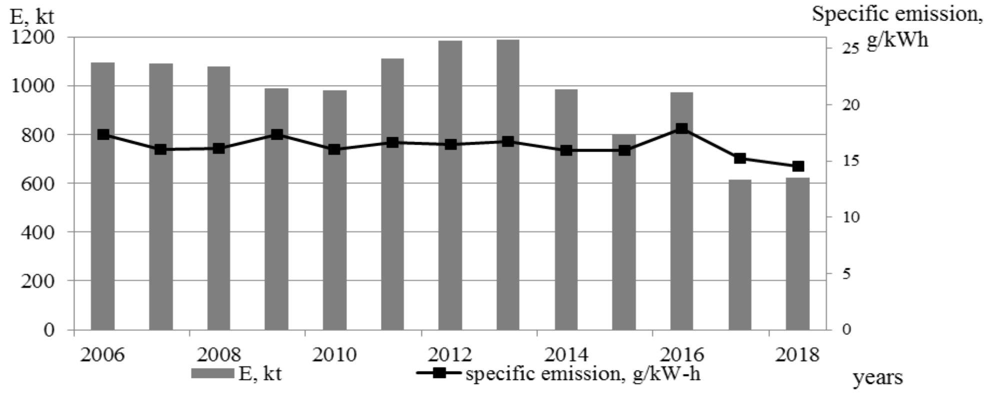

Fig. 1. Gross and specific emission of SO_2 at Ukrainian TPPs in 2006–2018

The values of specific SO_2 emissions at TPPs of Ukraine are high, they are at the level of 15–17 g/kWh of electricity, compared to 1.2 g/kWh of electricity – the average level of modern TPPs in the EU and the US, which are equipped with desulfurization plants (Lecomte et al., 2017; Gouw et al., 2014; Coal Unit Characteristics, 2019). Specific SO_2 emission at modern coal-fired power plants in India is 7.5 g/kWh, and in China, it is 0.1–1.0 g/kWh by the levels of consumption of coal equivalent for the released electricity of 278–321 g/kWh (Dai, et al., 2019; Ren et al., 2020; Wu et al., 2019).

The high values of specific SO_2 emissions at TPPs in Ukraine are explained by the lack of desulfurization plants and high levels of specific fuel consumption for electricity released at Ukrainian TPPs ((400±5) g/kWh) due to the predominant operation of TPP power units in shunting modes of variable loading (Volchyn et al., 2013).

3.2. Gross and specific emissions of dust at the power plants of Ukraine

Table 4 shows the operational data on gross dust emissions, E_{dust}, thousand t/y, at Ukrainian TPPs in 2017–2018 (Ministry of Energy of Ukraine, 2020). The Table also shows the calculated values of specific emissions per kWh of electricity released and dust concentrations c_{dust}, mg/Nm^3, in dry flue gas of TPPs of Ukraine in 2017 and 2018. Average dust concentrations were calculated by the formula:

$$c_{dust}=E_{dust}/V_{DFG}\cdot 10^{-6}, \qquad (18)$$

where V_{DFG} is the amount of dry flue gas, Nm^3, which is determined by formulas (2)–(6).

In recent years, about 100,000 tons of dust per year have been emitted into the air from Ukraine's thermal power plants. The values of specific dust emissions per kWh of released electricity are 0.8–13.1 g/kWh. Specific dust emissions at modern coal-fired power plants in the EU is 0.2 g/kWh (Lecomte et al., 2017) and in China, it is 0.05 g/kWh (Dai, et al., 2019; Ren et al., 2020). The dust concentrations in the flue gas at thermal power plants depend mainly on the ash content in the fuel and the efficiency of dust collectors and desulfurization plants. At Ukrainian TPPs, the dust concentration values in the flue gas are in the range of 300–1800 mg/Nm^3.

The assessment of the maximum allowable gross emissions of SO_2 and dust at TPPs of Ukraine was performed. The values of emission limit values (technological standards) defined in the order of the Ministry of Environment dated 16.02.2018 No. 62 (Technological standards..., 2018) were used as average concentrations. The results of calculations of gross emissions of SO_2 and dust for 2018 are summarized in Table 5.

Table 4

Operational data on gross dust emissions, specific emissions, and the average value of concentrations in dry flue gas of TPPs of Ukraine in 2017 and 2018

Thermal power plant	Coal brand	2017			2018		
		E_{dust}, thous. t/y	c_{dust}, mg/Nm^3	Specific emission, g/kWh	E_{dust}, thous. t/y	c_{dust}, mg/Nm^3	Specific emission, g/kWh
1	2	3	4	5	6	7	8
Slovianska	A, SA	4.1	449.5	1.96	7.8	578.2	2.48
Vuhlehirska	G, DG	5.8	382.9	1.55	5.8	360.4	1.48
Trypilska	A, SA	9.6	NA	13.08	16.0	1808.2	7.97
Zmiivska	G, DG	9.0	NA	7.94	6.2	738.1	3.27

Continuation of Table 4

1	2	3	4	5	6	7	8
Kryvorizka	A, SA, G	11.8	1160.7	5.07	8.3	855.2	3.69
Prydniprovska	G, DG	2.7	471.4	2.34	4.4	617.6	2.87
Zaporizka	G, DG	5.4	250.4	0.92	4.9	226.0	0.83
Burshtynska	G, DG	32.2	952.3	4.09	6.7	171.4	0,76
Dobrotvirska	G, DG	5.8	576,2	2.45	3.5	364.6	1.56
Ladyzhynska	G, DG	13.0	662.5	2.74	4.4	291.9	1.22
Kurakhivska	G, DG	33.2	NA	5.46	15.8	636.2	2.72
Luhanska	A, SA	7.7	736.1	3.33	8.4	916.8	4.22
TOTAL Average value		140.3	828.0	3.47	92.2	503.6	2.14

3.3. Estimation of the maximum possible emissions of SO_2 and dust according to the National Emission Reduction Plan of Pollutants from Large Combustion Plants

A comparison of the results of the calculations shown in Tables 3–5 showed that in 2018 the gross emissions of SO_2 and dust at TPPs of Ukraine did not exceed the permitted value according to the NERP. But to reduce emissions of pollutants from large combustion plants, the NERP provides for the reduction of annual emissions of SO_2 to 51.0 kt and dust – up to 5.2 kt in 2028. In addition, after 1.01.2029, Ukraine has to ensure compliance with the concentration of SO_2 in the flue gas of thermal power plants not more than 200 mg/Nm^3, and dust–20 mg/Nm^3, as required by Directive 2010/75/EU (Eur-lex, 2010). To achieve European environmental performance, it is necessary to dramatically increase the efficiency of existing dust cleaning equipment or build new modern gas cleaning equipment. It should be noted that the designing and construction of the desulfurization plants at TPPs takes 3–4 years, so work in this direction should begin today.

From June 30, 2020, all EU coal-fired power plants must meet the requirements of Directive 2010/75/EU (Eur-lex, 2010; Lecomte et al., 2017). The emission fee will be € 200 per ton of sulfur dioxide and € 50 per ton of dust. Today, 80 % of EU power plants exceed these standards (Climate analytics, 2020). The total cost of their modernization in accordance with the new standards for SO_2 and dust emission is about 9 billion Euros. In addition, the operating costs of these units with more efficient filters will also increase.

Many countries have gone the way of retrofitting coal-fired power plants to meet stringent environmental standards. In 1970, the introduction of flue gas treatment plants for harmful emissions began at US coal-fired power plants. About $ 12 billion was invested in it. During the period up to 2017, SO_2 emissions from US TPPs decreased by 86 %, dust – by 93 % (Coal Unit Characteristics, 2019). Specific emissions of sulfur dioxide are in the range from 0.02 to 5.7 g/kWh. But at the Whitewater Valley CHP (Indiana, Richmond) with an installed capacity of 100 MW, which was built in 1955 and which has no flue gas treatment plants, specific emissions of sulfur dioxide reach 14.8 g/kWh.

The cost of construction and installation of new modern equipment for flue gas cleaning from SO_2 at TPPs of Ukraine was estimated. According to the plans of rehabilitation and/or modernization, dismantling and decommissioning of power generating companies, the installed capacity of TPPs of Ukraine, according to our estimates, will be 16.7 GW. This corresponds to the estimates given in the Energy Strategy of Ukraine for the period up to 2035. The capital costs of installing sulfur treatment equipment at TPPs reach 200 Euros per kW, and dust cleaning is 50 Euros per kW of installed capacity. Therefore, the total estimated cost of such works reaches 4.0–4.5 billion Euros. Applying the practice of building a single scrubber with a "wet" chimney for several power units will reduce the specific capital and operating costs.

Table 5

Results of calculations of the maximum possible emissions of SO_2 and dust at the TPPs of Ukraine in 2018

Thermal power plant	Coal brand	c_{SO_2}, mg/Nm^3	E_{SO2}, thous. t	c_{dust},mg/Nm^3	E_{dust}, thous. t
2	2	3	4	5	6
Slovianska	A, SA	4500	60.7	400	5.3
Vuhlehirska	G, DG	5100	83.6	400	6.4
Trypilska	A, SA G, DG	4500 5100	45.7	1000	8.8

Continuation of Table 5

2	2	3	4	5	6
Zmiivska	G, DG	5100	44.4	1000	8.2
Kryvorizka	A, SA G	4500 5100	44.7	1000	9.7
Prydniprovska	G, DG	5100	37.5	1000	7.0
Zaporizka	G, DG	5100	110.1	400	8.6
Burshtynska	G, DG	5100	200.9	1000	39.0
Dobrotvirska	G, DG	5100	52.9	1000	9.7
Ladyzhynska	G, DG	5100	79.4	400	6.1
Kurakhivska	G, DG	5100	135.5	1000	24.6
Luhanska	A, SA	4500	41.5	1000	9.0
TOTAL			936.9		142.4

4. Conclusions

1. An algorithm for estimating the emission of pollutants depending on the amount of electricity and heat released at coal-fired thermal power plants has been developed.

2. The calculations of SO_2 emissions at TPPs of Ukraine in 2017 and 2018 were performed according to the developed algorithm. The results of calculations coincide with the available operational data of TPPs and the results of calculations according to the standard methodology based on information on consumption and elemental composition of coal. The values of SO_2 concentrations in the dry flue gas at TPPs of Ukraine in 2017–2018, depending on the fuel brand, sulfur content and type of boiler were in the range of 1520–5900 mg/Nm^3, and total gross SO_2 emissions were about 620 thousand tons The values of specific SO_2 emissions were at the level of 14–15 g/kWh of electricity released, against 1.2 g/kWh – the level for coal-fired thermal power plants in the EU.

3. About 100 thousand tons of dust were emitted at TPPs of Ukraine in 2017–2018. The values of dust concentration in the flue gases of Ukrainian TPPs were in the range of 300–1800 mg/nm^3. The values of specific dust emissions per 1 kWh of electricity were 0.8–5.1 g/kWh, compared to 0.2 g/kWh – the level of modern coal-fired power plants in the EU.

4. The level of gross emissions of SO_2 and dust at TPPs of Ukraine in 2018 did not exceed the maximum possible according to the National Emission Reduction Plan. But to reduce emissions of pollutants from large combustion plants. in 2028, the NERP provides for the reduction of annual emissions of SO_2 up to 51.0 thousand tons, and dust – up to 5.2 thousand tons, i.e reduction of SO_2 emissions by 10–15 times, and dust – by 20 times. In addition, after 1.01.2029, Ukraine must ensure compliance with SO_2 concentration in the flue gas not higher than 200 mg/nm^3, dust – 20 mg/nm^3, as required by Directive 2010/75/EU on industrial emissions. To achieve European environmental performance, it is necessary to dramatically increase the efficiency of existing dust cleaning equipment or build new modern gas cleaning equipment.

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