Influence of Technical Characteristics of Solid Fuels at Estimation of Emissions from Small Boiler Plants

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***Abstract*—The paper is concerned with the small-scale boiler plants, located in the coastal area of Lake Baikal. There are about 70 boilers of such kind (less than 1 Gcal/h) in the region. The fuel used by the boilers is wood and coal from various deposits. There is no data on harmful emissions into the atmosphere from the small-scale boiler plants in the Baikal natural territory. One of the indices that influence the amount of air pollutant emissions is technical characteristics of fuels. Normally, these characteristics are given in reference books and represent averaged data on coal grade and deposit. The experimentally determined technical characteristics of solid fuels from fuel storages of boiler plants differ greatly from the averaged reference ones. The calculations of the emission quantities, based on the reference and experimental data on technical characteristics show that the maximum single emission can differ by 1.5-2 times for various emission components (particulate matter, sulfur and nitrogen oxides). The research made it possible to draw a conclusion that the use of technical characteristics of fuels from reference sources distorts the results of the research. In order to receive reliable environmental estimates, technical characteristics of coals should be determined directly at energy facilities.**

***Index Terms*—Technical characteristics of fuel, coal, experimental determination, calculated emissions, particulate matter, sulfur and nitrogen oxides.**

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I. Introduction

Numerous small-scale boiler plants in East Siberia and the Far East burn different types of fuel. There is no statistical information on the emissions of pollutants into the atmosphere from such energy sources. However, the emissions from the small-scale boiler plants are normally not cleaned and go directly to the surface layer of the atmosphere. A general characteristic of the boiler plants (capacity, load, equipment) can be found at best in the technical certificates of housing and utilities sectors of individual districts and municipal entities that can be accessed upon special request only. The assessment of emissions is a particularly urgent issue in the protected environmental zones of Russia, including coastal territories of Lake Baikal.

An object of the research is coastal territories of Lake Baikal, a unique site of world significance, protected by UNESCO. The law on the protection of Lake Baikal was adopted in 1999 [1]. It stipulates environmental zoning of the Baikal natural territory, and regulates economic activity. According to the law, some kinds of activity are either prohibited or limited. The limitations especially concern the central ecological zone of the Baikal natural territory, and particularly the operation and construction of coal-fired plants [2]. The heat sources operating in the central ecological zone are represented by the Baikalskaya CHP and above 91 boiler plants of various capacity, including 66 coal-fired boiler plants, 15 electric boiler plants, 9 wood-fired and 1 fuel oil - fired boiler plants. The small-scale boiler plants with a capacity of less than 1 Gcal/h dominate (57 plants). These boiler plants are normally socially important and provide heat to the facilities of social infrastructure [3]: schools, kindergartens, pharmacies, hospitals and residential areas.

It is worth noting that according to the current environmental regulations of the Russian Federation, it is generally accepted that the greatest contribution to the pollution of the surface layer of the atmosphere by small-scale boiler plants does not exceed 5% of the maximum permissible concentration. Thus, when the pollution of the air basin is calculated, their contribution is not taken into account. In the coastal zone of Lake Baikal, however, the sources of harmful emissions are small boiler plants, and therefore, it is sensible to keep track of these emissions.

Thus, the objective of the research is to assess the amount of air pollutant emissions from small boilers. We can either use the existing emission calculation techniques that are approved by the Government of the RF [4, 5], or measure the emissions independently using some certain experimental base. In both cases, the reliability of the initial data is important for the environmental calculations. The amount of emissionsinto the atmosphere is known to depend on the volume, technical characteristics of fuels, conditions of their combustion and degree of flue gas cleaning. In the paper, we assess the impact of technical characteristics of fuels on the amount of emissions, all other conditions being equal.

II. Review of emission calculation techniques

Various methodological approaches have been developed to assess the negative impact of energy companies on the environment.

These methods can be classified by area of research: environmental assessment (environmental impact assessment); risk assessment; damage assessment; identification of sustainable development indices; and combined methods.

Every energy facility undergoes the environmental impact assessment at the state level. The procedure of the environmental impact assessment is carried out by specialized entities that have a license to conduct it. In fact, the environmental impact assessment is a technique for assessing the influence of energy facilities on all components of the environment [6-8]. It includes:

- An estimation of the amount of pollutants emitted into the atmosphere, contaminated discharges into water bodies, production of waste, noise, electromagnetic impact, etc.;
- An analysis of the environmental measures developed for an individual power facility;
- An assessment of monitoring system for environmental safety;
- An identification of zones of the influence on the environment components, flora, fauna and humans;
- An evaluation of possible consequences of an emergency under the energy facility operation;
- A calculation of economic viability of the nature protection measures.

This method involves the collection of a large number of various technical and economic parameters, and huge statistical information. Moreover, the environmental impact assessment is a complex and time-consuming process. As a rule, the procedure of environmental impact assessment is carried out for newly introduced facilities.

The risk assessment methods [9, 10] entail determining the expected frequency of undesirable effects (on population, living organisms, vegetation, etc.) arising from the concrete negative impact of pollutants.

The environmental risk has recently become one of the management factors in the energy sector, which is applied to calculate the ratings of attractiveness. The calculation of environmental risks of energy facilities is related to the consideration of environmental pollution and damage to the environment components, including living organisms.

The world standards produced by ISO are used as criteria for assessing the environmental risks.

The environmental risk assessment provides the quantitative values of factors that affect the state of the environment and its response. In fact, the probability of an event is calculated given the value of possible damage from this event.

One of the positive aspects of the risk assessment methods is the advance consideration of possible damage and its prevention. The disadvantages of the methods include the absence of a unified formula for the calculation of environmental risk.

The damage assessment methods [11, 12] are related to the assessment of harm to the components of the environment, expressed in both monetary and physical terms. The methods of assessing the environmental damage are mainly based on probabilistic approaches and often on the expert assessments, direct and indirect calculations, and also on the market mechanism methods.

Damage is assessed for those components of the environment that are directly affected by the negative impact. Under these conditions, it is difficult to take into account the entire chain of possible consequences.

The existing methods for assessing environmental damage are based on a normative method which is described by complex mathematical relationships and requires a large number of initial data.

Currently, there is no monetary valuation of ecosystems affected by negative impacts. The existing methods for calculating environmental and economic damage are based on outdated price indicators, and their consideration through inflation factors does not correctly reflect the value of both a component of the environment and ecosystem as a whole. As a consequence, there is no universal formula for calculating the economically justified value of damage.

The methods for determining the sustainable development indicators are widely used [13-14]. One of the latest investigations in this area is based on the method of ecological and economic sustainable development indicators of the Russian regions [15]. This method entails a theoretical framework for the development of sustainability indicators and their aggregation. This method calculates the depletion of natural capital (energy resources, balance of forest resources) and damage from the pollution (emissions of CO_2 and particulate matter). All values are calculated as a percentage of gross national income.

The advantage of this method is the ability to apply it both at the regional and inter-country levels.

The methods for the development of the sustainable development indicators have as a rule aggregated indexes, which in turn is a disadvantage because important features of the territories and sources of emissions located on them, including energy facilities, are not taken into account. These methods can serve as some benchmark for making management decisions.

The combination of different methods for assessing the impact of energy facilities on the environment makes it possible to use different mathematical tools and apply the available information for calculations, and also to take into account the regional features to the greatest extent.

An ecological and economic assessment of the energy development options in the region is important when developing regional energy programs. The assessment makes it possible to search for a correspondence between the anthropogenic load and the ability of the environment to bear it without irreversible negative consequences [16].

The main methods for assessing the impact of energy facilities on the environment include the methods for calculating pollutant emissions into the atmosphere by power plants and boilers with different capacities, that are officially approved in Russia [17-18]. This research is based on these particular methods for environmental assessment of technical characteristics of fuels.

Each of the presented methods has its advantages and disadvantages and can be applied depending on the objectives to be achieved.

III. Formulation of the Problem of Technical Characteristic of Solid Fuel

A technique for the calculation of an amount of emissions of different substances (fly ash, oxides of nitrogen (NOx) and sulfur (SO_2), carbon monoxide), that are formed as a result of fuel combustion, suggests the use of data on technical characteristics of the fuel burnt. The technical characteristics of solid fuel include the following indices: moisture content, ash content, volatile yield, ultimate composition, heating value, and sizes of lumps. Normally, technical characteristics of solid fuels are given in special information and reference editions that contain averaged values and limits for variations in the indices for grade and deposit. The reference values of technical characteristics are available for many fuels. At the same time, the natural variability of coal properties within an individual deposit, and development of new deposits make the list of reference values suitable only for rough engineering calculations [19]. The reference books, as a rule, do not have the data on technical characteristics of low-grade coal from small open pit mines, for example Tarasovsky lignite coal, Tugnuisky lignite coal and Kharanutsky lignite coal, that are used locally.

Currently, the determination of technical characteristics of fuel is regulated by a great number of standards: State standards of Russia and National standardization organizations, for example ISO, ASTM.

Different methods are used to determine technical characteristics of coal. For example:

- volatile matter is determined according to State Standard 6382-2001 “Mineral solid fuel” (ASTM D3175-17 Standard Test Method for Volatile Matter in the Analysis Sample of Coal and Coke) [20];
- fuel moisture content is determined by mass loss due to sample drying in a drying chamber at a temperature of 105°C according to State Standard R 52911-2013 “Mineral solid fuel, methods of total moisture content determination” (ASTM D3173 / D3173M - 17a Standard Test Method for Moisture in the Analysis Sample of Coal and Coke) [21];
- fuel ash content is found by mineral residue after a complete combustion of a sample in the muffle furnace according to State Standard 55661-2013 “Mineral solid fuel. Determination of ash content” (ASTM D3174-04 Standard Test Method for Ash in the Analysis Sample of Coal and Coke from Coal). [22];
- the lowest heating value of fuel is determined by the classical method of burning a sample in oxygen in bomb calorimeter according to State Standard 147-2013. “Mineral solid fuel” (ASTM D5865-13 Standard Test Method for Gross Calorific Value of Coal and Coke) [23].

Thus, in order to determine technical characteristics of fuels, laboratory needs to be equipped with a great amount of equipment. Therefore, a common practice in Russia is the determination of fuel characteristics on site of production or in laboratories of energy companies. In doing so, however, we obtain characteristics of the entire coal basin or large batches ready for delivery to a consumption site.

In the territory at issue, the consumers use the coals from six various deposits: Pereyaslovsky, Azeisky, Tarasovsky, Tugnuisky, Kharanutsky (lignite coals) and Cheremkhovsky (hard coal). The indicated coals except for the Pereyaslovsky coal belong to the local coals produced in the Irkutsk region and Republic of Buryatia. Fuel oil and Pereyaslovsky coal are used in larger boiler plants with a capacity from 6 Gcal/h, and are not considered in this research.

Table I presents the comparison of various reference data on qualitative composition of fuels burnt in small boiler plants of coastal zone of Lake Baikal (using the coefficients for conversion from one state to another [24]) [25-32].

Comparison of the same fuel characteristics from different reference sources shows that for some indices the difference is insignificant, for example, the moisture content of the Azeisky lignite. At the same time, the other indices of this coal differ greatly, for example, ash content varies from 16.5 to 28 %.

Table 1. Technical characteristics of fuel burnt in coastal zone of Lake Baikal.

Fuel	W^r,%	A^d,%	C^{daf},%	S^{daf},%	N^{daf},%	Q^{daf}, MJ/kg	Source
Hard coal							
Tugnuisky coal	11-15	19-27	n/d	0.2-0.5	n/d	29-35.7	[25]
Kharanutsky coal	7-8	11-13	77.0	0.8	n/d	27.7-28.3	[26]
Tarasovsky coal	12-14	16-19	n/d	0.7	n/d	24.7-26.8	[25]
Cheremkhovsky coal	14-16	29-35	n/d	2.2-3.7	n/d	28.8-34.0	[27]
	15.0	29.8	77.0	1.6	1.1	32.4	[28]
	12.0	15.0	77.0	1.6	n/d	n/d	[29]
	13.0	27.0	77.0	n/d	1.6	31.7	[30]
	15.0	34.0	77.0	1.6	n/d	29.9	[31]
	12.0	25.0	n/d	1.0	n/d	30.1	[32]
Lignite							
Azeisky coal	26-30	24-28	n/d	0.5-0.8	n/d	27.9-28.1	[25]
	25.0	17.0	81.0	0.7	1.6	30.4	[32]
	25.0	16.5	73.0	1.6	1.1	30.4	[30]
Biomass							
Fuel wood (pine, birch)	40.0	1.0	51.0	0	0.7	17.21	[25]

Note: W – moisture content, A – ash content, Q – heating value of fuel, r – as received, d – dry, daf – dry ash free fuel mass; n/d – no data.

The observed disagreement between the reference data is explained by a number of circumstances. Firstly, variability of coal properties within one deposit, which is confirmed by a great number of studies conducted by different companies. This fact can be seen on the example of Cheremkhovsky hard coal. Secondly, the reference values were obtained for the coal produced more than 15 years ago and consequently were published in the 15-year old literature at minimum [30-31].

IV. A METHODOLOGY FOR EXPERIMENTAL DETERMINATION OF TECHNICAL CHARACTERISTICS OF SOLID FUEL

Experimentally, the technical characteristics of solid fuels were determined using a simultaneous thermal analyzer manufactured by the firm NETZSCH Geratebau. The analyzer includes the block for thermal analysis STA 449 F1, the quadrupole mass spectrometer QMS 403 Aeolos, and the block of pulse thermal analysis PulseTA.

The application of the simultaneous thermal analyzer proved suitable since it simultaneously determines different parameters for one sample, which provides high reliability of measurements. Moreover, the thermal analyzer gets increasingly wider application in the energy studies [33].

The technique for the determination of technical characteristics of solid fuel suggests preparing a representative sample by the standard method of quartering. The representative sample of fuel with a mass of 20-30 mg is burnt in the air flow. The resulting combustion products are recorded by the quadrupole mass spectrometer.

The choice of sample mass is caused by both the bulk density of fuel and the possibility of its complete combustion in specified conditions. The complete combustion is provided by a sufficient quantity of oxidizer passing through the furnace. The oxidizer quantity is calculated based on theoretically possible amount of air necessary for complete combustion of the fuel sample according to [34].

V. RESULTS OF THE EXPERIMENTS

Special experiments were performed in this research to compare and analyze the data on technical characteristics of the fuels.

Figure 1 presents a standard thermo-analytical curve and mass peak intensity curves of gas phase macrocomponents produced during the Azeisky lignite combustion.

An analysis of Figure 1 shows that in a temperature range from the room temperature to 150°C, the surface water is produced. In a temperature range of 280 – 660°C the process of coal sample combustion occurs and the ultimate oxides (H_2O, CO_2, SO_2, NO_2) are produced. The ash content is determined by the coal sample combustion residue.

Using the technique for a quantitative analysis of thermo-analytical and mass-spectrometric data [35], we determined the experimental values of technical characteristics of the investigated coals.

An error of the component determination makes up ±3% for C, ±0.3% for H, ±1% for O, ±0.05% for S, and ±0.02% for N. The experimentally determined characteristics of fuels burnt in the boiler plants of central ecological zone are presented in Table II.

Comparison of the data from Tables 1 and 2 indicates that the reference values and the experimentally determined values have discrepancies. These discrepancies are explained by a number of circumstances. Firstly, the properties of coals vary within the field. Secondly, the

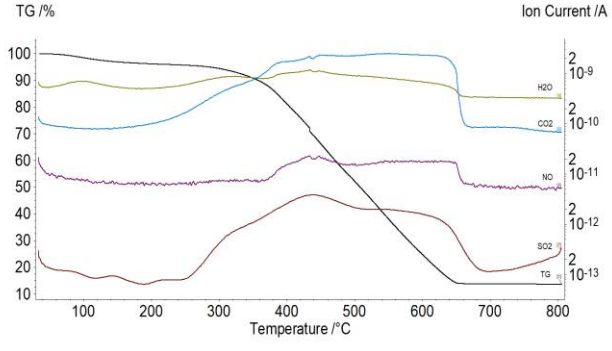

Figure 1. Thermo-analytical curve (% mass) and curves of intensity of peaks of burning masses of Azeisky coal.

Table 2. Technical characteristics of solid fuels determined by experiment.

Solid fuel	W^r,%	A^d,%	C^{daf},%	H^{daf},%	O^{daf},%	S^{daf},%	N^{daf},%	Q^{daf}, MJ/kg
Cheremkhovsky hard coal	3.3	16.8	70.2	4.5	23.2	1.0	1.3	26.9
Azeisky lignite	12.2	7.6	77.6	4.5	17.0	0.1	0.7	30.2
Kharanutsky hard coal	2.7	26.5	75.0	8.3	14.7	1.1	1.0	34.3
Tarasovsky hard coal	12.8	10.3	66.9	4.4	27.9	0.4	0.4	24.2
Fuel wood (pine)	47	1.3	53.9	5.8	40.3	0	0.4	19.9
Fuel wood (birch)	23	0.3	44.8	4.5	50.1	0	0.5	14.4

technical characteristics of coal change when it is stored and transported to the place of consumption. This is especially true if the fuel transportation is long and during this period coal undergoes several freeze-thaw cycles. The authors of [36] indicate that if the fuel quality control is not performed appropriately, the total losses in the energy value of fuel can be up to 20-30%. Thirdly, the coal samples studied in this research were taken not in the place of its extraction, but in the fuel storage of the boiler plants of the required level of power.

However, the difference in W^r cannot characterize the quality of measurement, since the experiments involved dried coal. Moreover, ordinary coals at deposits are known to have rather high moisture content reaching 40%.

We can also state that the reference value of ash content Ad is apparently overstated. It is probably assumed according to the upper value of a range of possible values [32], which is proved in [37] where the value of ash content is lower and close to an experimentally determined value. Thus, based on an analysis of the obtained results we can conclude that the reference value should be considered to be less accurate. In the case of biomass, the difference between the experimentally determined technical characteristics and reference values is explained by different structure and ultimate composition of pine and birch.

VI. Discussion and calculation of the pollutants

In the coastal areas of Lake Baikal most of the small boiler plants have hand-fired furnaces. Therefore, the calculations of emissions from combustion of various fuels in small boiler plants assume the hand-fed hot water boiler KVr-0.5. The main technical characteristics of such boilers can be found on websites of different companies [38].

The emissions of harmful substances into the atmosphere are calculated according to the technique approved by the State Committee of the Russian Federation for the Protection of Environment in 1999.

Table 3. Technical Characteristics of the boiler KVR-0.5, depending on the fuel type.

Index	Fuel type		
	Hard coal	**Brown coal**	**Fuel wood**
Carbon loss (q_4),%	6	7	1
Fly ash share (a_{fa})	0.22	0.19	0.25

The technique is intended for the determination of air pollutant emissions from fuel combustion in boilers with a capacity below 30 t of steam per hour or less than 20 Gcal/h [4, 5]. The calculation was done for four main components: particulate matter (M_S), SO_2 (M_{SO_2}), NOx (M_{NOx}), and CO (M_{CO}). The initial data on qualitative characteristics of fuels were reference data (Table 1) and experimentally obtained data (Table 2). Thereby, the reference data for Tugnuisky hard coal, Azeisky lignite and Cheremkhovsky hard coal are the data taken from the information and reference edition published by Rosinformugol in 2006 [25] that were assumed for raw steaming coal on average for a deposit.

Consumption of coal equivalent is assumed according to the technical data for boiler KVr-0.5 and equals 88 kg c.e./h [37]. Incomplete combustion (q_3) is assumed to equal 2% for all considered types of fuel. Data on carbon loss and ash content in the flue gas are presented in Table III [4, 25], there is no flue gas cleaning.

The calculated fuel characteristics by reference and experimentally determined values are presented in Table IV. The calculation is characterized as a maximum emission at a rated load of the boiler.

The qualitative characteristics of Tugnuisky hard coal were not measured. This is why this coal is not considered in the comparison of calculation results.

The comparison of the obtained results shows that the emission values calculated by the fuel characteristics taken from the reference literature in most cases exceed the calculation results based on experimentally determined characteristics by 1.5-2 times for different emission components (Table V).

In the case of Azeisky lignite and Cheremkhovsky hard coal, the overall difference for all pollutants makes up more than 2 g/s (or by 1.5-1.6 times). The close results are obtained for the emissions from biomass combustion. Moreover, the calculation results do not virtually differ for the quantities of nitrogen oxides and carbon oxide for all considered fuel types, whereas the divergence in the amount of particulate matter and sulfur dioxide is great. Nevertheless, the obtained results made it possible to compare the environmental indices of the fuel.

The highest emissions of SO_2 are observed at combustion of Cheremkhovsky hard coal - 1.35 g/s, and the lowest – at combustion of Tugnuisky hard coal - 0.18 g/s. The emissions of nitrogen oxides for all the studied fuels lie in a range of 0.55 – 0.63 g/s.

As for the amount of carbon monoxide emissions, they

Table 4. Calculated emission for reference and experimentally determined technical characteristics of fuel, g/s.

Fuel	Emission by component				Total
	Ms	Mso_2	M_{NOx}	Mco	
Reference technical characteristics					
Azeisky lignite coal	4.07	0.40	0.57	1.33	6.38
Cheremkhovsky hard coal	3.64	1.35	0.59	1.35	6.94
Tugnuisky hard coal	2.80	0.18	0.62	1.36	4.94
Tarasovsky hard coal	2.23	0.29	0.62	1.35	4.49
Kharanutsky hard coal	2.02	0.33	0.63	1.35	4.33
Fuel wood (pine, birch)	0.32	0	0.55	1.42	2.29
Experimentally determined technical characteristics					
Azeisky lignite coal	1.97	0.04	0.63	1.33	3.97
Cheremhovsky hard coal	2.33	0.48	0.62	1.35	4.78
Tarasovsky hard coal	1.96	0.21	0.60	1.35	4.12
Kharanutsky hard coal	2.75	0.42	0.64	1.35	5.15
Fuel wood (pine)	0.34	0	0.55	1.42	2.31
Fuel wood (birch)	0.26	0	0.56	1.42	2.23

Table 5. Comparison of calculation results of emission for reference and experimentally determined fuel characteristics (difference).

Fuel	Components of emissions				Total
	Ms	Mso_2	M_{NOx}	Mco	
Difference (between the calculations based on reference data and calculations based on measured data)					
Azeisky lignite	2.10	0.36	-0.06	0	2.41
Cheremkhovsky hard coal	1.31	0.87	-0.03	-0.02	2.16
Tarasovsky hard coal	0.27	0.08	0.02	0	0.37
Kharanutsky hard coal	-0.73	-0.09	-0.01	0	-0.82
Fuel wood (pine, birch)	-0.02	-	0	0	-0.02
Multiplicity factor (between the calculations based on reference data and calculations based on measured data)					
Azeisky lignite	2.1	10.0	0.9	1.0	1.6
Cheremkhovsky hard coal	1.6	2.8	0.95	1.0	1.5
Tarasovsky hard coal	1.1	1.4	1.03	1.0	1.1
Kharanutsky hard coal	0.7	0.8	0.98	1.0	0.8
Fuel wood (pine)	0.9	-	1.0	1.0	0.99

appeared to be almost the same for the considered coals (1.33 – 1.36 g/s), and the emission from fuel wood combustion is a bit higher – about 1.42 g/s.

The emissions of particulate matter (fly ash) depend largely on ash content in the fuel. Therefore, they were the highest for the most high-ash (Cheremkhovsky and Kharanutsky) hard coals.

VII. Conclusion

The data on technical characteristics of solid fuels, particularly coal, from reference books considerably distort the findings of the research, i.e. the amount of pollutant emissions coming to the atmosphere from small boiler plants burning them. The final result for the maximum single emission for one and the same type of coal can differ by 1.5-2 times for various emission components (particulate matter, sulfur and nitrogen oxides).

In order to calculate more accurately the amount of emissions, we recommend the use of characteristics experimentally determined directly at energy facilities rather than reference data.

Large-scale energy companies determine technical characteristics of coal on a mandatory basis. However, small boiler plants do not make such measurements. Moreover, the quality of coals gets considerably worse at storage, which increases carbon loss and unburnt fuel as well as the share of fly ash. Consequently, the amount of emissions into the atmosphere rises. Therefore, it is especially important to measure moisture, ash and sulfur content of the fuel, because the calculated values of particulate matter and sulfur oxides emissions diverge greatly depending on the initial characteristics of solid fuels.

Thus, the conducted studies allow us to draw the following conclusion. The emissions of pollutants from combustion of Azeisky lignite are lower by 1.6-2.2 times compared to the other considered types of coal. Table VI demonstrates the specific emission into the atmosphere per ton of burnt fuel for the considered types of coal and fuel wood. Specific emission is calculated as a sum of three main components: particulate matter, sulfur and nitrogen oxides when burning 1 ton of fuel.

However, as the calculations show, from an environmental perspective, fuel wood can become the best alternative to coals, as the specific emission from fuel wood combustion is much lower.

Table 6. Specific emission into the atmosphere from combustion of 1 ton of fuel (or 1 m^3 of firewood), T of emission/t of fuel.

Coal			**Fuel wood**
Azeisky lignite coal	**Cheremkhovsky hard coal**	**Tugnuisky hard coal**	
0,11	0,24	0,18	0,005

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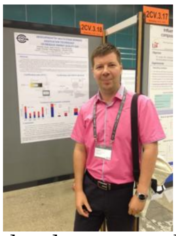

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