VARIABILITY OF CARBON EMISSION FACTORS FROM LIGNITE OF THE KOSTOLAC BASIN IN TIME

by

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This paper presents experimental tests of lignite from the Kostolac open-pit mine, used to operate the boiler of the Kostolac B2 thermal power plant in 2022. Experimental tests were conducted to determine the emission characteristics and carbon emission factor and compare these values with those taken and determined in 2016. A total of 31 samples taken in April 2022 were tested. As with our previous work, the experimental methodology includes proximate analysis, ultimate analysis and determination of calorific value, for the 'as received', 'as determined' and dry basis. Corresponding correlations were established for the tested Kostolac lignite. The emission characteristics of the Kostolac lignite from 2022 were compared with the corresponding values from 2016. Certain changes in the values of the carbon emission factor over time are a regular phenomenon and therefore periodic sampling and experimental determinations are inevitable to follow the changes in the values. For this change in coal properties, new values for the carbon emission factor are proposed, which should be used to calculate the total carbon dioxide emissions in the last period.

Key words:*Laboratory analysis, Carbon emission factor, Kostolac lignite.*

1. Introduction

In order to mutually harmonise the inventory of greenhouse gas emissions, a methodology has been proposed at the international level (2006 IPCC Guidelines for National Greenhouse Gas Inventories, with some rafinements - 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories) [1, 2, 3], adopting, for simplification, as already stated, predefined values for the net calorific value and the carbon emission factor (CEF) for fossil fuels. For the case in this paper and according to [2, 3], the proposed default value for the emission factor for lignite is 27.6 tC/TJ. The proposed default value for the net calorific value for lignite is 11.9 TJ/Gg,

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which is within a wide range of upper (5.5 TJ/Gg) and lower (21.60 TJ/Gg) limits. However, the use of these default values leads to an error in the calculation of the GHG emissions inventory. For this reason, the international methodology [1, 2, 3] recommends the use of more accurate data with the aim of a more precise emission calculation. In the case of lignite from open-pit mines of the Republic of Serbia used in the boilers of the thermal power plants of the Joint Stock Company Electric Power Company of Serbia, the CEF and low-temperature values deviate significantly from the recommended default values due to constant exposure to the atmosphere. The values change over time, so it is necessary to determine them experimentally on a regular basis. The calculation of the CEF for fuels for the production of electricity and thermal energy in the Republic of Serbia Joint Stock Company Electric Power Company of Serbia and the comparison with the IPCC standard values and other experimentally determined CEF values for lignite were presented [4, 5 and 6]. In the Laboratory for Thermal Engineering and Energy, "Vinca" Institute of Nuclear Sciences, an alternative experimental methodology [5, 6, 7, 8, 9 and 10] was adopted and applied to determine the necessary characteristics. For the determination of the lower heating value, a simple method with a calorimeter bomb is sufficient, which provides precise data in a very short time. The CEF is determined according to experimental measurements and simple calculations and the dependencies are determined. It is found that the values of the emission factor are inversely proportional to the lower heating value, i.e. as the heating value increases, the value of the emission factor decreases and converges towards a certain value.

The ultimate and proximate analysis was also presented and described in detail [11]. Based on the results obtained, the Kostolac CEF was calculated. A comparison of the results with those of the Kostolac lignite from 2016 [7] was presented with the corresponding conclusions.

2. Sample preparation and laboratory methodology

A total of 31 lignite samples from the Kostolac open-pit mine were tested (used in the Kostolac B2 thermal power plant TPP Kostolac B2, in 2022). Sample preparation and laboratory analysis were performed at the Laboratory for Thermal Engineering and Energy of the"Vinca" Institute of Nuclear Sciences, Department for fuel characterisation. Sample preparation was carried out prior to laboratory measurements in accordance with the standard ISO 5069-2: 1993. For the experimental laboratory tests, the samples were considered on an “as received”, “as determined” and “on dry” basis. Proximate analysis, ultimate analysis and determination of calorific value were performed in accordance withASTM D7582, ASTM D5373 (Standard Test Methods for Determination of Carbon, Hydrogen and Nitrogen in Analysis Samples of Coal and Coke),ASTM D3176 (Standard Practise for Ultimate Analysis of Coal and Coke) and the standard ISO 1928: 2009, respectively.

3. Results and comparison

Experimental tests were performed for all 31 Kostolac samples, on an “as determined” basis, and the contents for the other two bases (“as received” and “dry”) were calculated from the first. The contents of the Kostolac samples on an“as received” basis are shown in the tab. 1. Correlations were made on the basis of the results obtained: total Carbon content and combustible content, total hydrogen content and combustible matter content, total Carbon content and lower heating value and correlation between CEF and lower heating value.

Table 1. The results of experimental test of lignitesamples from Kostolac open-pit mine, “as received” basis, sampling year 2022

Sample N°	Proximate analysis					Ultimate analysis				
	W	A	C_{fix}	*Comb.*	H_d	C	H	$S_{tot.}$	S_g	$N + O$
	[%]	[%]	[%]	[%]	[kJkg^{-1}]	[%]	[%]	[%]	[%]	[%]
1	38.69	21.95	15.41	39.36	8728	26.02	2.30	0.88	0.35	10.70
2	38.65	21.77	15.75	39.58	8986	25.73	2.36	1.03	0.41	11.07
3	37.85	23.04	15.52	39.11	8687	24.63	2.31	1.06	0.46	11.70
4	36.74	23.00	16.54	40.26	8996	25.38	2.38	1.04	0.50	11.99
5	37.60	21.67	16.50	40.73	9109	25.88	2.39	1.03	0.48	11.98
6	36.97	22.72	15.92	40.31	9118	25.61	2.40	0.98	0.34	11.96
7	37.79	21.33	16.40	40.88	9340	26.22	2.39	0.97	0.38	11.89
8	37.98	23.87	14.83	38.15	8487	24.18	2.26	0.98	0.48	11.23
9	38.04	22.24	15.84	39.72	8961	25.92	2.36	0.98	0.51	10.93
10	39.80	21.14	15.78	39.06	8884	25.42	2.33	0.99	0.53	10.78
11	40.84	22.00	14.91	37.16	8780	25.14	2.15	1.02	0.54	9.33
12	39.59	22.19	15.32	38.22	8655	24.86	2.17	1.01	0.50	10.70
13	39.17	22.57	15.40	38.26	8602	24.94	2.28	0.98	0.50	10.55
14	38.98	23.86	14.73	37.16	8332	24.47	2.21	0.99	0.55	9.93
15	40.32	20.16	15.93	39.52	8871	25.29	2.32	1.04	0.56	11.36
16	41.35	20.73	15.26	37.92	8404	24.39	2.24	0.90	0.35	10.94
17	41.21	22.07	14.68	36.72	8031	23.67	2.17	0.91	0.44	10.42
18	40.34	22.06	14.98	37.60	8419	24.23	2.22	0.93	0.39	10.76
19	40.90	21.41	15.18	37.69	8349	24.14	2.22	0.86	0.37	10.96
20	39.54	24.01	14.38	36.45	8016	23.80	2.18	0.88	0.33	10.14
21	38.64	23.38	15.10	37.98	8572	24.60	2.26	0.95	0.52	10.61
22	38.28	25.02	14.59	36.70	8243	23.83	2.18	1.00	0.49	10.19
23	38.79	22.94	15.46	38.27	8529	24.77	2.26	0.89	0.44	10.81
24	38.56	23.69	14.98	37.75	8420	24.60	2.24	0.93	0.46	10.45
25	39.38	21.56	15.86	39.06	8850	25.51	2.30	0.97	0.54	10.72
26	41.60	19.37	15.71	39.03	8828	25.38	2.28	0.99	0.51	10.86
27	40.19	18.62	16.67	41.19	9345	26.96	2.40	0.98	0.47	11.37
28	41.25	19.37	16.00	39.38	8787	25.75	2.29	0.95	0.47	10.87
29	40.31	21.01	15.62	38.68	8724	25.34	2.24	0.95	0.35	10.75

Sample N°	Proximate analysis					Ultimate analysis				
	W	*A*	C_{fix}	*Comb.*	H_d	*C*	*H*	$S_{tot.}$	S_g	*N + O*
	[%]	[%]	[%]	[%]	[kJkg^{-1}]	[%]	[%]	[%]	[%]	[%]
30	41.87	16.68	16.95	41.45	9455	27.36	2.39	1.05	0.50	11.18
31	40.11	21.45	15.32	38.44	8557	24.73	2.26	0.92	0.49	10.96

According to the experimental data presented (Tab. 1.), the dependence of the total carbon content on content of combustibles, is linear. The experimental data are presented with square dots and correlated with the linear equation,Eq. (1):

$$2022: \quad C = 0.648 \cdot Combustible - 0.00245 \qquad (1)$$

For comparison, the diagram (Fig. 1) shows the correlation of the same variables based on sampling and experimental results from 2016, Eq. (2):

$$2016: \quad C = 0.658 \cdot Combustible - 0.211 \qquad (2)$$

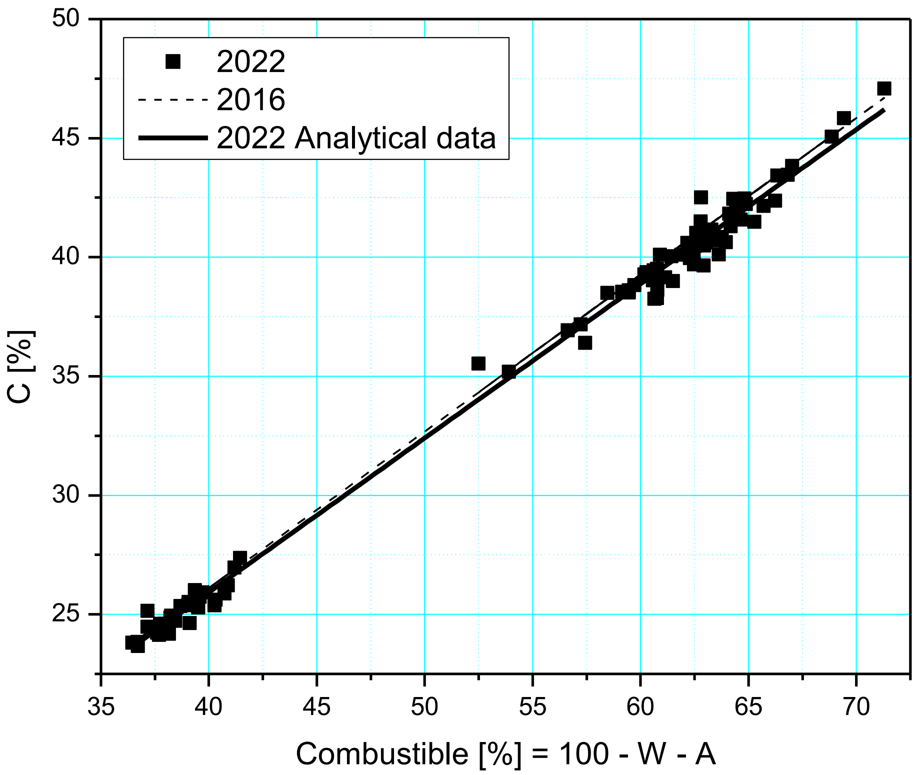

Figure 1. Total carbon content as a function of combustiblescontentfor the samples of lignite from the Kostolac open-pit mine, 2022 and 2016

In order to compare the dependence H = f (Combustibles), which determines the hydrogen content as a function of combustibles in the lignite samples, the analytical dependencies from the years 2022 (Eq.(3)) and 2016 (Eq.(4)) are shown side by side (Fig. 2).

2022 : $$H = 0.059 \cdot Combustible + 0.017 \quad (3)$$

2016: $$H = 0.057 \cdot Combustible - 0.04 \quad (4)$$

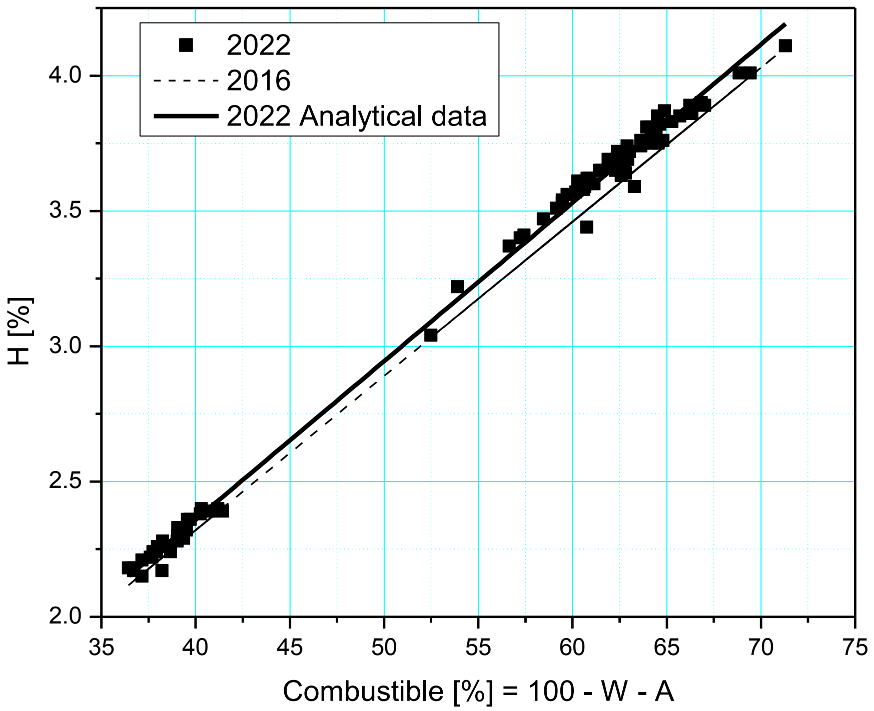

Figure 2. Total Hydrogen content as a function of combustibles content for the samples of lignite from the Kostolac open-pit mine, 2022 and 2016

Linear correlation,total carbon content – lower heating value, based on tested samples during 2022, has been presented by the following dependency, Eq.(5):

2022: $$C = 2.260\ H_d + 5.389 \quad (5)$$

The linear dependence of the same quantites, based on experimental data in 2016 is,Eq.(6), [6]:

2016 : $$C = 2.297\ H_d + 5.419 \quad (6)$$

Experimental and analytical data for dependency $C = f\ (H_d)$, for years 2022 and2016, has been presented on diagram, (Fig. 3).

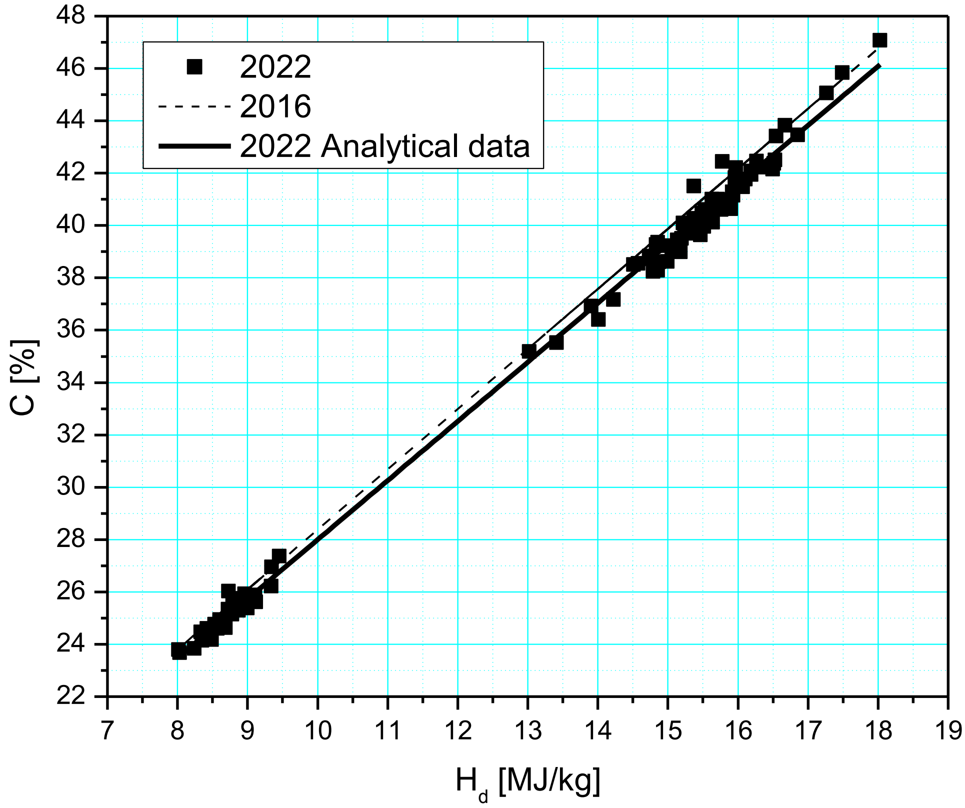

Figure 3. Total Carbon content as a function of low heating value for the samples of lignite from the Kostolac open-pit mine, 2022 and 2016

The analytical correlation of *CEF* on $H_d$has been obtained by dividing (Eq.(5)) and (Eq.(6))according to the following (Eq. (7)) and (Eq. (8)):

2022: $$CEF = 10\ C / H_d = 22.60 + 53.88 / H_d \tag{7}$$

2016: $$CEF = 22.97 + 54.19 / H_d \tag{8}$$

And has been presented on diagrams on(Fig. 4) and (Fig. 5).

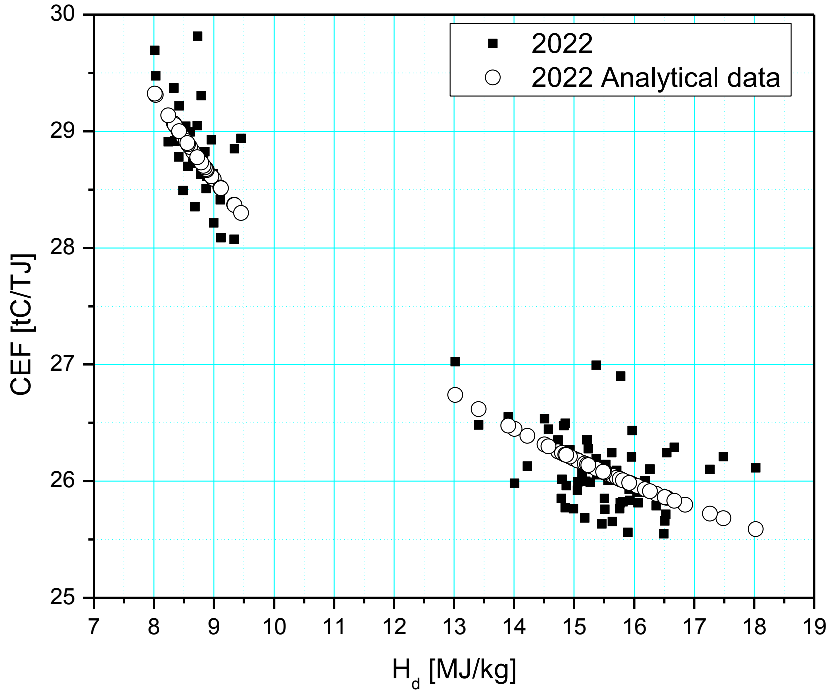

Figure 4. Carbon Emission Factoras a function of lowerheating value for the samples of lignite from the Kostolac open-pit mine, 2022 and 2016

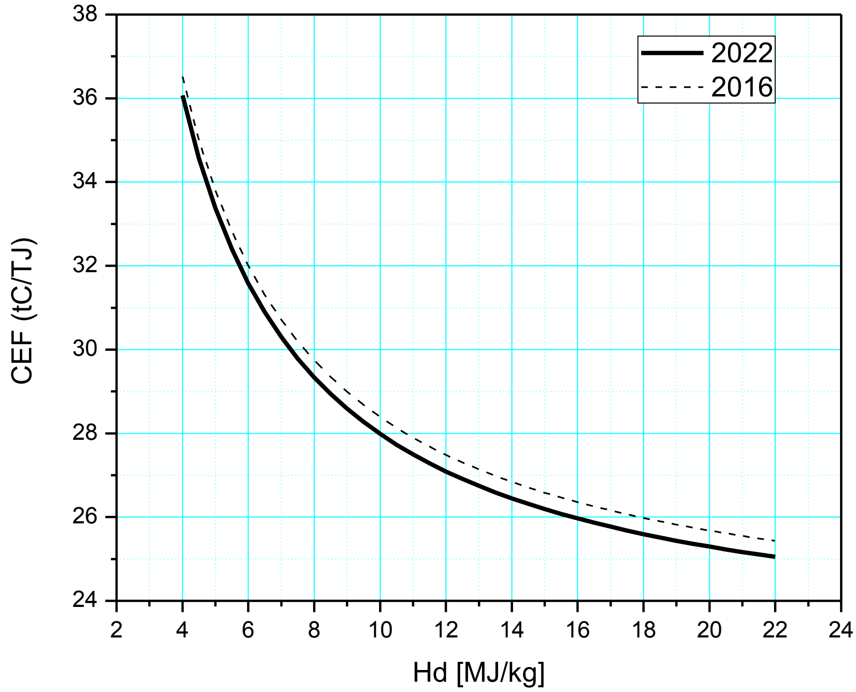

Figure 5. *CEF*as a function of$H_d$for the samples of lignite from the Kostolac open-pit mine, 2022 and 2016

The obtained results from the work presented in this paper are commented in terms of:

- Deviation of linear dependencies *C = f (Combustible)*, *H = f (Combustible)* and $C = f(H_d)$, for 2016 and 2022,
- Dependence deviation $CEF = f(H_d)$, for the 2016 and 2022 and
- Deviation of *CEF* in relation to the value recommended by the *IPCC*, for "as received" basis, for 2016 and 2022.

The deviation of the linear dependence (Eq. (1)) in relation to (Eq. (2)) is negligible and does not exceed 1.1% (Fig. 1). In relation to the dependency*H = f (Combustible)* for 2016 and 2022, the deviation is no more than 4% (Eq. (3)), (Eq. (4)) and (Fig. 2). Similarly, the deviation of the dependence $C = f(H_d)$ for the same years is not more than 3.3%. The dependencies shown indicate that the composition and quality of Kostolac lignite have not changed significantly over a six-year period. The real indicator of the extent to which the quality of the lignite has changed is the dependence on $CEF = f(H_d)$. The deviation of the CEF value for 2022 compared to 2016 is no more than 2% (Fig. 5). Taking into account the consumption of lignite from the Kostolac Basin for the operation of the TPPs Kostolac-A and Kostolac-B, simple calculations show that more than eight million tonnes of CO_2 are emitted annually (Eq. (9)):

$$CO_2 = G \cdot H_d \cdot CEF \cdot x \cdot 44/12 \qquad (9)$$

where are:

G [kt/year] – annual production of lignite. Annual lignite production from the Kostolac basin, used by theTPPs Kostolac-A and Kostolac-B is about 9000 kt/year,

$H_{d.}$ [MJkg^{-1}] – heating value, net calorific value. Assumed mean value of Kostolac lignite is about 9 MJ/kg^{-1},

CEF [tC/TJ] - carbon emission factor and

x – carbon oxidation factor, recommended value x = 1 for all types of coals [2].

The annual difference in CO_2 emissions for 2016 and 2022 is more than 115,000 tonnes, which is a significant emission burden. It can be concluded that even a very small change in the emission factor leads to significant changes in total emissions.

The deviation of the CEF value of the emission factor from the standard value prescribed by the IPCC and for lignite on an "as received" basis ($6 \leq H_d \leq 10$ MJkg-1) is of considerable importance and can be commented on according to the enlarged part of the diagram, (Fig. 6).

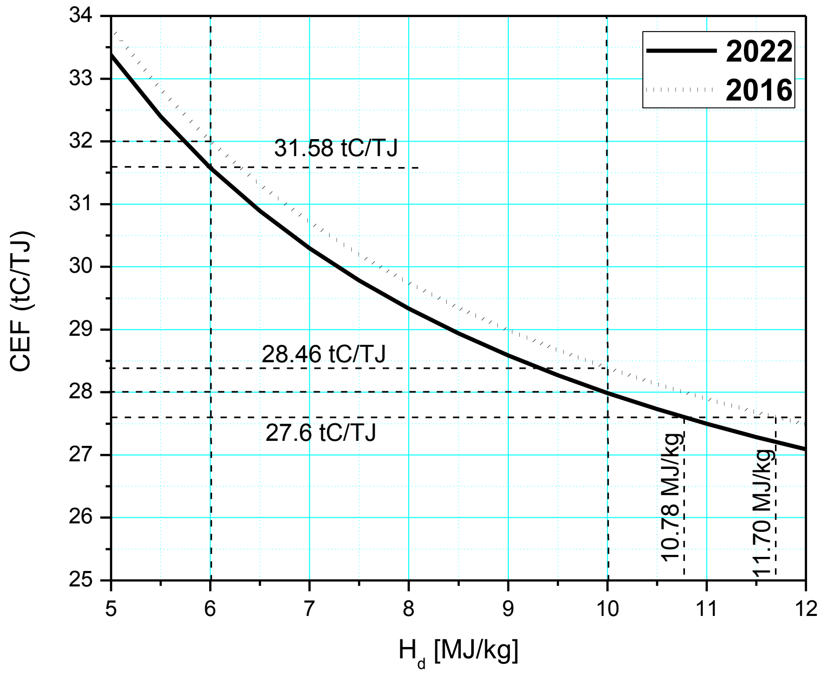

Figure 6. Deviation of CEF values as a function oflower heating values in range 6 ≤ H_d ≤ 10 $MJkg^{-1}$for the samples of lignite from the Kostolac open-pit mine, 2022 and 2016

The major deviations of *CEF* are for limit valuesH_d = 6MJkg^{-1}and10MJkg^{-1}).For H_d = 6MJkg^{-1},*CEF* values are 32 and 31.58 tC/TJ for 2016 and 2022, respectively. For H_d = 10 MJkg^{-1},*CEF* values are 28.46 and 28, respectively. It is evident that for the both limit values, *CEF* values are certainly higher than the prescribed one(27.6 tC/TJ). For the values of heat value H_d = 10.78 MJkg^{-1} and H_d = 11.70 MJkg^{-1}, the value of the emission factor is 27.6 tC/TJ, that is, the standard recommended value according to the *IPCC*.

Conclusion

The paper presents the results of an experimental study aimed at determining the emission characteristics of lignite from the Kostolac open-pit mine using the methodology presented previously. Samples from April 2022 were tested, the CEF factor was determined, compared with the test results from 2016, conclusions were drawn and appropriate recommendations were made for the periodicity of sampling and monitoring of changes in emission characteristics over time.

From the previous results it can be seen that the change in the emission factor of Kostolac lignite for the six-year period 2016 - 2022 is within the limit of 1.5%. Such a small deviation of the CEF factor value during the six-year period seems negligible. However, if we take into account the additional values (quantities) that are included in the calculation of carbon emissions (carbon dioxide), the indicated difference in CEF values is not negligible. In fact, we are talking about several million tonnes of emitted CO_2. Assuming that the mean value of H_d of Kostolac lignite is about 9 MJ/kg^{-1}, based on the dependence of Eqs. (7) and (8), diagram in (Fig. 6), the values of CEF factor for the years

2016 and 2022 are 28.99 tC/TJ and 28.59 tC/TJ, respectively, and the share of annual lignite production from the Kostolac basin, used by theTPPs Kostolac-A and Kostolac-B is about 9000 kt/year. Consequently, CO_2 emissions for 2016 and 2022 are 8,438,153 and 8,320,435 tCO_2/year, respectively, and their difference is 117,718 tCO_2/year.The most recent Regional Greenhouse Gas Initiative (RGGI) quarterly auction, held on March 3, 2021, resulted in a clearing price of $7.60 per short ton of carbon dioxide (CO_2) wich implies the difference in tax cost of $894,656.8 with using different values of CEF. Therefore, it is necessary to sample and test these lignite and lignite from other open-pit mines at regular intervals (2-3 years) to monitor the changes in emission characteristics and calculate the emitted amounts.

Using the experimentally determined lower heating value and the CEF calculated on the basis of experimental analyses, it is possible to determine the CO_2 emissions from industrial and thermal energy sources and the total CO_2 emissions at country level, knowing the fuel consumption data.

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Nomenclature

A – ash content [%],

C – Carbon content [%],

CEF – carbon emission factor [tC/TJ].

Combustible – combustibles content [%],

G – annual production of lignite[kt/year],

H – Hydrogen content [%],

$H_{d.}$– heat value, net calorific value determined at constant pressure [$kJkg^{-1}$] [$MJkg^{-1}$],

N + O – Nitrogen + Oxygen content [%],

S – Sulfur content [%],

W – moisture content [%],

x – carbon oxidation factor.

Subscripts

d - lower heat value (lower calorific value),

fix. – fixed,

g – combustible,

tot. – total.

Abbreviations

TPP - Thermal Power Plant,

IPCC – Intergovermental Panel on Climate Change,

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