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Thermal Energy and Exhaust Emissions of a Gasifier Stove Feeding Pine and Hemp Pellets

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Abstract: This paper presents the results of research on the energetic use of self-combusted hemp pellets and co-firing with pine pellets. The tests were carried out with the use of a boiler equipped with a Lester Projekt Company gasifying burner and an automatic fuel feeding system. The boiler is equipped with an additional heat exchanger that enables the simulation of any heat load. The experimental stand so built guaranteed to obtain results adequate to the real operating conditions. The research material consisted of pellets made of waste biomass of the Futura 75 sowing hemp and pine sawdust pellets. The experiment was carried out in five proportions by mass of mixtures of both fuels (C-hemp, P-pine): 0:100 (P100), 25:75 (C25/P75), 50:50 (C50/P50), 75:25 (C75/P25), 100:0 (C100). For each variant, the following were determined: effective boiler power, boiler energy balance, boiler energy efficiency, the volumetric composition of flue gas (carbon monoxide, carbon dioxide, hydrogen, sulfur dioxide, nitrous oxide), excess air coefficient and the dust content of particle matter—PM10, PM2.5. The heating value was also determined for hemp pellets and pine sawdust pellets, accordingly 17.34 and 19.87 MJ·kg^{-1}. The obtained test results were related both to the volume of exhaust gases leaving the boiler and to one kilowatt hour of heat produced. The obtained test results showed that the boiler fed with pine pellets achieved the highest thermal power (P100)—14.17 kW, while the smallest—hemp pellets (C100)—4.92 kW. The CO_2 emissivity increased with the addition of pine pellets, from 26.13 g (C100) to 112.36 g (P100) relating to 1 m^3 and from 430.04 g (C100) to 616.46 g (C25/P75) relating to 1 kWh of heat. In terms of dust emissions, it was found that the combustion of hemp pellets and mixtures thereof is a little worse than that of pine pellets.

Keywords: biomass gasification; renewable energy source; hemp pellet; pine pellet; climate change; exhaust gas emission

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1. Introduction

The ongoing economic and climate changes make it necessary to pay special attention to the possibilities of obtaining energy. This is reflected in many studies around the world and climate policy, including the European Union, which imposes an obligation on member states to limit the production of electricity from coal. The current situation in the international arena forces the necessity to increase the share of obtaining energy from renewable sources. In 2018, renewable energy supplies accounted for approximately 14% of the total global primary energy supply [1]. According to estimates, by 2026, global demand for biofuels may increase to 41 billion liters [2]. Technological solutions are sought, above all, more efficient in terms of energy but also more environmentally friendly [3–5], with an ecological and economically sustainable approach to the management of, e.g., sewage sludge [6] through an alternative form of recycling nutrients and organic matter from

waste [7–9], and also economically viable [10]. The use of sewage sludge on poor-quality soils and in unfavorable climatic conditions or the use of crops for energy purposes [11,12] from reclaimed areas [13] does not compete with conventional food production [14]. The digestate, which is a sub-product of a biogas plant (RES), thanks to its low cost, can be gasified after drying and granulation, so waste from one energy production process becomes a substrate in another energy production process [10].

The global trend to move away from fossil fuels to reduce harmful substances to the environment [15,16] is also starting to apply in the household sector (heating), where the use of biofuels is starting to play an increasingly important role. One of the direct effects of these activities is the orientation of interdisciplinary research [17] toward energy generation and conversion of biomass, which is one of the most commonly used renewable energy sources [18]. It is a particularly attractive solution at the local level due to its stability, its key feature in the context of energy security. Produced locally, it lowers transport costs and simplifies the associated logistics [19]. In order to facilitate transport and storage, the biomass is briquetted or pelleted, as a result of which its density increases, the water content decreases, and energy concentration per unit volume increase [20]. Most types of biomass for briquette and/or pellet production require the use of a binder [21].

Particularly noteworthy is hemp biomass, which, apart from being used for the production of liquid biofuels [22], can also be used in direct combustion [23]. No chemical additives are used for the production of pellets or briquettes from hemp biomass, and the shredded material sticks together under the influence of steam and high pressure [24]. The predictability of biomass includes relatively constant calorific value, the possibility of combustion in conventional coal installations, also as part of co-combustion, and above all, its availability, which is more easily available and cheaper to produce compared to, for example, hard coal.

The use of biomass contributes to meeting the requirements of the European Union aimed at reducing greenhouse gas emissions and promoting the consumption of energy from renewable sources while ensuring environmental protection in Directives 2009/28/EC and 2009/30/EC. They specify the required levels of greenhouse gas reduction due to the use of biofuels and the conditions to be met by the sources of raw materials for their production) [25]. Hence, the need for many studies on Life Cycle Assessment (LCA) to determine the most sustainable and energy efficient integrated bioenergy systems and the level of environmental impact, with particular emphasis on greenhouse gas emissions [26].

According to the Report of the International Renewable Energy Agency (IRENA) (2022) [27], biomass and its varieties are the third largest renewable energy source in the world. In recent years, in the European Union countries, the percentage of energy derived from biomass of wood products accounted for almost 50% of the produced ecological energy. In Poland, it is the second—after wind energy—the most widely used renewable energy source, and in 2019—biomass and biogas—accounted for 19% of the share of installed RES capacity.

There are many methods of obtaining energy from biomass, but they differ significantly in terms of energy and economic efficiency, depending on the method of its processing. Depending on the chemical composition, biomass can be used for direct combustion, biogas production, or converted into liquid fuel (biodiesel or bioethanol) [28,29].

Due to the low cost of the process, most biomass is often burned. Energy can also be generated by thermochemical methods; pyrolysis, gasification, as well as in the process of esterification or fermentation [30]. The energy yield also depends on the type of plant, species, and even variety used in energy production [24,31]. In the thermochemical conversion of biomass, where bonds between adjacent carbon, hydrogen and oxygen molecules are broken down to release the chemical energy stored in them through photosynthesis, the process changes with the amount of O_2. The thermochemical conversion with excess O_2 is combustion. A process without O_2 supply and without the influence of other oxidants is pyrolysis [32]. During the process, a solid, e.g., briquette, pellet or liquid, is thermally decomposed into smaller volatile particles; it is carried out in suitable boilers with the use

of grates resistant to high temperature and increased humidity. Gasification is a thermochemical conversion process with a limited amount of supplied O_2 [33]. Other gasification agents are air, oxygen-enriched air, and steam [34]. The characteristics of these methods are presented in Table 1.

Table 1. Characteristics of thermochemical conversion pathways [1].

Process	Amount of Oxygen	Process Temperature [°C]	Useful Products
combustion	excess	above 800	heat
pyrolysis	absence	350–550	char, bio-oil
gasification	limited	700–1100	syngas

[1] Own elaboration based on [34].

The syngas produced in the gasification process can be directly used for heating and/or electricity generation, as well as for the production of raw chemical materials. The method has many advantages; it is used for processing and disposal of waste, reduces the need for space for solid waste storage and the risk of groundwater contamination, increases resource efficiency, and reduces unfavorable climate changes, e.g., reduces methane (CH_4) emissions from landfills [35,36] although it is not deprived of certain limitations [37]. Research to reduce or eliminate tar content in syngas has been conducted [34].

Gasification boilers operate similarly to natural gas stoves. Instead of a standard large grate, as in coal-fired boilers, there is a burner nozzle in the center of the combustion chamber. In this nozzle, wood gasification takes place, and wood gas is burned. Such a solution also allows for the accumulation of the heat obtained and a high combustion temperature, thereby significantly increasing its efficiency. The results also show that pellet gasification provides lower exhaust emissions compared to raw biomass [38].

According to Eurostat, in 2019, the hemp cultivation acreage was 34,960 ha (2019), which is approx. 75% increase compared to 2015 (19,970 ha) [39]. Yields in this period increased from 94,120 tons in 2015 to 152,820 tons in 2019—an increase of over 62%. In Europe, the leaders in hemp production are France—over 70% of European production, followed by the Netherlands—10% and Austria 4%. According to estimates by the European Industrial Hemp Association (EIHA), the hemp cultivation area in Europe continues to grow, reaching 55,000 hectares in 2021 [40]. In European countries, the cultivation of industrial hemp is regulated in various ways depending on the country, and the main influence on these regulations is the United Nations Single Convention on Narcotic Drugs from 1961. In Poland, the area declared in the RDP 2014–2020 applications is 3109.03 ha [41]. In Poland, the Act of 24 March 2022 [42] amending the Act on counteracting drug addiction [43], enables hemp cultivation for many industries; textile, chemical, cellulose and paper, cosmetic, pharmaceutical, energy, seed and scientific research, in order to breed varieties of hemp, reclamation and remediation land [44], food, veterinary, fodder, beekeeping, fertilizer and insulation, for the production of composite materials, building materials and natural plant protection products [45,46]. Hemp, by improving energy efficiency in industry, can play an important role in achieving Sustainable Development Goals, net zero targets, and carbon neutrality by 2050, which is one of the goals of the European Green Deal. Hemp has great potential for energy production. A very important aspect when assessing the technology of preparing biofuels from hemp, both cut and pelleted, is the separation of technological operations in order to calculate the direct energy inputs (fuel and electricity) incurred for their processing and, finally, the energy efficiency index [24]. Determining energy efficiency is an operation necessary to carry out plant production intended for energy purposes [47,48]. At the same time as the energy benefits, the cultivation of hemp has many environmental benefits. Research shows that during the photosynthesis process, cannabis plants store a significant amount of carbon, and one ton of plants can absorb up to 1.6 tons of CO_2. As such, 1 ha of hemp cultivation stores—sequestration—from 9 to 15 tons of CO_2. They are easy and undemanding to cultivate and are water efficient [49,50]. They do not need intensive fertilization, prefer soils with a neutral reaction to alkaline

and yield best in the temperate climate zone, in the range of average air temperatures of 16–27 °C [51–53]. The average hemp biomass yield is approx. 10–15 t·ha^{-1} [51]. The heat of combustion is approx. 19 MJ·kg^{-1}, thanks to which they can achieve energy efficiency in the range of 200–260 GJ·ha^{-1} [3,51]. Their processing is characterized by the absence of waste; all hemp parts can be used or reprocessed, among others, for energy purposes, thus contributing to the development of a circular economy [54,55].

CO_2 is created and emitted as the main product of complete combustion. Incomplete combustion leads to unburned carbon emissions in the form of pollutants such as carbon monoxide, hydrocarbons, polycyclic aromatic hydrocarbons, tar and soot [56]. Wood combustion results in lower emissions of some pollutants [57]. Hemp combustion can decrease health risks compared to wood burning [58]. The high concentration of CO_2 causes the temperature to rise on Earth and causes climate change. It has been estimated that about 35 billion tons of CO_2 are emitted from fossil fuels and industry annually in the world [59]. The need to mitigate these changes and reduce the pace at which they occur has established the concept of carbon neutrality [60].

Generally, it is assumed that the combustion of biomass shows a zero CO_2 balance and does not cause additional emissions of this gas, the amount of which is approximately equal to the amount consumed by plants in the photosynthesis process [26]. An additional advantage is the possibility of using the resulting ash as a fertilizer for the cultivation of other energy crops [61].

In most studies, the authors focus only on the specification of the calorific value of fuel and combustion residues. This is a very important parameter, but it does not consider the scale of the device, as only a small sample of biomass is burned. There is also little work on the chemical composition of exhaust gases [62].

This paper presents the results of research carried out under laboratory conditions but reflects the operation of a boiler used in real-world conditions. The measurements were carried out on a boiler with a rated output of 20 kW, the most common boiler used in domestic heating systems. Because of allowing precise fuel dosing, the boiler with a gasification burner was used. This method reduces the partial combustion and the content of carbon monoxide in the exhaust gas. A novelty in the article is also the reference of the test results to the flue gas emission stream and, above all, to the unit of heat produced. Therefore, the determination of the parameters studied can be of particular importance not only in research work but in practical application also. Based on the energy produced, the costs of heat production were estimated. The results obtained will be helpful for decision-making in the choice of heating fuel by individual consumers. Thanks to the analysis performed in this way, it is possible to forecast the obtained energy and emission parameters for boilers of similar construction and other powers. The analysis of the results showed that the use of biomass for energy purposes could bring potential benefits, not only in energy but also in the environment.

2. Materials and Methods

The research material was obtained from the Wood Stocks company (www.woodstocks.pl, accessed on 30 November 2022). Pine sawdust pellets and hemp pellets with a mass moisture content of 6.7% and 11%, respectively, were used in the research. Both types of pellets were made with the same technology and met the standard for the production of pellets [63]. The view of the tested pellets is shown in Figure 1.



(**a**) (**b**)

Figure 1. Tested pellet: (**a**) Pine; (**b**) Hemp.

The following mixtures of both tested pellets were composed for the tests, with proportions on a mass scale: C100—100% hemp, C75/P25—75% hemp and 25% pine, C50/P50—50% hemp and 50% pine, C25/P75—25% hemp and 75% pine, P100—100% pine.

The object of the research was a boiler equipped with a solid fuel gasification burner made according to patent No. 208551 [64]—Figure 2.

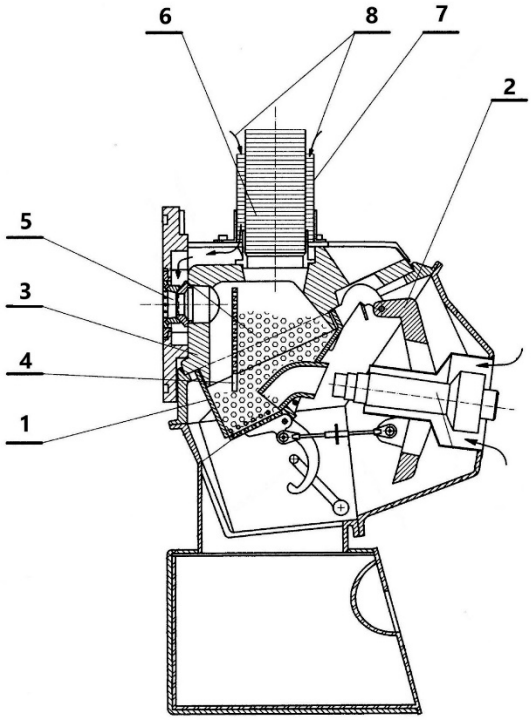
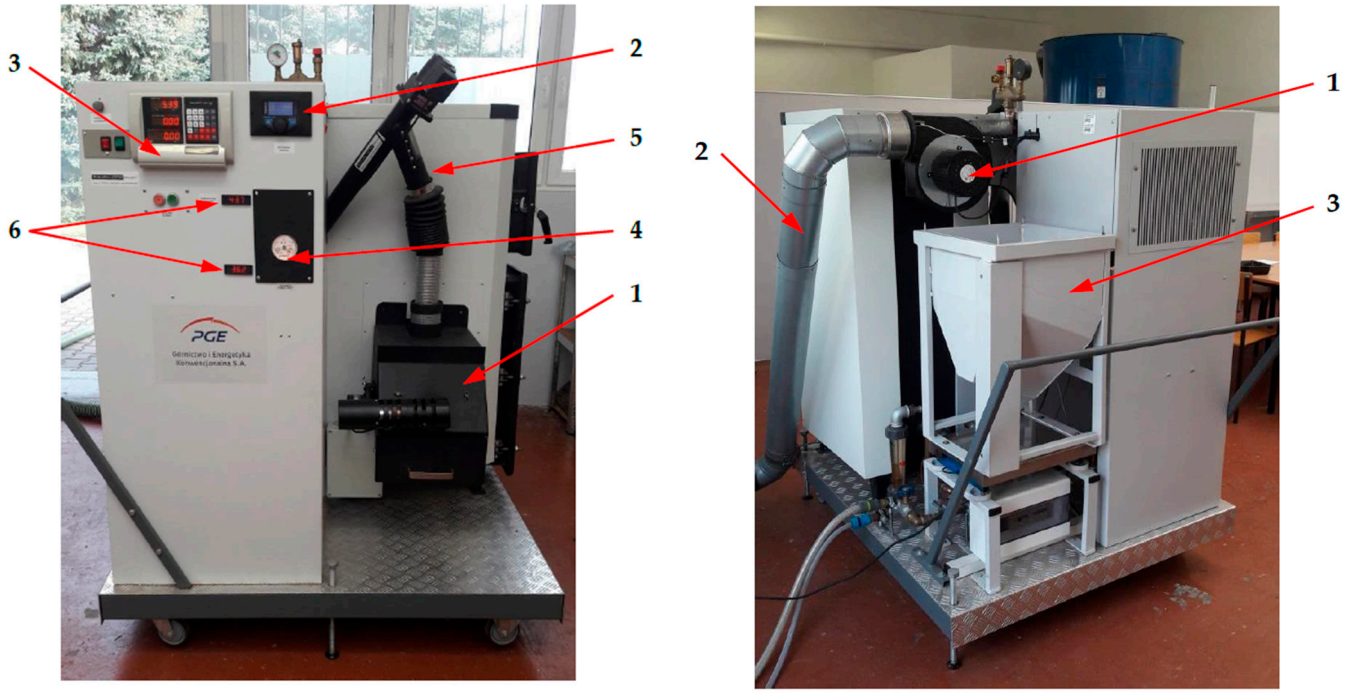


Figure 2. The scheme of gasification burner [64]: (1) the grate; (2) the counterweight; (3) the burner body; (4) perforated partition; (5) the nozzles; (6), (7) the spaces supplying secondary air; (8) secondary air intake.

The pellet burner for the central heating boiler is installed outside the boiler body, together with an exhaust fan to discharge the fumes to the chimney. The burner has a grate (1) with a counterweight (2) suspended to the burner body (3) in such a way that it serves as a weight for the pellet being loaded. The grate (1) has a partition (4), perforated with holes, between the pellet gasification zone and the gas ignition zone on the nozzles (5). The burner has a charging pipe, constructed in such a way that it is a part of two coaxial metal flexible pipes, where the middle one carries pellets to the grate, and the space between the pipes (6, 7) is sucked on the nozzles (5), secondary air (8) to combustion, additionally cooling the pipe (6) and the body (3). The view of the boiler equipped with a gasification burner is shown in Figure 3.



(**a**) (**b**)

Figure 3. Experimental stand: (**a**) Front view: 1—gasification burner, 2—burner controller, 3—pellet weight measuring system, 4—water flow meter, 5—screw feeder, 6—water temperature indicator at the inlet at the outlet; (**b**) Back view: 1—exhaust fan, 2—chimney pipe, 3—pellet bunker.

In order to make a thermal balance of the boiler fed with the tested fuels, the following parameters were measured: the weight of the pellet being fed, the volume of water flowing through the heat exchanger, and the water temperature at the inlet and outlet of the boiler. The following relationship was used for the calculations (1):

$$Q = \frac{c_w \cdot m\ \Delta T}{1000}, \quad (1)$$

where:

Q—heat obtained [MJ],
c_w—water specific heat [4.2 kJ·(kg·K)$^{-1}$],
m—water weight [kg],
ΔT—water temperature difference [K].

In order to analyze the exhaust gases, the MRU Vario Plus analyzer was used [65], partly using the methodology described in the paper [66]. It measured: CO_2, H_2, Airflow ratio, O_2. The analyzer was operated in a continuous mode. Average values of the obtained measurements were adopted for the analysis.

Measurements of the content of SO_2, NO_2 and PM in the flue gas were made with the Atmonfl mobile measuring probe by Nanosens. Measurements were carried out in the flue gas stream. The built-in GPS module allows you to associate the measurement results with the location and height of the probe. The device meets the harmonized standards [67,68] and the essential requirements of the EU directive [69].

To determine the mass emissions of individual exhaust gas components, their molar masses were determined and then compared to the fuel mass stream or the amount of heat produced.

In the first stage of the study, cup plant biomass humidity was determined by the dry oven test. Subsequently, the calorific value of cup plant dry biomass was tested in an IKA C 2000 calorimeter on the basis of the isoperibolic method [70]. For the calorific value tests, the test material was ground in a laboratory mill to a size below 0.2 mm.

Each time, the measurements were started with the launch of pine pellets. Next, the boiler was heated up to obtain a constant water temperature in the inlet system, which is about 315 K. Then, the tested mixture was introduced into the boiler. Measurements were started after one hour of boiler operation on the tested mixture. Then, for another hour, heat balance and emissivity tests were carried out.

The boiler operation settings were not changed. The system of automatic regulation of the boiler operation was set in the same way each time. After the measurements, the boiler was put out. Each test was carried out only once a day in order to run a cold boiler under the same conditions each time.

The exhaust gas samples were taken at regular intervals. The exhaust fan of the boiler operated at a constant speed of 2350 rpm. The scheme of the experiment is shown in Figure 4.

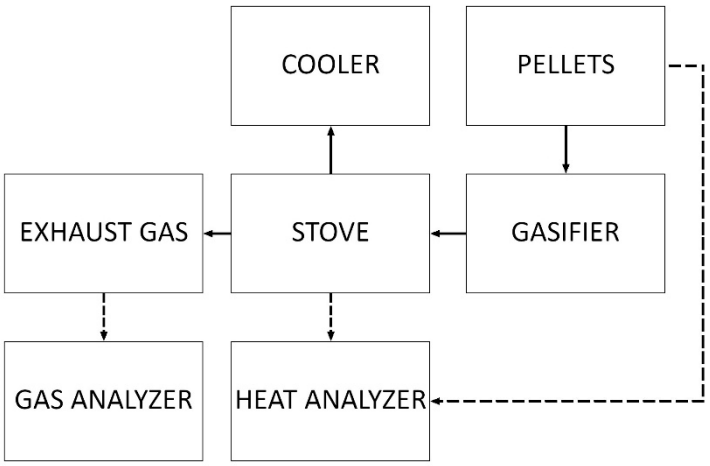


Figure 4. The scheme of experimental stand and measuring system.

3. Results and Discussion

All the measured values are summarized in Table 2. The values of measurement errors (measured and calculated) are each time presented graphically with positive error bars. The calculations were made using Microsoft Office 2016 version 2210 Excel spreadsheets.

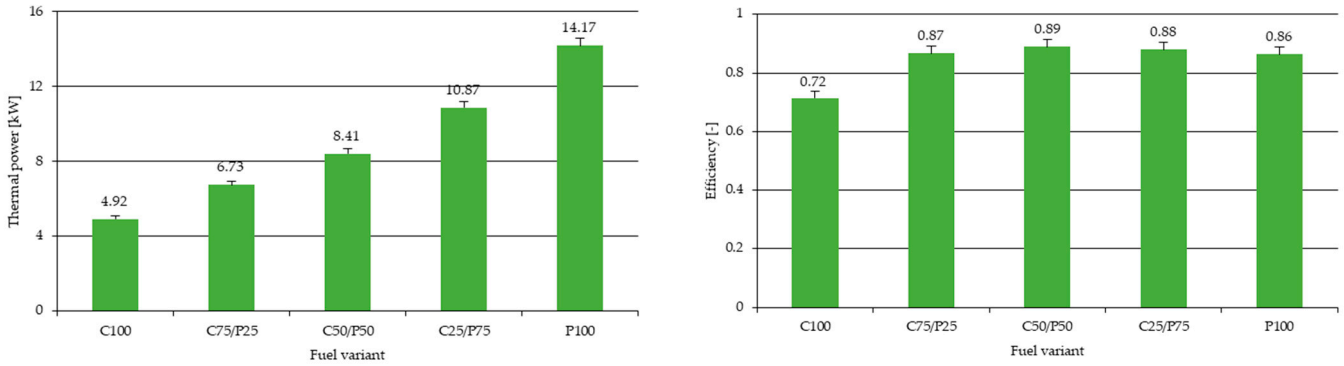
The measurement errors of the analyzers were at most 2%, according to their technical specifications. The measurement errors of the calculated quantities were determined by the method of the complete differential.

Table 2. Summary of study results.

Fuel Type	C100	C75/P25	C50/P50	C25/P75	P100
Heating value [MJ·kg^{-1}]	17.34	-	-	-	19.87
Pellet weight in the period [kg·h^{-1}]	0.99	1.56	1.83	2.31	2.98
Exhaust gas temp. [K]	361.95	381.81	393.26	396.10	406.61
Water temp. difference [K]	3.45	4.98	6.44	7.97	10.20
Water flow [kg·h^{-1}]	1222.44	1254.24	1254.29	1265.46	1287.32
H_2 [% vol.]	0.17	0.31	0.43	0.61	0.75
O_2 [% vol.]	19.28	18.38	16.95	15.61	14.06
CO_2 [% vol.]	1.33	2.34	3.22	4.61	5.72
SO_2 [ppm]	9.97	11.79	12.15	13.71	16.39
NO_2 [ppm]	0.16	0.02	0.00	0.00	0.00
PM10 [µg·m^{-3}]	998.00	661.00	636.00	568.00	298.00
PM2.5 [µg·m^{-3}]	999.00	652.00	627.00	560.00	293.00

The amount of PM is decisively influenced by the degree of compaction of the biomass pellet, Yang et al. (2019) [71] found higher PM 10 content for higher density corn stalk pellets.

On the basis of the measured values, the calculations of energy and emission indices were made, and they were presented in the diagrams (Figures 5–12).



(**a**) (**b**)

Figure 5. Boiler parameters depending on the fuel: (**a**) Thermal power; (**b**) Efficiency.

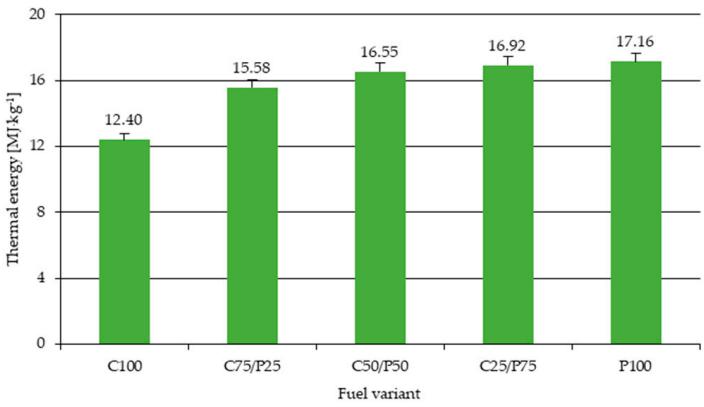
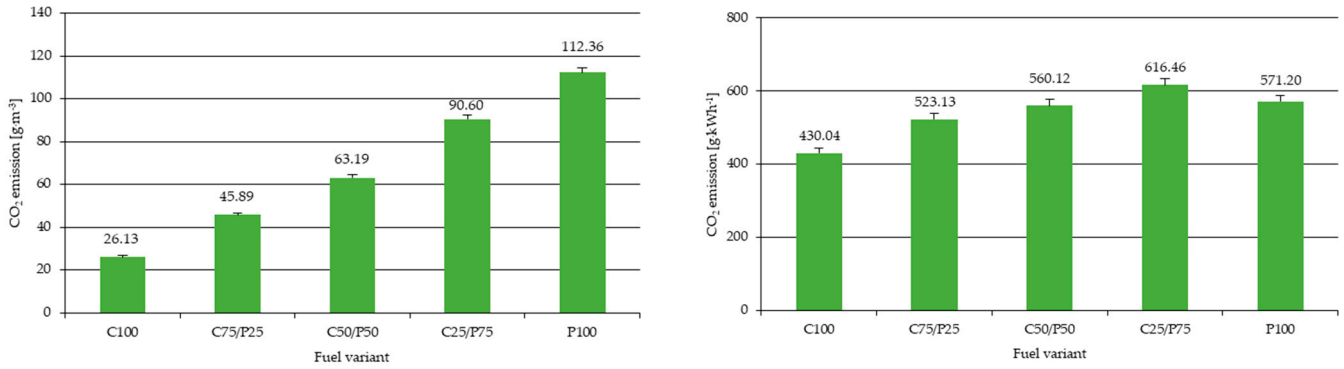
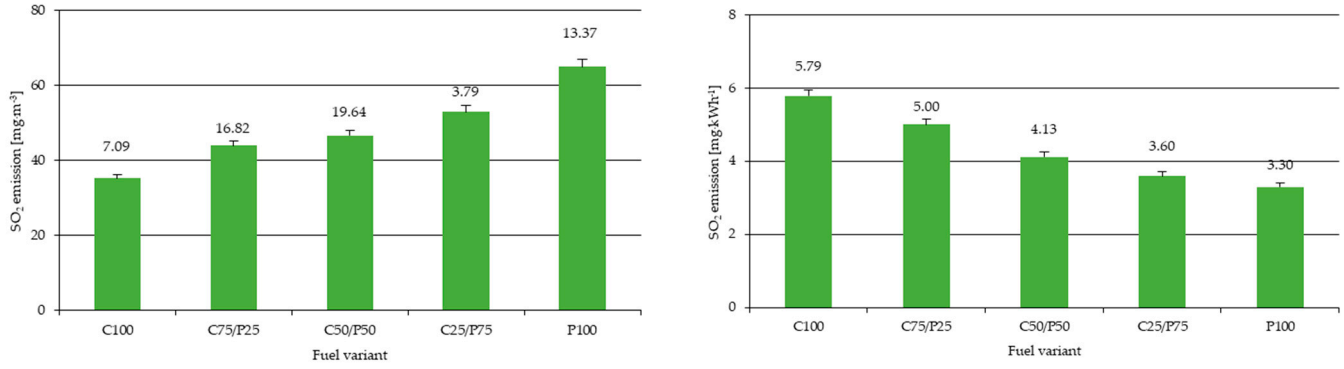


Figure 6. Average heat yield per kilogram of fuel.



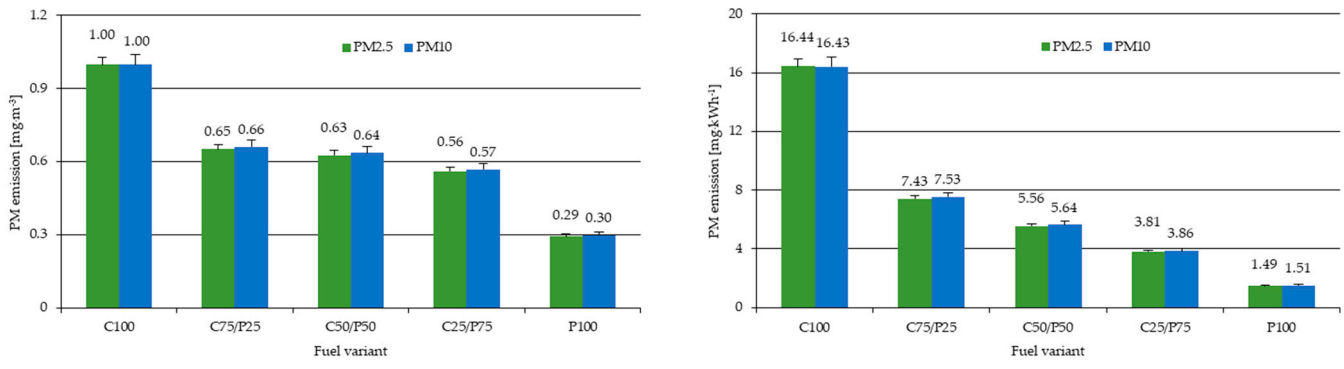
(**a**) (**b**)

Figure 7. CO_2 emission per (**a**) 1 m^3 exhaust gas; (**b**) 1 kWh thermal energy.



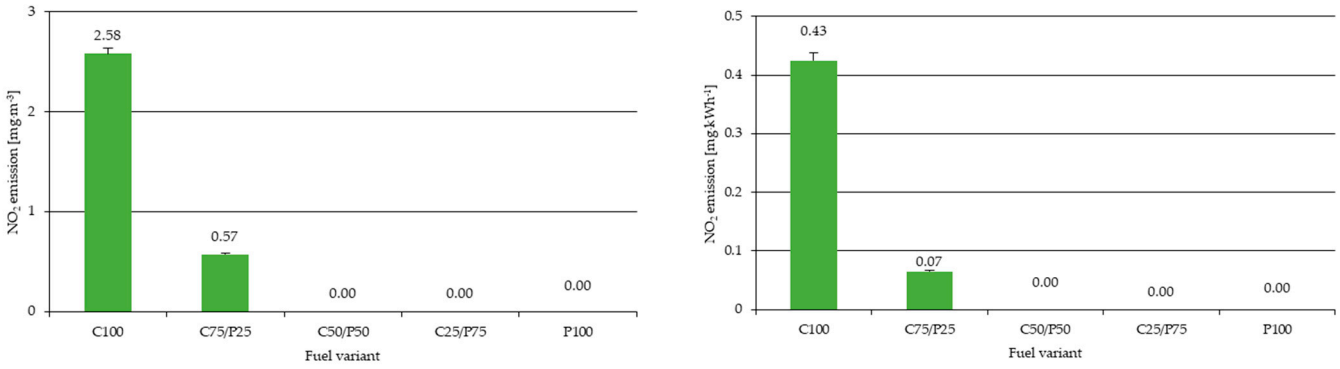
(**a**) (**b**)

Figure 8. SO_2 emission per (**a**) 1 m^3 exhaust gas; (**b**) 1 kWh thermal energy.



(**a**) (**b**)

Figure 9. PM emission per (**a**) 1 m^3 exhaust gas; (**b**) 1 kWh thermal energy.



(**a**) (**b**)

Figure 10. NO_2 emission per (**a**) 1 m^3 exhaust gas; (**b**) 1 kWh thermal energy.

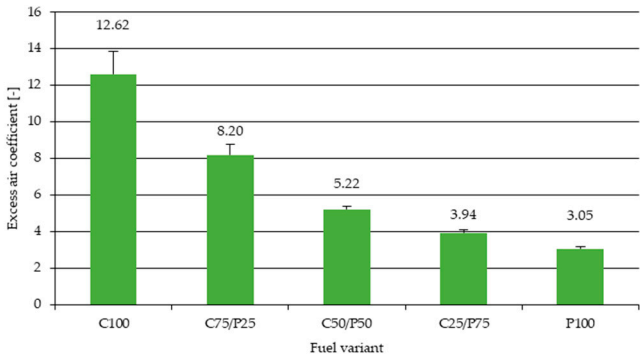


Figure 11. Dependence of the excess air coefficient on fuel variant.

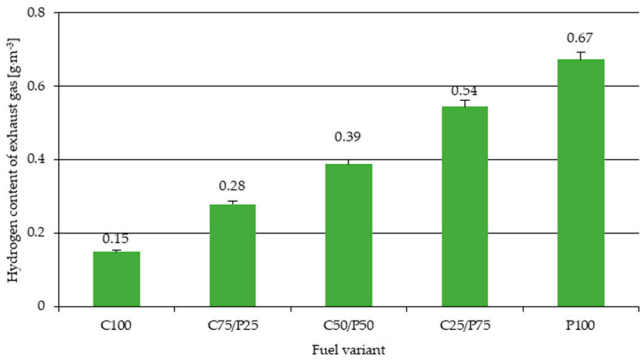


Figure 12. Hydrogen content in 1 m^3 of exhaust gas.

Figure 5a shows the boiler power obtained for individual fuel blends. The highest power was obtained for a boiler fed with pine pellets. In the case of hemp pellets, the boiler output was about three times smaller. The reason for this is the much lower bulk density of hemp pellets. Despite the identical settings of the devices regulating the pellets containing hemp to the boiler, the pellets containing hemp were fed too slowly, so the obtained thermal power was much lower. This is also confirmed by the results of studies by other authors [57,72], who observed a significant reduction in the power of heating devices during the combustion of low-density biomass.

The high efficiency of the boiler (Figure 5b) was obtained thanks to the use of a gasification burner. In the first stage, synthesis gas was obtained in the gasification chamber of the burner, which was then burned directly in the heat exchanger. Due to this division of the process, the exhaust gas temperature was the highest in the heat exchange zone. The

lowest efficiency was obtained for hemp pellets. The flame from hemp pellets was the smallest, so the zone with the highest temperature was still in front of the heat exchanger.

Figure 6 shows the average amount of heat obtained from burning one kilogram of the pellet tested. According to the thermal balance made, the highest heat of combustion (17.16 MJ·kg^{-1}) was obtained for pine pellets.

For comparison, according to Skibko et al. (2021) [73], the heat of combustion of oxytrees at the constant volume was 17.74 MJ·kg^{-1} and a total humidity of 11.3%.

Figure 7 shows the emission of carbon dioxide, which, in terms of one cubic meter of flue gas, was the highest for pine pellets. It should be noted that even in this case, the excess air coefficient was greater than one, which proves the complete combustion of the biomass. For one kilowatt hour of heat produced, carbon dioxide emissions—an important parameter determining the environmental impact are similar for all fuel mixtures. All of the fuel variants were gasified in the same conditions. The biggest difference of about 30% is in favor of C100 over C25/P75. CO_2 emission for hemp is more favorable compared to pine. This is due to the physicochemical properties of different plants kind [74].

In the studies by Jasinskas et al. (2020) [24], the CO_2 content in the exhaust gas during the combustion of three hemp varieties ranged from 3.7% to 5.0%.

As a result of combustion, sulfur contained in the biomass was chemically transformed into SO_2 in the flue gas [56]. The sulfur content of plants varies from species to species. Wisz et al. (2005) [75] noticed that the sulfur content in biomass depended not only on the plant species but also on the location of the land it comes from, e.g., sawdust briquettes of trees growing in south-west Poland (industrial and mining area) were characterized by higher sulfur content (up to 0.12%) than from other places—0.08% on average. According to Hałuzo and Musiał (2004) [76], the content of sulfur compounds in wood chips does not exceed 0.05% and is three times lower than in straw (0.15%) and several times lower than in coal (0.8%). In the studies of Vassilev et al. (2010) [77], the sulfur content in pine sawdust did not exceed 0.1%. Burczyk (2015) [78], after Cichy (2013) [79], states that the sulfur content in the dry matter of hemp is 0.08%, and according to Brazdausks et al. (2015) [80], in hemp chaff, sulfur constitutes 0.2 ± 0.01%. A similar sulfur content in hemp pellets—at the level of 0.04%, was found by Petlickaite et al. (2022) [45]. According to the research by Aleksiejczuk and Teleszewski (2022) [81], the emission of SO_2 from the combustion of wood pellets in a retort furnace for servicing a single-family house was 1.64 kg·year^{-1}. Knutel et al. (2022) [82] found SO_2 emissions during the combustion of hemp pellets at the level of 800 ppm. In this study, sulfur emissions for C100 fuel were twice that of P100 per one kilowatt hour of energy (Figure 8).

An important indicator of the combustion quality of energy resources is dust emission. On the basis of the conducted research, it was found that the content of PM 2.5 and PM 10 dust in one cubic meter of flue gas was the highest for hemp pellets (Figure 9). As the pine pellet content in the tested mixture increased, the dust content was lower and lower. During the degassing process and subsequent combustion, the light hemp biomass is entrained and transferred to the flue gas by the secondary air stream. Contrary to heavier pine biomass, the amount of hemp ash escaping with the exhaust fumes is about three times greater than that of pine.

The NOx content in the exhaust gas is strictly dependent on the nitrogen content in the biomass [83]. Wang et al. (2019) [62] reviewed different combustion technics, where NOx emissions ranged from 17.3 to 127 kg·MJ^{-1}, while Jasinskas et al. (2020) [24] ranged from 88 to 117 ppm. The source of nitrogen oxides in the exhaust gas is also nitrogen contained in the air. The mechanism of the formation of nitrogen oxides is associated with combustion at high temperatures with high rates of excess air. In the conducted experiment, however, it can be concluded that this mechanism did not occur because the exhaust gas temperatures were not high enough to favor the formation of nitrogen oxides. These tests showed that nitrogen dioxide was very low and was detected only for C100 and C75/P25 fuels (Figure 10).

By analyzing the obtained values of the excess air coefficient, it can be concluded that in all cases, the combustion was complete and complete (coefficient value greater than 1). No carbon monoxide content was found in the exhaust gas, which confirms this hypothesis. With a very similar amount of available air in each of the tested cases, the highest air excess factor was obtained for the C100 fuel. For the P100 fuel, the value was four times lower (Figure 11). It should be noted that the characteristic feature of the tested boiler is the safe way of controlling the fuel fed. Even with an uncontrolled reduction of the air supply, the fuel mass remaining in the gasification burner chamber is so small that its combustion will not result in the emission of carbon monoxide.

The analysis of the exhaust gas composition also showed that one of the components of the exhaust gases (although in small amounts) is hydrogen, which is mainly present in the exhaust gases of the P100 fuel. This is probably because with a similar elemental composition of pine and hemp (hydrogen content 6–7%) [51], not all the hydrogen will be able to separate from the biomass and burn during the operation of the boiler fueled with P100 fuel, so its residues may appear in the flue gases (Figure 12). However, also Jasinskas et al. (2020) [24] observed unburned hydrocarbons HC at concentrations of 26.0–127.9 ppm in the flue gas of hemp pellets.

According to the research by Frankowski and Sieracka (2021) [84], the caloric value of hemp biomass of the Henola variety was 18.3 kJ·kg^{-1} with a heat of combustion of 17.1 MJ·kg^{-1}. Knutel et al. (2022) [82] obtained the caloric value of hemp pellets 17.01 MJ·kg^{-1}, with a low ash content (7.26%). Kraszkiewicz et al. (2019) [51] obtained the calorific value of hemp pellets: 16.6 MJ·kg^{-1}, while the calorific value of straw pellets was 15.82 MJ·kg^{-1}, while the calorific value of wood pellets was 17.49 MJ·kg^{-1}. The studies by Stolarski et al. (2022) [31] showed that the type of tree significantly differentiated all quality parameters of pellets, and only pellets made of two out of seven tree species studied by them (*P. sylvestris* and *P. strobus*) met the most restrictive standards. In their comparative studies, the highest calorific value for pine pellets was obtained by 20.55 MJ·kg^{-1} dry matter. The briquetting technologies were reviewed by Kaur et al. (2017) [85], Roman et al. (2019) [86] and (2022) [87]. Our research did not take into consideration this parameter (pellet quality), but its calorific value. The quality of pellets was not tested because the boiler on which the tests described in this paper were carried out "tolerates" pellets that are even crushed, which does not adversely affect its efficiency.

Hemp is characterized by a high dry matter content, a high energy concentration per hectare and a good energy efficiency to input [51,88] which, combined with the relatively low cost of producing a unit of energy and the simultaneous intensive increase in the acreage of industrial hemp, and recently also medical hemp, which is strongly correlated with the amount of waste depending on the directions of use, puts it in the position of a promising renewable energy source with great prospects.

According to the wolnekonopie.org portal and market research, the price for autumn 2022 of wood pellets in Poland is, on average, 600 EUR·t^{-1}, and hemp pellets—380 EUR·t^{-1}. The production costs of hemp pellets, compared to wood pellets, reduce the possibility of resigning from drying out (necessary in wood pellet production) and the natural adhesives contained in the hemp. In both cases, the costs of fragmentation of the material are incurred [89]. Assuming the prices of pellets quoted above, on the basis of the obtained results, the amount of heat obtained from one kilogram of fuel (Figure 13).

The cost of producing 1 kWh of thermal energy will be approx. EUR 0.117—for hemp and EUR 0.134—for pine. Considering the boiler power and its efficiency in individual variants, the most effective fuel was the C75/P25 mixture, for which the cost of generating one kilowatt hour of heat was the lowest—0.107 EUR·kWh^{-1}.

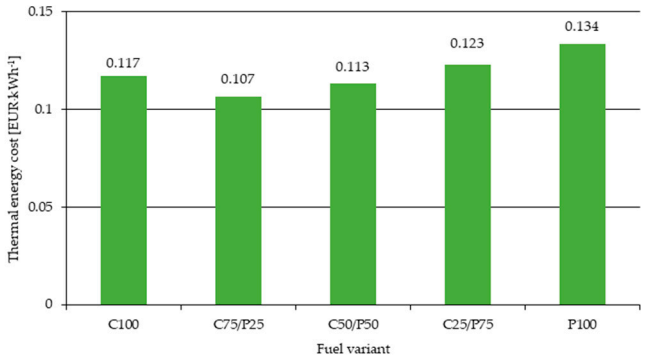


Figure 13. The average cost of producing 1 kWh of heat from the fuels studied under Polish conditions.

4. Conclusions

The study showed the benefits of using hemp for energy purposes. Due to their application, the obtained energy parameters and emissions related to the unit of energy produced are lower or comparable to pine biomass. The use of hemp pellets resulted in a reduction in the power of the tested heating device, which was mainly due to the lower bulk density of the hemp fuel. This effect can be eliminated by changing the boiler automatics—increasing the fuel dose. This regulation was not used in the research so as not to change the experimental conditions, which were the same for each type of mix. It was found that hemp, which is a waste material, is an economically viable substitute for pine raw material. Due to the depletion of fossil fuels resources and the climate policy aimed at reducing the emission of harmful compounds to the atmosphere, fuels made from biomass, especially non-woody fuels, will enable the achievement of environmental goals and, at the same time, will be one of the cheaper materials used to generate heat.

The obtained research results are an inspiration and will be used to design field studies aimed at broadening the knowledge about the impact of hemp cultivation technology on their energy potential and the number of emissions of individual gases in the exhaust gases during gasification. They will facilitate the design of favorable scenarios for the environment, which will fill the knowledge gap in this regard.

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