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Selected Parameters of Oat Straw as an Alternative Energy Raw Material

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Abstract: Straw is treated as agricultural waste, and it is available in almost every region of Poland. A total of 30 million tons of straw is produced per year, of which there is a surplus of approximately 13.5 million tons of undeveloped straw. For energy purposes, straw from cereals or rapeseed is most often used. When analyzing scientific publications, it was noticed that, in Poland, large amounts of oat straw are produced, and there is no alternative use for it. Hence, we conducted research to determine the energy value of oat straw. Raw material was obtained from an individual farm from 2018 to 2020. Selected energy parameters for straw burned alone (100%) or co-fired with coal were analyzed in the following weight proportions: 70/30, 80/20, and 90/10 coal/oat straw. It was shown that changing weather conditions, in particular years, had a modifying effect on some of the energy parameters of straw. The calorific value of straw was lower than that of coal, but its impact on environmental pollution turned out to be significantly lower. The difference in combustion heat between coal and straw was 11.74 MJ·kg^{-1}. Investigations into pollutant concentrations were performed for cubes of compressed straw and hard coal. Mixtures of these fuels were not studied in this part of the work. The combustion of straw resulted in a reduction of harmful NO, NO_X, and SO_2 pollutants and an increase in CO compared to coal combustion. As for hydrogen content—it was the highest in carbon and the lowest in straw. In the case of analytical moisture, an inverse relationship was observed. In the case of both coal and straw, the ash content varied throughout the years of research. As the boiler power increased from 5 to 25 kW, the consumption of burned raw material increased significantly. The results indicate that the surplus of oat straw can be rationally used to obtain thermal energy, including co-combustion with coal. This will allow one to avoid burning straw in the fields, which causes great harm to the natural environment.

Keywords: *Avena sativa* L.; solid biofuel; biomass; straw; co-firing; energy parameters; energy efficiency; calorific value; renewable energy

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1. Introduction

Environmental protection (in particular, protection against air pollution) is an extremely important global policy in many countries. The problem of air pollution is particularly significant in Poland, where the heating market is one of the largest in Europe and is based on 74% of the use of fossil fuels, in particular hard coal [1]. Therefore, much attention is paid to the use of biomass as an energy source. By replacing some fossil fuels with biomass, the goal is to reduce the consumption of conventional fuels and greenhouse gas emissions [2–4]. Biomass can be of forest origin (e.g., woodchips, wood waste), agricultural origin (e.g., straw and other plant residues, which constitute waste material in agricultural production), animal excrement, or organic waste generated in the agri-food industry. Biomass is a specific commodity and requires proper harvesting, transport, storage, and utilization [5–7]. Agricultural biomass can be used for energy purposes in direct solid biofuel combustion processes (e.g., wood, straw), or converted to gas (e.g., agricultural biogas). However, compared to other popular energy resources, biomass is more difficult to use, mainly because it is not homogeneous and has a low energy content relative to its volume [8–10]. Straw is agricultural waste, available in almost every region of Poland. The resources of unnecessary straw in our country amount to approximately 13.5 million tons per year. Nearly all kinds of straw can be used for energy purposes. Straw as an energy carrier reduces the costs of heat generation, improves the profitability of agricultural generation, and has a positive impact on the environment [4,11,12]. The replacement of some fossil fuels with biomass aims to reduce the consumption of conventional fuels and greenhouse gas emissions [2,4]. Weiser et al. [13] believe that straw is one of the agricultural waste that can be utilized largely for energy purposes. Compared to other agricultural raw materials, it does not compete on the market with food or fodder. Thompson [14] indicates that in the case of agricultural energy resources, ethical questions regarding their impact on food security are often raised. In turn, Gomiero et al. [15] believe that the large-scale use of crop residues or agricultural waste for energy production may pose a threat to soil fertility and biodiversity. Hence, only the surplus of undeveloped straw should be burned.

The topic of straw utilization has already been discussed more than once in publications all over the world [1–5,9,10]. In Poland, smaller heating installations still burn direct biomass in an untreated form, cubes, pellets, or briquettes. Straw is also used as an additive to fossil fuels (coal). Baum et al. [16] and Kaczmarczyk et al. [17] predict that straw will be used not only for the production of heat energy, but also electricity or biofuel.

In the 1980s, straw was mainly used as bedding material, feed ingredient, or an element for insulating livestock buildings. At present, however, it is not profitable and that is why many farmers have resorted to burning excess straw in the field, but it is prohibited due to the damage it causes to the environment [3]. The use of straw as a fuel is a new alternative that is beneficial for the environment and farmers [18]. Agbor et al. [19] state that biomass energy has long been accepted as a useful renewable energy source, especially in reducing greenhouse gas emissions. In addition, the energy from biomass is CO_2 neutral. Various biomass raw materials have been co-fired in coal and gas power plants for many years. As a result, NOx and SOx emissions are reduced. However, the future of biomass energy management depends on many factors, including political decisions and changes in legal regulations [19]. Gonzalez-Salazar et al. [20] report that gas-fired power plants emit more NOx and CO than coal, but less CO_2 and SOx. Therefore, co-firing of biomass with fossil fuels is a promising alternative in the heating sector for the near future, allowing for the reduction of high manufacturing costs and the defect connected with low efficiency of boilers burning only biomass. In many countries, co-firing has gained the status of the most cost-effective way to obtain a target of CO_2 reduction, which results from not only replacing fossil fuels with biomass, but also from the mutual interaction of fuels of different origins; that is, coal and biomass [21,22]. By the term 'co-firing biomass waste with coal', we understand a juxtaposition of processes that involve the combustion of hybrid coal systems with various selected types of coal. Co-firing technology combines the use of renewable energy sources with fossil fuels [18].

Karampinis et al. [21] states that coal and biomass have different chemical compositions, which significantly affect the composition of flue gases and ashes in the process of their co-combustion. During co-combustion, the process chemistry changes in comparison to burning fuels separately. The co-combustion process can be realized in several technological variants:

- Direct co-combustion, where a stream of coal and biomass or a suitable mixture of them is fed to the boiler combustion chamber;
- Co-combustion in a parallel system, where coal and biomass are burned in separate combustion chambers;
- Indirect co-combustion in a pre-combustion plant where the biomass is burned in the pre-furnace, from where the heat generated in the form of exhaust fumes is fed to the main combustion chamber;

- Indirect co-combustion with gasification, where the biomass undergoes a gasification process and the resulting gas is fed and burned in the main coal combustion chamber;
- Mixed co-combustion technology, which is a combination of different methods of biomass and coal combustion and co-combustion [21].

Due to relatively low capital expenditure and the possibility to adapt existing boilers, the most popular method is direct and parallel co-combustion. This solution is the cheapest, and maintaining constant boiler operating parameters is not a major problem. Biomass acts as a cheap and clean energy carrier, while coal stabilizes the combustion process, compensating for periodic changes in the quality and quantity of biomass. An important advantage of co-combustion is the reduction of carbon dioxide and sulfur dioxide when burning large amounts of biomass.

In the own experiment, the parameters of straw combustion and co-combustion of straw with coal in a boiler with a lower power of 5–25 kW were assessed. These boilers are usually used in single-family houses to obtain heat from central heating and/or domestic hot water. The research hypothesis assumed that oat straw could be a valuable energy source, including for co-combustion with hard coal.

The most important parameters characterizing straw as a fuel are its calorific value, moisture, or the degree of wilting. The calorific value determines the amount of heat, which will be obtained during the combustion of a mass unit of solid fuel in the oxygenic atmosphere and will be decreased by the heat of evaporation [23,24]. In the case of straw, this value will be mainly influenced by moisture. Higher moisture results in the acquisition of smaller amounts of energy and a higher emission of pollutants in exhaust gases. In addition, the calorific value depends on the type of plant and the weather conditions in which the harvest took place. When fresh, the so-called 'yellow straw' contains many alkali metals and chlorine compounds, which have an influence on rapid corrosion processes and the formation of slag. To eliminate these harmful ingredients, the straw is left until it turns 'grey'. This is the so-called wilting process, which consists of the washing out of harmful compounds by precipitation. The degree of wilting indicates how long the straw remains in the field and how it is subjected to changeable weather conditions until harvest. Niedziółka et al. [25] confirms that the energy parameters of straw depend on many factors, including fragmentation, humidity, or the form in which it is burned (e.g., briquette).

2. Materials and Methods

2.1. Material for Research

Oat straw was harvested for research in 2018, 2019, and 2020. Oat cultivation was located on an individual farm in Rzeszów (50°00′ N 22°00′ E), Podkarpackie Province, Poland. In the experiment, the energy parameters of oat straw burned alone (100%) or co-fired with coal in weight proportions: 70/30, 80/20, and 90/10 (coal/oat straw) were compared. Furthermore, an analysis of the combustion gases from the straw and hard coal combustion process was performed in the upper combustion boiler with a capacity of 20 kW. Hard coal was sourced from Polish deposits located in Lower Silesia; it is found in a typical coal outlet.

For energy research, coal with biomass was mixed in appropriate mass fractions of fuels. The mixed fuels were further ground for better homogenization. The prepared fuel mixture was tested for its energetic use in the combustion process. The preparation of fuel samples and the measurement of energy parameters were performed in accordance with the applicable standards [26–28]. At least three repetitions were made for all energy measurements and pollutant concentrations.

The farm from which the straw was obtained conducts plant production in a conventional system. Energy parameters were tested on raw straw and hard coal. Straw with a bulk density of approximately 20 kg/m^3 was used to test combustion heat, hydrogen content, ash content, and humidity. Combustion products were tested on straw pressed and formed into a cube with dimensions of approximately 20 × 10 × 15 cm and hard coal. In the boiler with the analysis of pollutant concentrations, it is possible to burn solid fuels in the form of hard coal or biomass in the form of briquettes. Therefore, it was decided that the raw and loose straw would be pressed under high pressure, without additional binders. The size of the cubes was adjusted to the exemplary dimensions of briquettes of other fuels. Straw pressing was performed in the Laboratory of Energy Conversion and Pro-ecological Technologies at the Rzeszow University of Technology. A hydraulic press with a pressing force of 10 tons was used for pressing. The density of the pressed straw was approximately 350 kg/m^3.

2.2. Laboratory Analysis

The following actions were carried out for the collected samples of oat straw, among others:

- Calculation of analytical moisture (W^a);
- Calculation of the ash content in the analytical sample (A^a);
- Calculation of the hydrogen content in the analytical sample (H^a);
- Testing the heat of combustion of the analytical sample (Q_j^a).

The measurements of the heat of combustion and the calculations of the calorific value were made based on PN-81G04513—solid biofuels. Measurements of moisture content in fuels were made based on the standard PN-80/G04511—solid biofuels. The determination of the ash content in solid fuels by combustion method was carried out according to the standard PN-80/G-04512—solid biofuels [26–28].

Before the drying process (STD SLW 53 laboratory dryer), the crucibles were weighed and filled with approximately 1 g of biomass milled in a mill (IKAM M 20). All samples were placed in the device and the drying program was turned on for 1.5 h at 105 °C. When the drying process ended, the crucibles were weighed (XA/X 220 analytical balance), the results were recorded, and the calculations were performed. Then the analytical moisture in the sample was calculated from Equation (1):

$$W^a = \frac{m_1 - m_2}{m_1 - m_3} \cdot 100, [\%], \tag{1}$$

where m_1—mass of the vessel with the weighed amount of fuel before drying, g, m_2—mass of the vessel with the weighted amount of fuel after drying, g, m_3—mass of the empty vessel, g.

The calculation of the ash content in the analytical sample (A^a) consisted of weighing the crucible and then placing the crucible with the sample and placing all samples in a muffle furnace (FCF 5SHM). The program was started, and after 30 min, the temperature was raised to 500 °C. After another 40 min, it was increased to 815 °C, and roasting continued for another 90 min. At the end of the roasting process, the crucibles were weighed with the residue and the results were recorded.

The ash content (A^a) was determined using the equation:

$$A^a = \frac{m_3 - m_1}{m_2 - m_1} \cdot 100, [\%], \tag{2}$$

where: $m_1$mass of the empty vessel, g; $m_2$mass of the vessel with a sample of solid fuel, g; $m_3$mass of the vessel with the residue after incineration of the solid fuel sample, g.

Calculation of the hydrogen content in the analytical sample (H^a) was determined based on the formula with the use of the ash content, sample moisture, and the conversion factor:

$$H^a = \frac{100 - A_a - W}{b}, [\%], \tag{3}$$

where: A_a—ash content in the analytical sample, %; W_a—moisture in the analytical sample, %, b—the conversion factor.

Testing the heat of combustion of the analytical sample (Q_j^a) required the use of 6300 Parr calorimeter. Before placing the sample in the crucible, it was necessary to ground it beforehand in a laboratory mill. The crucible was then placed in an analytical balance, the amount of biomass was weighed in a range of 0.9–1.1 g, and the result was recorded. The crucible was placed in the head of the calorimeter bomb, and an auxiliary igniter was fitted in the sample. The head was placed in the bomb cylinder and rotated 1/16 turns closing the bomb. The cover was closed, the measurement started, and the weight of the sample was entered into the calorimeter system. After completion, the value of the sample combustion heat was read out of the device and saved.

The calorific value in the analytical state (Q_j^a) was determined, based on the equation:

$$Q_j^a = Q_s^a - r \cdot \left(8.94 \cdot \frac{H^a}{100} + \frac{W^a}{100}\right), \left[\frac{\text{kJ}}{\text{kg}}\right], \quad (4)$$

where: Q_s^a—combustion heat of the analytical sample, kJ/k, $r$combustion heat of water at 25 °C, kJ/kg; H^a—the hydrogen content in the analytical sample, %, W^a—moisture in the analytical sample, %.

Analysis of oat straw combustion with coal consisted of determining an amount of hard coal fuel (mixture) depending on the power of the boiler and the calorific value of the mixture created by the co-firing process. Measurements were taken for mixtures prepared in ratios of 90/10, 80/20, and 70/30 (coal/oat straw).

The calorific value of the mixtures in operating conditions was determined using the equation:

- for the ratio of 90/10:

$$Q_{90/10}^r = 0.9 \cdot Q_{coal}^r + 0.1 \cdot Q_{biomass,}^r \left[\frac{\text{MJ}}{\text{kg}}\right], \quad (5)$$

where: $Q_{\frac{90}{10}}^r$—calorific value of mixture, $\frac{\text{MJ}}{\text{kg}}$; Q_{coal}^r—calorific value of hard coal, $\frac{\text{MJ}}{\text{kg}}$, $Q_{biomass}^r$—calorific value of the used biomass, $\frac{\text{MJ}}{\text{kg}}$.

For proportions 80/20 and 70/30, a particular share of hard coal and biomass is different. The value of η_k, i.e., the efficiency of the boiler was assumed to be 70%.

The weight of the fuel used for the process was determined from the equation:

$$B = \frac{Q_D}{Q_{mixture}^r \cdot \eta_k}, \left[\frac{\text{kg}}{\text{s}}\right], \quad (6)$$

where: Q_D—boiler power, kJ/s; $Q_{mixture}^r$—calorific value of the fuel mixture, kJ/kg; η_k—boiler assumed efficiency, %.

2.3. Statistical Analysis

The results obtained were statistically analyzed with the analysis of variance (ANOVA). The significance of differences between the characteristic values was found based on Tuckey's half-confidence intervals. Statistical analysis was performed using TIBCO Statistica 13.3.0 (TIBCO Software Inc., Palo Alto, CA, USA).

2.4. Analysis of Gaseous Pollutants

In the last stage of the investigation, measurements of the flue gas from the coal and straw combustion process were carried out in the upper combustion water boiler.

The facility where the post-process gases were tested was the Defro Optima Komfort low temperature upper combustion water boiler with a rated power of 20 kW, manufactured by Defro (Warsaw, Poland). Figure 1 shows a diagram of the boiler with the measurement system.

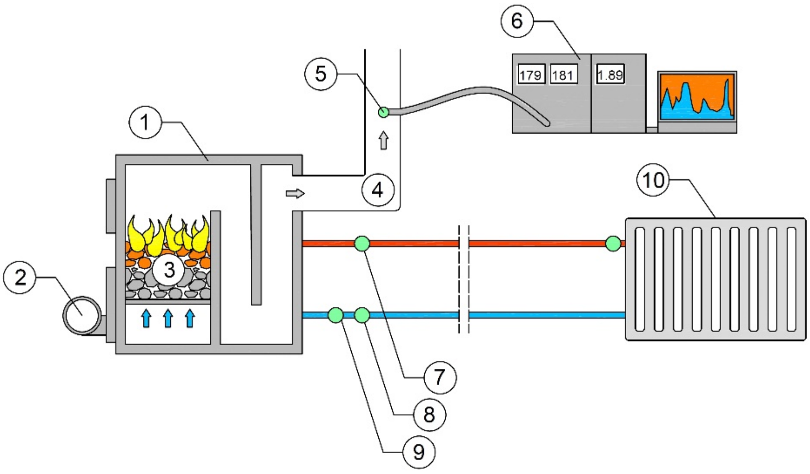

Figure 1. Diagram of the tested boiler with the measurement system, where: 1—Defro Optima Comfort boiler, 2—fan, 3—fuel burned, 4—chimney, 5—exhaust gas analyzer probe, exhaust gas temperature and pressure probe, 6—exhaust gas analyzer, temperature analyzer and flue gas pressure, 7—hot water temperature sensor, 8—cold water temperature sensor, 9—flow meter, 10—heat receivers (heaters).

It is a charging boiler used in single-family houses in which solid fuels such as coal, wood, or biomass in the form of briquettes are burnt. In this type of boiler, the fuel is supplied to the container in which the combustion process takes place and the heat is produced for the needs of central heating and/or domestic hot water. The furnace has a movable grate that is moved by hand, allowing it to be cleaned of ash during operation. As a standard, the boiler is equipped with a supply fan operation controller and a heated water boiler temperature sensor.

The authors of the study did not make any changes to the boiler structure that could disrupt the combustion process. The only intervention was the retrofitting of measuring equipment and a system for monitoring and recording process variables, such as supply and return temperatures, water flow in the heating system, pressures, and concentrations of selected compounds in the flue gas. The Gasmet DX-4000 multiparameter exhaust gas analyzer by OMC ENVAG (Vantaa, Finland) was used to measure exhaust gas composition. The Apator FAUN heat meter from Apator (Toruń, Poland) was used to measure the power of the boiler using the direct method and the temperature of the water in the supply and return pipelines. A flow meter by Powogaz (Poznań, Poland) was used to measure the heating water flow. The exhaust gas composition was measured in the section behind the boiler in specially prepared measurement openings. One-time measurement was carried out continuously. At this point, exhaust gas flow and temperature were also tested using the Delta Ohm HD 2134P.2 micromanometer (Warsaw, Poland).

The same amount of dry wood and paper waste was prepared to light the appropriate fuel. After loading the entire batch of the proper fuel, the fuel was set on fire from above with the use of wood and sparking. In such a fired boiler, the burning fuel heats the fuel below the fire zone, which degasses. The resulting flammable gases pass through the fire zone and they are burnt. As the fuel burns out, the fire zone is reduced until only coke coal remains. During this stage, the boiler operation stabilized. Boiler power, flue gas temperature, and heated and heated water temperatures remained constant. The authors decided that this was the most reliable stage in which the composition of the exhaust gases was examined. The research process was carried out with care to best reflect the actual conditions under which fuels are burned in this type of boilers.

Based on the measurements, it can be seen that while the boiler's operation stabilized, its power was different during the combustion of selected fuels. During the combustion of hard coal, the power was obtained equal to 18.21 kW and 16.57 kW during the combustion of straw. This change may result, among other things, from different values of the heat of combustion and the calorific value, the content of the carbon element, the hydrogen element, and the moisture content of the fuel itself. In both cases, the outside temperature was very similar, being −3.2 °C when burning coal and −3.5 °C when burning straw. The water flow through the boiler was provided by a pump whose flow parameters were the same in both tests and amounted to 0.241 kg/s. Table 1 presents the basic parameters of the fuels tested and the boiler.

Table 1. Energy parameters of individual fuels and the boiler during measurement.

Specification	Coal	Straw
Fuel charge weight, kg	20.12	20.03
Boiler power, kW	18.21	16.57
Heated water temperature, °C	56.4	56.2
Hot water temperature, °C	74.2	72.6
Outdoor temperature, °C	−3.2	−3.5
Water flow through the boiler, kg/s	0.241	0.241
Vacuum in the chimney, Pa	13.5	14.1

One-time measurements were performed in a continuous manner from the moment of ignition to the burning of all the fuel. The presented results were selected from the entire measurement and they cover a period of 10 min. During this period, the boiler operated at constant power, the fuel was fully lit, and changes in pollutant concentrations were small, so it was considered the most representative sample.

3. Results

Hard coal had the highest calorific value, as expected, and straw the lowest. As a result, increasing the share of straw in the mixture with coal resulted in a reduction in calorific value. In the case of the heat of combustion, the same relationships were found. The difference in combustion heat between coal and straw was 11.74 $MJ \cdot kg^{-1}$. Straw had the highest analytical moisture and coal the lowest. As a result, increasing the share of straw in the combustion mixture with coal resulted in an increase in the analytical moisture. The hydrogen content was the highest in carbon and the lowest in straw. However, only a mixture of coal with straw in the proportion of 70/30 significantly decreased the measurements of this parameter in relation to coal. The calorific value and heat of combustion varied over the years of research. The lowest measurements of both parameters were recorded in 2020. In the case of the analytical moisture and hydrogen content, no variability of the results obtained was found in the study years (Table 2).

The experiment showed that the ash content in individual energy raw materials depended on the interaction of the factor tested with the years of research. In 2019, the ash content in the coal was significantly higher compared to the ash content in the mixtures with straw and straw alone. In 2018 and 2020, the ash content in the coal did not differ significantly from the mixture of coal and straw in the 90/10 proportion. It should also be noted that, in the case of both coal and straw, the ash content was variable in the years of research. However, such a relationship was not observed for mixtures of coal with straw (Figure 2).

As the boiler power increased from 5 to 25 kW, the consumption of the mixture of coal and straw that was burned and the straw itself increased significantly. This relationship was repeatable in 2018–2020 (Table 3). In the case of the boiler capacity of 25 kW and straw combustion alone, the demand for biomass was 7.814 to 2.286 kg/h in 2018 and 0.97 to 0.966 kg/h in 2020, respectively.

The increase in the share of straw in the mixture with coal significantly increased the consumption of the raw material. The highest biomass demand in kg/h was achieved for straw alone.

The lowercase letters mean significant differences between the averages for the boiler output and the uppercase letters mean significant differences between the averages for individual raw material mixtures.

Table 2. Energy parameters of individual raw materials.

Specification	Calorific Value MJ·kg^{-1}	Heat of Combustion MJ·kg^{-1}	Analytical Moisture %	Hydrogen Content %
		Tested factor—TF		
Coal	27.73 ^{a}	28.49 ^{a}	5.54 ^{e}	4.81 ^{a}
Oat straw	15.52 ^{e}	16.75 ^{e}	8.62 ^{a}	4.52 ^{c}
Coal + oat straw (90/10)	26.51 ^{b}	27.32 ^{b}	5.85 ^{d}	4.78 ^{ab}
Coal + oat straw (80/20)	25.29 ^{c}	26.14 ^{c}	6.16 ^{c}	4.75 ^{ab}
Coal + oat straw (70/30)	24.08 ^{d}	24.97 ^{d}	6.46 ^{b}	4.72 ^{b}
		Years—Y		
2018	24.21 ^{a}	25.03 ^{a}	6.42 ^{a}	4.60 ^{a}
2019	24.05 ^{a}	24.98 ^{a}	6.65 ^{a}	4.75 ^{a}
2020	23.24 ^{b}	24.19 ^{b}	6.53 ^{a}	4.82 ^{a}
		ANOVA		
TF	***	***	**	*
Y	*	*	n.s.	n.s.
TFxY	n.s.	n.s.	n.s.	n.s.

***, **, * indicate significant differences at $p < 0.001$, $p < 0.01$, and $p < 0.05$, n.s.-non-significant, according to Tukey's honestly significant difference test (HSD). The mean values with different letters (a–e) in columns are statistically different.

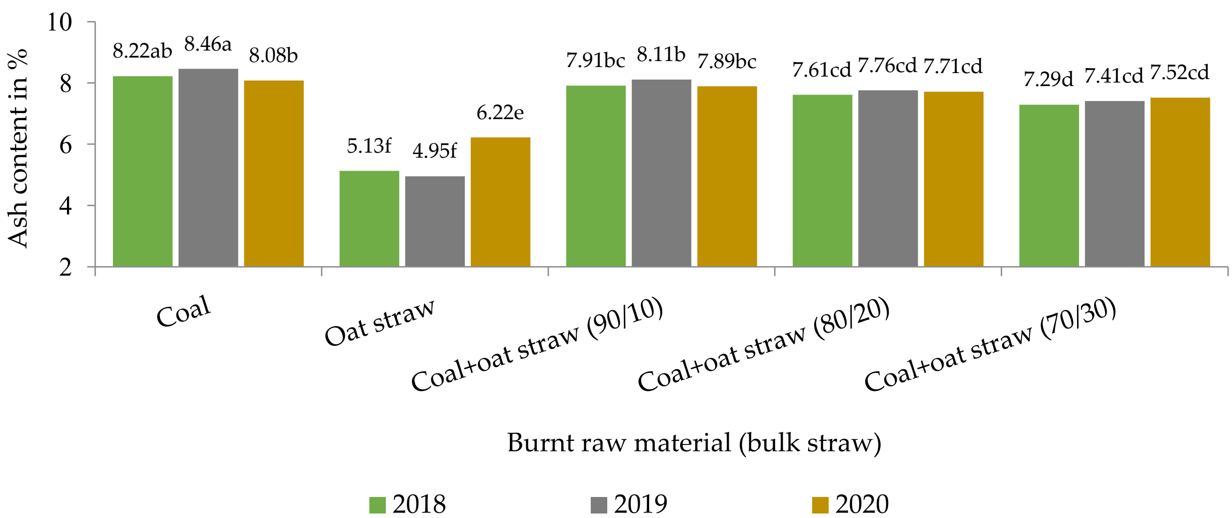

Figure 2. Ash content (A_a) in %. Significant interaction differences at $p < 0.05$. Mean values with different letters (a–f) in the columns are statistically different.

The oxygen content in the exhaust gases is on average 11.03% for hard coal and 11.63% for straw. Higher CO concentrations were recorded during straw combustion, which averaged 4114.17 mg/m^3_u. During coal combustion, the CO concentration is significantly lower and amounts to an average of 2301.67 mg/m^3_u. The concentrations of the remaining pollutants were lower during straw burning. NO concentrations for straw were averaged at 184.17 mg/m^3_u, for coal 333.1 mg/m^3_u. The average NO_X concentration for straw is 329.33 mg/m^3_u and 597.23 mg/m^3_u for hard coal. The average concentrations of SO_2 during straw combustion are almost 4.3 times lower than those of coal. The average CH_4 concentrations for both fuels were very similar. For straw, this value is 23.68 mg/m^3_u, and for coal, 24.22 mg/m^3_u.

Table 4 presents the results of the analysis of pollutants from the coal and straw combustion process in the 20 kW upper combustion boiler.

Table 3. Raw material consumption (kg/h) depending on the power of the boiler and the percentage of oat straw.

Years	(kW)	Coal/Oat Straw			Oat Straw 100
		90/10	80/20	70/30	
2018	5	0.970	1.017	1.069	1.657
	10	1.940	2.034	2.137	3.315
	15	2.910	3.051	3.206	4.972
	20	3.880	4.068	4.274	6.629
	25	4.850	5.085	5.343	8.286
2019	5	0.970	1.017	1.068	1.653
	10	1.940	2.033	2.136	3.306
	15	2.910	3.050	3.204	4.959
	20	3.880	4.067	4.272	6.612
	25	4.850	5.083	5.340	8.266
2020	5	0.966	1.009	1.056	1.563
	10	1.933	2.018	2.112	3.689
	15	2.899	3.028	3.168	4.689
	20	3.866	4.037	4.224	6.252
	25	4.833	5.047	5.281	7814

Table 4. Results of the measurement of pollutants from the combustion of hard coal and straw.

Specification	Coal			
	Min	Max	Average	Standard Deviation
O_2, %	10.9	11.2	11.03	0.12
CO, mg/$m^3{}_u$	2131.1	2519.8	2301.67	164.38
NO, mg/$m^3{}_u$	312.2	354.7	333.1	16.78
NO_X, mg/$m^3{}_u$	561.5	637.2	597.23	29.89
CH_4, mg/$m^3{}_u$	21.1	29.2	24.22	2.97
SO_2, mg/$m^3{}_u$	416.2	512.3	477.42	34.61
Specification	**Straw**			
	Min	**Max**	**Average**	**Standard Deviation**
O_2, %	11.3	12.1	11.63	0.28
CO, mg/$m^3{}_u$	3756.2	4325.4	4114.17	222.61
NO, mg/$m^3{}_u$	178.3	191.8	184.17	5.42
NO_X, mg/$m^3{}_u$	307.4	343.8	329.33	13.45
CH_4, mg/$m^3{}_u$	19.5	33.1	23.68	4.83
SO_2, mg/$m^3{}_u$	105.3	117.5	111.14	4.89

4. Discussion

4.1. Combustion Products Analysis

Today, much attention is paid to the elimination of heat sources that pollute our environment. Air pollution is a dangerous form of environmental contamination due to its direct impact on all living organisms, covering large areas and allowing easy movement. Therefore, air protection is one of the priority tasks of each region [29,30]. Bhui and Vairakannu [31] report that the main cause of greenhouse gas emissions to the environment is the burning of fossil fuels. Therefore, there is depletion of the ozone layer, global warming, acid rain, etc. Therefore, alternative raw materials should be sought to obtain energy. One of them is biomass, which is already used in many countries as a renewable energy source.

Grain and straw are two examples of agricultural raw materials that can be used to produce energy. From an economic point of view, the costs of producing energy, both from grain and straw, are lower or close to the market price of fossil fuels. Thus, if there is a shortage of conventional energy resources or policy instruments that limit their use, biomass (e.g., straw) may be an alternative [32,33]. While examining the prepared samples, it was found that the calorific value of straw and its other parameters allow it to be used for energy purposes as an independent fuel and as a fuel co-fired with hard coal (Table 2). The experiment confirmed that hard coal has the highest calorific value and heat of combustion and straw the lowest. Furthermore, the calorific value and heat of straw combustion were different in the years of research. The lowest measurements of both parameters were recorded in 2020. Increasing the share of straw in the burned mixture resulted in an increase in analytical moisture compared to coal combustion. Kwong et al. [34] showed that the increase in moisture in the combusted coal-biomass mixture resulted in a decrease in SO_2, NOx and CO_2 emissions, but also a decrease in the energy obtained and an increase in CO emissions. Nowak and Rabczak [1] also showed that the increase in biomass content in the combustion mixture with coal results in a decrease in boiler efficiency but contributes to the reduction of SO_2, HCl, and VOC emissions.

Following the analysis conducted, it appears that a biomass share in combination with hard coal influences the amount of the mixture used (Table 3). That is why the most optimal option should be chosen. From the perspective of ecology and economy, the mixture with 70/30 proportion yields the most positive results, although it is only slightly higher than in 80/20 and 90/10 mixtures. Oladejo et al. [35,36] showed that a 30% share of oat straw in the mixture with coal resulted in the best combustion parameters. A mixture of such proportions significantly improved the effects of burning low-quality coal. In other studies, Oladejo et al. [37] proved that oat straw contains large amounts of potassium, which allows the use of ash for agricultural purposes. This is an important aspect in the context of biomass combustion. Nicholls and Zerbe [38] conclude that biomass co-fire is one of the fastest ways to reduce CO_2 emissions in the case of small coal-fired boiler houses. Al-Mansour and Zuwala [39] note that the co-fire of biomass in large coal-fired CHP plants is an opportunity to increase the share of RES in the energy balance of many countries. Additionally, emissions of CO_2, SO_2, and NOx will be reduced. Karampinis et al. [21] showed that co-firing installations are not expensive, but the share of biomass in relation to coal is usually 10%. The undoubted advantage of biomass is the greater possibility of ash disposal.

4.2. Co-Combustion of Biomass with Coal

The experiment showed that the ash content in individual energy raw materials depended on the interaction of the factor tested factor with the years of research. In 2019, the ash content in coal was significantly higher compared to the ash content in mixtures with straw and straw alone (Figure 2. The straw harvested in different years had a different chemical composition. Hence, the burning of straw had a large impact on the ash content in the combusted raw material.

Sami [5] notes that coal and biomass have a different composition, therefore their co-combustion, depending on the proportion in the mixture, will have various effects, both favorable and unfavorable. Nowak [40] with the increase in biomass in the mixture obtained a reduced concentration of greenhouse gases and some nitrogen, sulfur, and hydrocarbon compounds. However, the efficiency of the boiler decreased. Therefore, it is important to determine the optimal content of biomass in the mixture, at which the efficiency of the boiler will be satisfactory.

However, it should be remembered that the higher the share of biomass in fuel, the less environmental pollution, the costs of biomass are significantly lower than those of hard coal, and biomass is practically inexhaustible, which cannot be said of conventional fuels [22]. Inayat et al. [41] points out, however, the potential for disruptions in the supply of biomass due to harvest seasonality, climatic conditions, and transport costs.

4.3. Straw as an Energy Resource

Bielski and Marks [4] showed that in Poland there are regions with an overproduction of undeveloped straw. Most of the straw is used in agriculture (fertilizer, bedding), while the surplus can be used for energy purposes. However, to make straw a valuable fuel, it is necessary to store and transport it properly. Here, we may encounter some barriers. The first restriction on the use of straw in the energy sector is its dispersion. Small farms do not have high-compaction presses because of their high prices, and intermediaries between agriculture and the energy sector are not interested in contracting straw from small areas. Another barrier is the diversity of straw as a raw material. Its composition depends on the plant species, its variety, fertilization, soil, and weather [18]. The heterogeneity of straw creates special requirements for the regulation of air in boilers that burn it. In addition, straw is a bulky material, which affects transport and storage costs. To reduce them, it is recommended to convert straw crops into briquettes or pellets [12]. In the conducted experiment, along with the increase in the share of straw in the mixture with coal, the consumption of the raw material burned increased significantly. The highest biomass demand in t/h was obtained for straw alone (Table 3).

Weiser et al. [13] believe that straw can be rationally used for energy purposes, but in regions with its surplus and appropriate technical infrastructure. Chen [22] indicates that the co-fire of straw with coal may lower the price of coal on the world market and, in turn, may increase the demand for coal. Therefore, international efforts are needed to reduce the share of fossil fuels in energy. The information available so far shows that the co-combustion of straw with coal limits the mission of greenhouse gases, especially SOx and NOx [21], CO, CO_2, [34], as well as the emission of polycyclic aromatic hydrocarbons (PAH) and trace metals [42].

4.4. The Effects of Co-Firing of Straw

In the authors' own research, higher concentrations of CO were recorded during straw combustion, which averaged 4114.17 $mg/m^3{}_u$. During coal combustion, the CO concentration was significantly lower and averaged 2301.67 $mg/m^3{}_u$. The concentrations of the remaining pollutants (NO, NO_X, SO_2) were lower during straw combustion. The mean CH4 concentrations for both fuels were similar (Table 4).

According to Miedem et al. [43], the dissemination of co-firing of biomass with coal can significantly reduce greenhouse gas emissions. The effects obtained will be temporary and will depend on the scale of the co-combusted biomass. Moreover, Baxter [44] believes that co-firing of biomass with coal is a temporary solution, but beneficial to the environment. He also emphasizes that existing technical problems in the co-firing of biomass can be solved. Kraszkiewicz et al. [45] states that the emission of pollutants during the combustion of oat straw (pellets or briquettes) without modification of the combustion chamber was characterized by similar emissions in terms of CO and NO, and more than twice as high as the SO_2 emission for the briquettes. However, after modification of the combustion chamber and the use of gaseous fuel, a reduction of CO was achieved by 15%. Wielgosiński et al. [46] concludes that the emission of some pollutants from biomass combustion is higher than for hard coal. Therefore, research in this area should continue to minimize or eliminate the risks associated with it. In this aspect, Milićević et al. [47] and Akhtar [48] showed that the type of biomass co-combustion influences the amount of unburned carbon in the ash compared to the combustion of lignite alone.

Sami [5] believes that despite all the problems and concerns about the combustion of the coal-biomass mixture, it appears to be a promising technology for energy extraction. Ziętara and Zieliński [11] believe that the use of surplus straw for energy purposes may reduce the consumption of hard coal by 12.6%. The weakness of this solution is the significant loss of nutrients contained in the straw. Therefore, straw should be the first source of humus in the soil. According to Marks-Bielska et al. [49], it should be remembered that biomass is often a local fuel that is used to generate energy for individual consumers. On the other hand, increasing the scale of biomass use is possible in large heat and power plants. Kaczmarczyk et al. [17] and Ravina et al. [50] emphasize that in the near term it is necessary to replace old boilers with new ones and to broadly promote renewable energy sources in Poland. Long et al. [51] and Gomiero [52] believe that this requires estimating the bioenergy potential of the available biomass. Therefore, research on the bioenergy potential of individual regions of the world is particularly important [53–55].

5. Conclusions

Increasing the share of straw in a mixture with coal resulted in a reduction in the calorific value and heat of combustion. The increase in the proportion of straw in the burnt mixture increased the analytical moisture of the raw material. The hydrogen content was the highest in carbon and the lowest in straw. However, only the mixture of coal with straw in the proportion of 70/30 significantly decreased the measurement of the said parameter in relation to coal. The ash content in the tested energy raw materials depended on the interaction of the factor tested factor, with the years of research. The increase in the share of straw in the mixture with coal significantly increased the consumption of the raw material. The highest demand for biomass in t/h was obtained for straw alone. Based on the conducted research, it was shown that the combustion of straw, compared to hard coal, is characterized by the reduction of harmful pollutants, such as NO, NO_X, and SO_2, and an increase in the exhaust gas of CO. The average CH_4 concentrations for both fuels were very similar. Based on the conducted research, it has been shown that the surplus of oat straw can be used as an energy resource, including for co-combustion with hard coal. This will slowly increase the share of biomass in the energy balance and reduce greenhouse gas emissions.

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Abbreviations

MJ	megajoule
kW	kilowatt
NO	nitric oxide
NO_X	nitrogen oxides
SO_2	sulfur dioxide
SO_x	sulfur oxides
CO	carbon monoxide
CO_2	carbon dioxide
CH_4	methane
$mg/m^3{}_u$	milligram of substance per cubic meter of waste gas with reference to contractual conditions

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