energies

Article

The Experimental Study of the Efficiency of the Gasification Process of the Fast-Growing Willow Biomass in a Downdraft Gasifier

Savelii Kukharets [1,*], Algirdas Jasinskas [1], Gennadii Golub [2], Olena Sukmaniuk [3], Taras Hutsol [4,*], Krzysztof Mudryk [5], Jonas Čėsna [6], Szymon Glowacki [7] and Iryna Horetska [8]

1 Department of Agricultural Engineering and Safety, Faculty of Engineering, Agriculture Academy, Vytautas Magnus University, Studentu Str. 15A, Akademija, LT-53362 Kaunas, Lithuania
2 Department of Tractors, Automobiles and Bioenergy Resources, National University of Life and Environmental Sciences of Ukraine, Heroev Oborony Str. 15B, 03-040 Kyiv, Ukraine
3 Department Machines Processes and Agroengineering Equipment, Polissia National University, Staryi Blvd 7, 10-008 Zhytomyr, Ukraine
4 Department of Mechanics and Agroecosystems Engineering, Polissia National University, Staryi Blvd 7, 10-008 Zhytomyr, Ukraine
5 Faculty of Production and Power Engineering, University of Agriculture in Krakow, 30-149 Krakow, Poland
6 Department of Mechanical, Energy and Biotechnology Engineering, Faculty of Engineering, Agriculture Academy, Vytautas Magnus University, Studentu Str. 11, Akademija, LT-53362 Kaunas, Lithuania
7 Department of Fundamentals of Engineering and Power Engineering, Institute of Mechanical Engineering, Warsaw University of Life Sciences (SGGW), 02-787 Warsaw, Poland
8 Innovative Program of Strategic Development of the University, European Social Fund, University of Agriculture in Krakow, 30-149 Krakow, Poland
* Correspondence: kikharets@gmail.com (S.K.); wte.inter@gmail.com (T.H.)

Abstract: In this work, a study was performed on the influence of the ratio of height to the diameter of the reduction zone of a small-size downdraft gasifier as well as of the fuel fraction sizes on the gas quality (the quality was evaluated for *CO* content). The ratio of a full side area to the volume of a fuel fraction (*SVR*) was used as a fuel parameter. The maximum *CO* concentration was observed when using a small fuel fraction with *SVR*—0.7–0.72 mm^{-1} and when adhering to the ratio of height to the diameter of the reduction zone *H/D*—0.5–0.6. The maximum electric power for gasoline generators (nominal power equaled 4 kW) when using the gas received from the fast-growing hybrid willow biomass equaled 2.4 kW. This power is 37.5% lower than when using gasoline and 7.0% lower than when using the gas received from the hardwood biomass. The emissions of harmful gases into the atmosphere by the gasoline generator engine equaled 0.12–0.14% *CO* and 24–27 mln^{-1} C_xH_y. The emissions were 64.8 times less for *CO* and 8.5 times less for C_xH_y when compared with using gasoline.

Keywords: carbon monoxide; biomass; gasification; reduction zone; gasoline generators; electric energy; harmful gases

check for updates

Citation: Kukharets, S.; Jasinskas, A.; Golub, G.; Sukmaniuk, O.; Hutsol, T.; Mudryk, K.; Čėsna, J.; Glowacki, S.; Horetska, I. The Experimental Study of the Efficiency of the Gasification Process of the Fast-Growing Willow Biomass in a Downdraft Gasifier. *Energies* **2023**, *16*, 587. https://doi.org/10.3390/en16020578

Academic Editor: Alok Kumar Patel

Received: 13 December 2022
Revised: 27 December 2022
Accepted: 29 December 2022
Published: 4 January 2023

1. Introduction

The reduction of greenhouse gas emissions and the improved energy supply can be achieved through the increased use of biofuel [1–5]. The lignin–cellulose mass from plants is an important raw material for biofuel production [6,7]. As a result of energy conversion, it is possible to obtain biogas, diesel biofuel, bioethanol, biohydrogen, fuel briquettes, etc. [8–10]. Agricultural production allows to receive a great amount of biomass available for energy conversion [11–13]. However, the use of biomass for energy conversion can result in a decrease in food production as well as in some negative impacts on the environment [14–16]. Therefore, the choice of a raw material is an important efficiency factor in the energy conversion of biomass. An efficient choice of a raw material can provide the lowest cost as well as the lowest emission of harmful substances into the atmosphere at all stages of energy conversion [17].

There is an opinion regarding the low efficiency of the energy conversion of biomass [18,19]. The energy conversion of biomass can disrupt the environmental and economic stability of agricultural production [8,9,19]. An increase in the number of types of agricultural crops can increase the stability of agricultural production [20].

One such species can be fast-growing hybrid plants, in particular, hybrid poplar, hybrid willow, and hybrid aspen [21]. The plantations of fast-growing hybrid plants are a source of biomass with a high potential for energy conversion [22]. The sources of wood raw material, such as hybrid poplar and hybrid willow and particularly aspen and northern hardwoods, are potential sources of wood biomass for obtaining thermal and electric energy as well as for ethanol production [23]. The use of fast-growing hybrid plants is appropriate in view of the reduction of carbon dioxide emissions (CO_2) [24].

Some scientists state that growing fast-growing hybrid plants is cost-effective if subsidized [25]. Therefore, it is necessary to pay attention to the energy conversion efficiency of fast-growing hybrid plants. In particular, the efficiency depends on the parameters of the working machines used in the relevant technological processes. These parameters are equipment ratio, cost of consumables (fuel and energy), cost of equipment, etc. [26–28]. There are some technical obstacles for efficient biofuel production from the biomass of fast-growing hybrid plants, for example, a significant energy requirement, a high cost of the necessary equipment, and some difficulties in providing the necessary technological conditions. Such technical and financial aspects pose serious problems for the commercial viability of many technologies of energy conversion of fast-growing hybrid plants [29].

One of the widespread and promising fast-growing hybrid plants for energy conversion is the hybrid willow Salix Viminalis [30,31]. The fast-growing willow is mainly used in the processes of direct combustion as it has a high heating value (from 17 to 19.5 MJ/kg) [32,33]. It is common to use the fast-growing hybrid plant's biomass in the form of pellets, briquettes, sawdust, chips, etc. [9,34]. The fast-growing hybrid willow biomass is suitable for efficient torrefaction [35]. It is easy to obtain energy from the fast-growing hybrid willow biomass by combustion. However, direct combustion causes some difficulties due to biomass heterogeneity and high ash content [36]. The hard deposits (agglomerates) are accumulated on the work surfaces of the heating equipment through ash melting in the process of biomass combustion [37]. In addition, biomass combustion in small and medium volumes allows to obtain only thermal energy for the consumers. To obtain electric energy, it is necessary to use large energy complexes that run on biomass [38].

The fast-growing hybrid willow biomass is also suitable for biofuel production by biochemical transformation, for example, for bioethanol production [31], or by thermochemical transformation—pyrolysis [32]. Bioethanol production and biomass pyrolysis are rather complicated and energy-intensive technological processes, which can be appropriate in large-scale industrial production. However, under the conditions of small and medium enterprises, particularly, agricultural ones, such technologies are not economically and energetically reasonable. Therefore, to achieve a steady energy supply under conditions of small and medium agricultural or industrial enterprises, it will be reasonable to use the gasification technologies in which hard biomass is transformed into a combustible gas, known as a producer gas [10,36,39–42]. Herewith, the use of a small-size downdraft gasifier is preferable because of a smaller amount of tar output and fewer requirements for the gas cleaning that is economically attractive and technically more reliable [39,41]. However, when using a small gas generator with a downward flow, the geometric parameters of the working zones and the properties of the fuel have a significant impact on the quality of the gas. In [43], a study was performed of a downdraft gasifier operation process running on five types of biomasses, in particular on a hybrid willow.

The studies were aimed at assessing the influence of the equivalence ratio (*ER*) change, that is the air supply into a work zone, on the chemical composition of the received gas. The influence of the gasifier geometric parameters and of the fuel fraction size were not assessed. In the scientists' opinion, they have a significant influence on the quality of the received gas. The use of a fluidized bed gasifier allows to reduce the impact of side parameters on the quality of the received gas and to increase its heating value [44,45]; however, the design of such a generator is complicated, and the improvement of gas quality is insignificant. The authors suppose that the use of a downdraft gasifier in the process of gas production in small and medium volumes is reasonable. The producer gas that was received in the process of gasification can be used as fuel for gasoline generators at small and medium enterprises or for the internal combustion engine *CHP* system at large enterprises [46,47]. Such systems can produce electric and thermal energy. In particular, the performance efficiency of a small-scale cogeneration plant was evaluated in [47,48], but the level of harmful gas emissions by a combustion engine with which the plant was equipped was not studied.

Though previous scientific research proves that the gasifier construction is very important, there is still a small number of multifactorial studies describing the effect of the recovery zone height on the quality of the gas depending on the size of the fuel particles when the combustion zone and the recovery zone of the gasifier have the same diameter without barriers for fuel movement. The goal of the current study is to optimize the ratio of the gasifier recovery zone height and diameter when the gasifier combustion and recovery zone have the same diameter without barriers for fuel movement.

2. Materials and Methods

The purpose of the research is to study the features of energy conversion of a fast-growing willow Salix Viminalis biomass by means of a small-size downdraft gasifier. Two experimental plants were used for this purpose. The influence of fuel fraction sizes and the reduction zone parameters of a gasifier on the quality of the received generator gas were studied in the first plant (Figure 1a,b). The plant was built on the basis of the experimental downdraft gasifier (position 5 in Figure 1b). In the suggested downdraft gasifier, the combustion and the reduction zones have the same diameter. Such a construction feature allows to improve the efficiency of biomass gasification by 15% as compared with the analogs [49]. The diameter of a reduction zone equaled 200 mm, and the height (the working length) of the reduction zone could change from 40 to 160 mm. The height to diameter ratio *H/D* was chosen as a parameter of the reduction zone (Table 1).

Table 1. The reduction zone characteristics.

The Reduction Zone Height *H*, mm	The Reduction Zone Diameter *D*, mm	*H/D*, mm/mm
40	200	0.2
100	200	0.5
160	200	0.8

The air flow into the reduction zone was 0.012 m^3/s in order to reach a rational equivalence ratio (*ER*). With that air flow, the *ER* stayed in the range of 0.3–0.35 and provided the highest gas quality (according to earlier studies conducted by the authors [40,49]).

The equivalence ratio (*ER*), which was used in the article, shows the ratio of the oxygen amount supplied to the gasifier to the oxygen amount required for stoichiometric fuel combustion [50,51]:

$$ER = \frac{0.21m_2}{xm_1 + 0.25ym_1 + 0.5zm_1} \quad (1)$$

where m_1—fuel (biomass) consumption during gas formation, mol/s;

m_2—air consumption, mol/s;

x—number of carbon molecules per mole of fuel;

y—number of hydrogen molecules per mole of fuel;

z—number of oxygen molecules per mole of fuel.

In the research, a fuel biomass of a fast-growing willow Salix Viminalis was divided into four fractions according to the geometrical sizes (Figure 2, Table 2). The fuel pellets that were made of the ground biomass of a fast-growing willow were used as well.

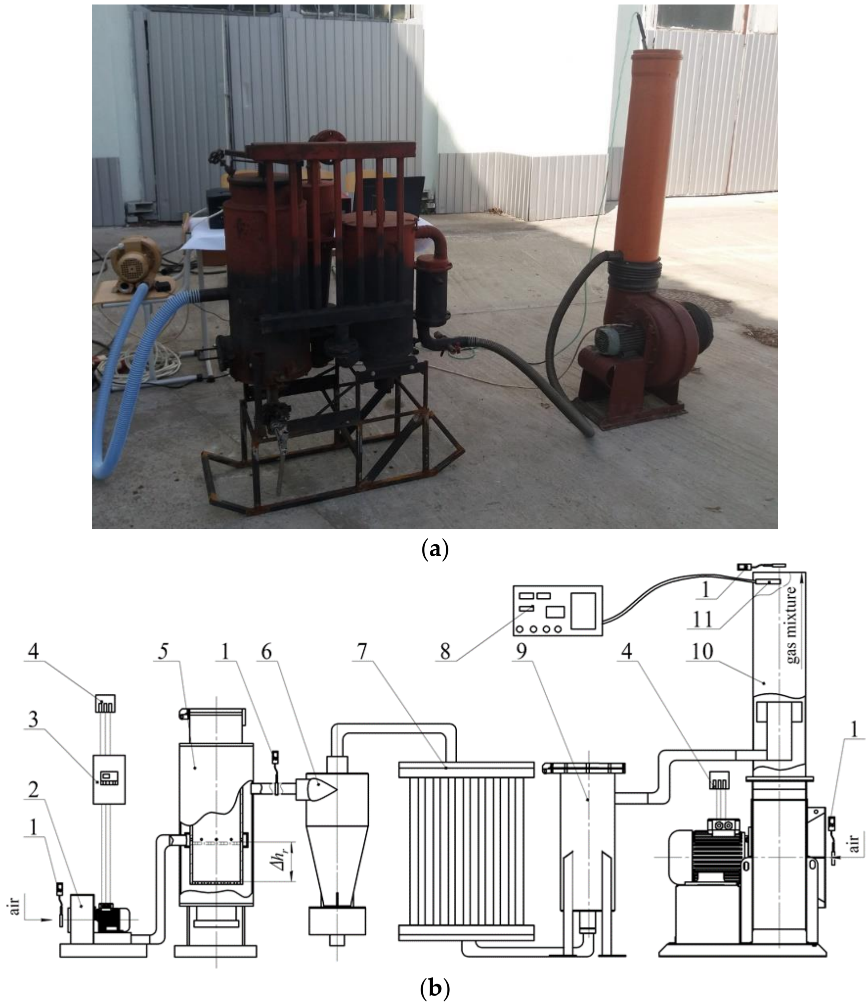


Figure 1. General view (**a**) and a scheme (**b**) of plant number 1 for conducting research: 1—an anemometer, 2—an air blower (an oxidant blower), 3—a frequency converter, 4—an electric power source, 5—a downdraft gasifier, 6—an intermediate purification filter, 7—a cooler, 8—a chemical analyzer of gas content, 9—a filter for final gas purification, 10—a mixer, and 11—an analyzer sensor 8.

Figure 2. Fractional composition of the fuel from the biomass of a fast-growing willow Salix Viminalis: 1—a large fraction, 2—a medium fraction, 3—a small fraction, 4—a very small fraction, and 5—fuel pellets.

Table 2. Fuel fraction characteristics.

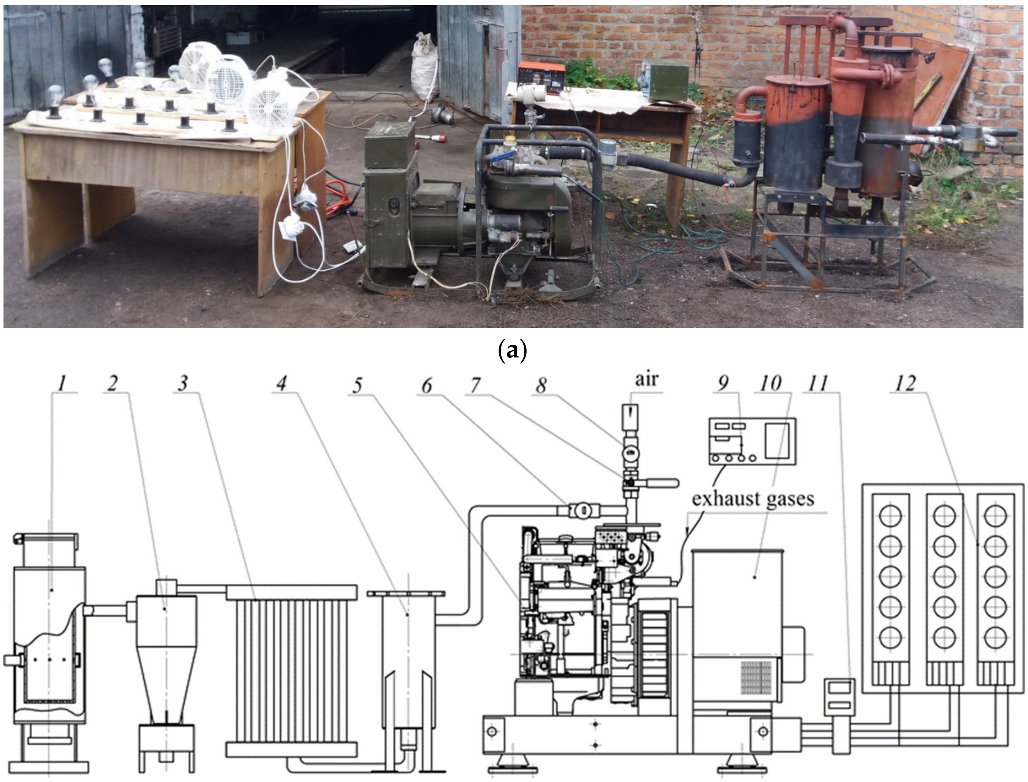
Fraction	No.	Average Sizes, mm			Average Area of a Full Surface S, mm^2	Average Volume V, mm^3	SVR, S/V mm^{-1}
		Length	Width	Thickness			
Large	1	40	15	12	2520	7200	0.35
Medium	2	30	12	8	1392	2880	0.48
Small	3	20	9	5	650	900	0.72
Very small	4	10	4	4	192	160	1.20
Fuel pellets	5	10	4 (diameter)		192	160	1.20

A ratio of a full side area (S) to a fraction volume (V) of fuel—SVR [39] was used as a fuel parameter (Table 2).

As the fuel with the lowest possible relative humidity was used in the experiment, the producer gas quality was determined according to the carbon monoxide (CO) concentration [36,40].

The experiment with each fuel fraction and the reduction zone height was repeated three times. The homogeneity of variances of the experimental data was assessed by Cochran's criterion; the significance of the regression equation coefficients was assessed by Student's criteria, and the adequacy of the received regression equations was assessed by Fisher's criterion.

In the second experimental plant, the influence of the producer gas on the process of electric energy generation was studied with an electric generator (nominal power 4.0 kW) equipped with an internal combustion engine (Figure 3a,b).



(**a**)

(**b**)

Figure 3. General view (**a**) and a scheme (**b**) of plant number 2 for conducting research: 1—a downdraft gasifier; 2—a filter for intermediate gas purification; 3—a refrigerator; 4—a filter for a final gas purification; 5—an internal combustion engine; 6—a gas meter; 7 –a mixer for regulating the air supply into the engine; 8—an air meter; 9—an analyzer of the chemical composition of exhaust gases; 10—an electric generator; 11—wattmeter; and 12—a standard electrical load consumer.

The second experimental plant was built on the basis of a downdraft gasifier. The height of the reduction zone of a generator equaled 110 mm (H/D = 0.55). The fuel with fraction №3 (SVR 0.72, Table 2) was loaded into a gasifier. The process of studying the influence of a producer gas on the process of electric energy generation is described in detail in the authors' publications [52,53].

3. Results and Discussion

As a result of the data analysis of the experimental studies of the gasification process of a fast-growing willow Salix Viminalis, an empirical equation (2) was received that describes the dynamics of change in the *CO* concentration depending on the sizes of the fuel fractions and the geometric sizes of the reduction zone:

$$C_{CO} = -18.27 + 80.80\frac{H}{D} + 53.61SVR - 59.03\left(\frac{H}{D}\right)^2 - 21.02\frac{H}{D}SVR - 31.34SVR^2 \quad (2)$$

where C_{CO}—the concentration of carbon monoxide (*CO*), %;

H/D—the height to the reduction zone diameter ratio, mm/mm;

SVR—the ratio of the full side area to the volume of a fuel fraction, mm^{-1}.

Visually, Equation (1) can be shown in graphs (Figures 4–6).

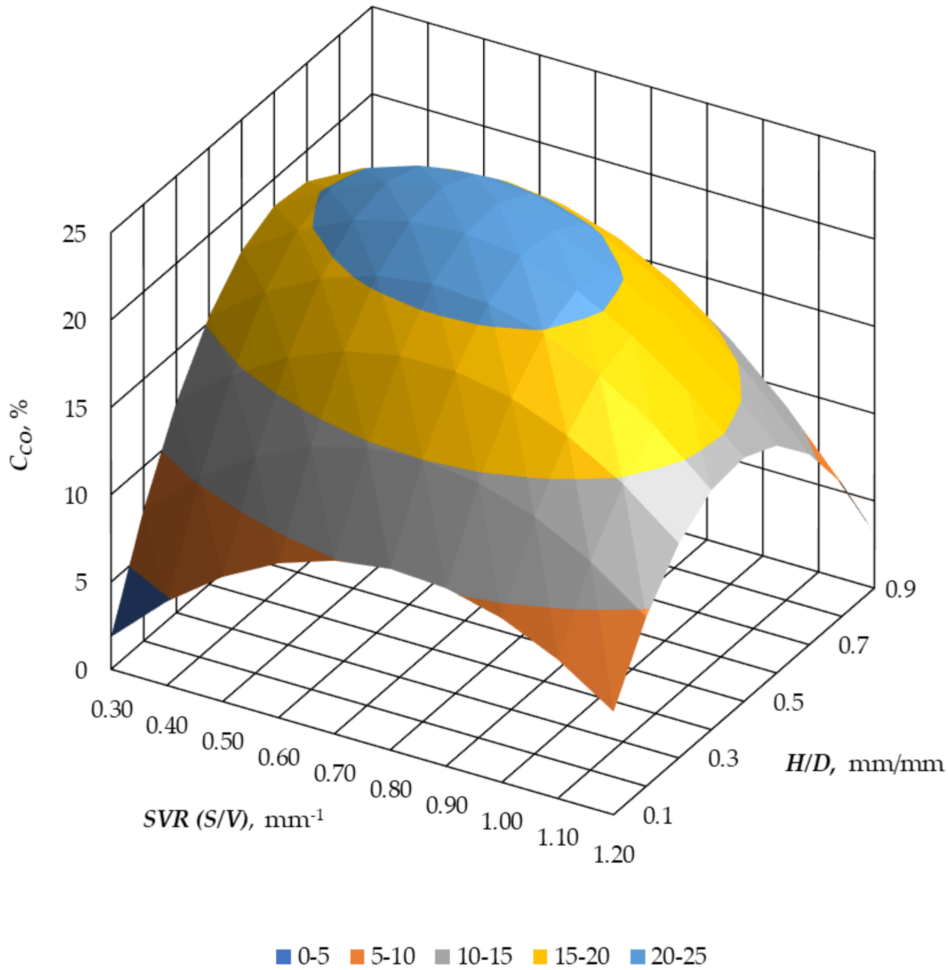


Figure 4. Graphic image of the dependence of *CO* concentration in the received gas on the ratio indicators of height to the reduction zone diameter (*H/D*) and on the ratio of the full side area (*S*) to the volume (*V*) of a fuel fraction (*SVR*).

As follows from the analytical study of the graphs (Figures 4–6), the maximum *CO* concentration in the gas equals 22.2–22.3%. The maximum *CO* concentration is observed when using a small fuel fraction *SRV*—0.7–0.72 mm^{-1} and when keeping to the ratio of height to the reduction zone diameter *H/D* at the level of 0.5–0.6. Such a ratio for a given experimental gasifier is achieved when the reduction zone height is within 100–120 mm.

In the authors' opinions, when the reduction zone height is more than 120 mm, the resistance for the air flow (oxidizer) increases, and it results in gas quality deterioration (*CO* concentration decreases). If the reduction zone height is less than 100 mm, the *CO* concentration decreases as well. It can be explained by the fact that under a low height of the reduction zone, the producer gas does not pass in full.

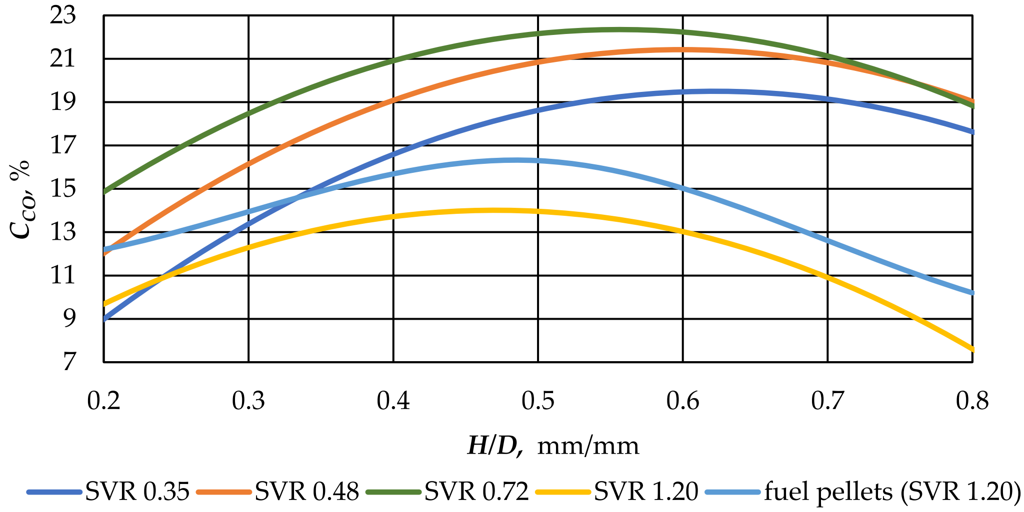


Figure 5. Graphic image of the dependence of *CO* concentration in the received gas on the ratio indicators of height to the reduction zone diameter (*H*/*D*).

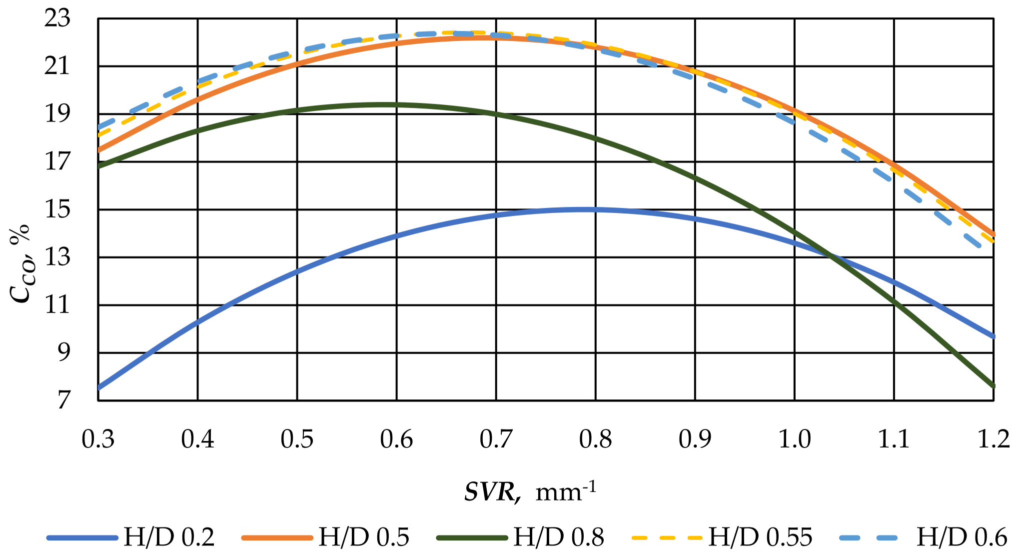


Figure 6. Graphic image of the dependence of *CO* concentration in the received gas on the ratio of the full side area (*S*) to the volume (*V*) of a fuel fraction (*SVR*).

Due to the decrease in the fuel fraction, the intensity of gas formation increases, and the process of gas renewal improves. However, when the fuel fraction is very small, there is a significant increase in the resistance for the air flow, and, as a result, the process of gas formation slows down, and its quality deteriorates.

For comparison, a maximum concentration of *CO* in the process of hardwood gasification in an analogical gasifier was 27.5% [40]. A higher *CO* content in the gas from the hardwood as compared with the fast-growing willow was caused by the denser wood structure of the hardwood. The paper [43] evaluated the chemical composition of fuel received from the willow biomass; the *CO* content equaled up to 30%, and the content of other combustion gases was insignificant. The *CO* content for other hardwoods was somewhat higher. As follows from the analysis of the mathematical models [54], the *CO* content in gas that was received from the biomass is within 22–27%. The content of other combustion gases (except *H*) is insignificant. Thus, the next stage of the research can be the evaluation of the *H* content.

The authors also state that it is not reasonable to use fuel pellets made from fast-growing willow in gasifiers. The quality of the received gas is somewhat lower in this case. Furthermore, fuel pellet production needs additional economic and energy costs.

The authors also studied the efficiency of using the gas received in the process of gasification of the fast-growing willow biomass for the work of small-scale gasoline generators. The analysis of the results and their comparison with the previous results of the authors' research [49,52] are given in graphical form in Figures 7–10.

Figure 7. Power generator capacity.

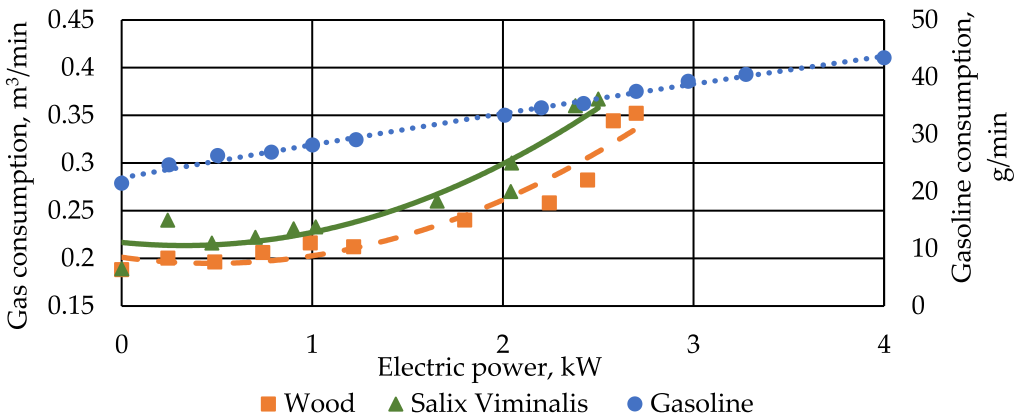


Figure 8. Fuel consumption.

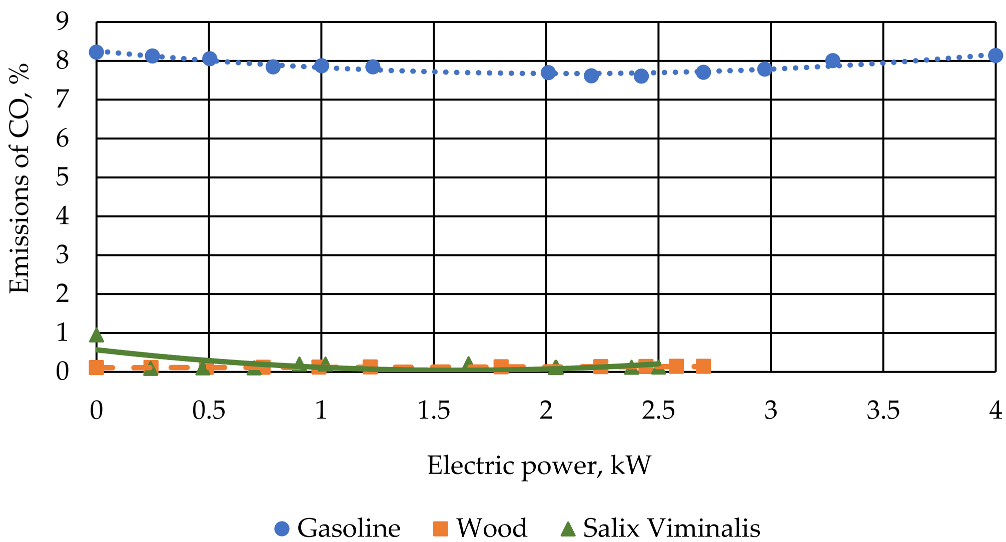


Figure 9. Emissions of CO.

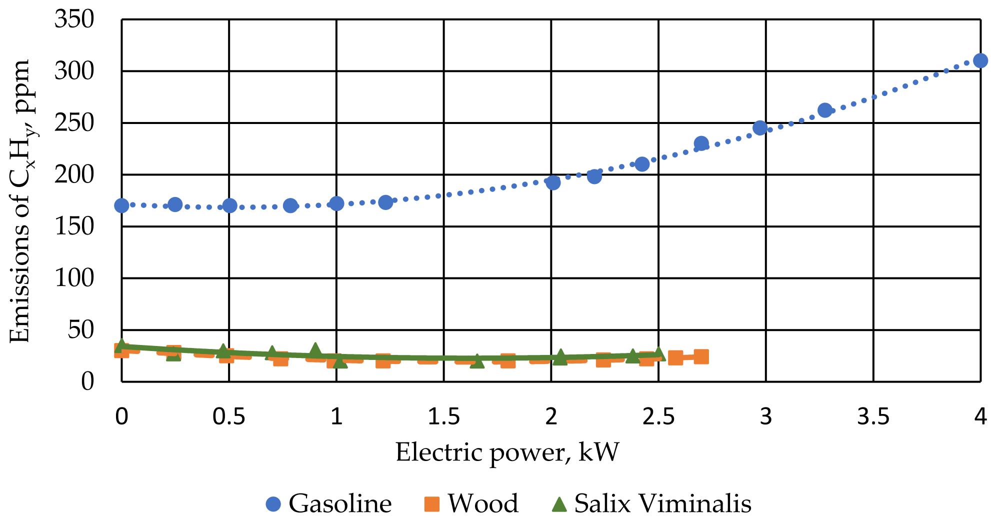


Figure 10. Emissions of C_xH_y.

It is necessary to mention that the maximum electric power when using the gas received from the fast-growing willow biomass equaled 2.4 kW. This power is 37.5% lower than when using gasoline and 7.4% lower than when using the gas received from the hardwood biomass. This can be explained by a smaller lower heating value (*LHV*) of the gas received from the fast-growing willow (*LHV* of the gas—9–10 MJ/m^3, *LHV* of gasoline—43–44 MJ/l [36,52]).

The consumption of the gas that was received from the fast-growing willow was somewhat higher (by 6.7% on the average) as compared with the consumption of the gas received from the hardwood biomass (Table 3, Figure 8). This can be explained by a smaller LHV of the gas received from the fast-growing willow (LHV of the gas received from the fast-growing willow—9–10 MJ/m^3, LHV of the gas received from the hardwood biomass—10–13 MJ/m^3 [36,52]).

Table 3. Fuel consumption.

Fuel	Empirical Equation	The Number of the Equation	Confidence Level (R^2)
Gasoline	$Q_1 = 5.35N + 22.72$	(3)	0.99
Gas from the hardwood biomass	$Q_2 = 0.029N^2 - 0.027N + 0.20$	(4)	0.91
Gas from the biomass of the fast-growing willow Salix Viminalis	$Q_2 = 0.031N^2 - 0.020N + 0.22$	(5)	0.90
where Q_1—gasoline consumption, g/min; Q_2—gas consumption, m^3/min; and N—electric power, kW			

As for the toxic gas emissions, their amount was practically the same when using both the gas received from the hardwood and the gas received from the fast-growing willow—0.12–0.14% *CO* and 24–27 ppm C_xH_y. In addition, when using gasoline, the toxic gas emission was 64.8 times less for *CO* and 8.5 times less for C_xH_y (Figures 9 and 10).

The results of the research help to draw a conclusion about the environmental efficiency of using small-scale cogeneration plants that run on the gas received in the process of fast-growing willow gasification. However, the received electric power is lower than when using fossil fuels, gasoline in particular. To increase the energy efficiency of using fast-growing willow biomass, it is possible to use torrefied biomass [35,55,56].

The authors are planning to conduct research into the gasification rate of different fractions of fast-growing willow biomass to determine the ash content and to estimate the rate of ash melting in the process of biomass gasification, to conduct a comparative study of the effectiveness of the torrefied biomass gasification, and to conduct an economic assessment of the expediency of receiving energy by a small-scale cogeneration plant that uses fast-growing willow biomass as fuel.

4. Conclusions

In the process of gasification of a fast-growing willow Salix Viminalis in a downdraft gasifier, the maximum CO concentration in a producer gas equals 22.2–22.3%. The maximum CO concentration is observed when using a small fraction of fuel SRV—0.7–0.72 mm^{-1} and when keeping to the ratio of height to the diameter of the reduction zone H/D—0.5–0.6.

The maximum electric power for gasoline generators (nominal power—4 kW) when using the gas received from the fast-growing willow biomass equaled 2.4 kW. This power is 37.5% lower than when using gasoline and 7.4% lower than when using the gas received from the hardwood biomass.

When using the gas that was received from the hardwood and the fast-growing willow, the emissions of harmful gases by the gasoline generator engine into the atmosphere were practically the same and equaled 0.12–0.14% CO and 24–27 ppm C_xH_y. The studies testify to the expediency of energy conversion of the fast-growing willow biomass by the gasification processes.

Author Contributions: Conceptualization, S.K. and A.J.; methodology, S.K., G.G., T.H. and O.S.; validation, K.M. and J.Č.; formal analysis, S.G. and I.H.; project administration, S.K.; Supervision, T.H. All authors have read and agreed to the published version of the manuscript.

Funding: Financed from a subsidy of the Ministry of Education and Science for the Hugo Kołłątaj Agricultural University in Kraków for the year 2022.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kucher, O.; Glowacki, S.; Andreitseva, I.; Dibrova, A.; Muzychenko, A.; Szeląg-Sikora, A.; Szparaga, A.; Kocira, S. Energy Potential of Biogas Production in Ukraine. *Energies* **2022**, *15*, 1710. [CrossRef]
2. Golub, G.A.; Kukharets, S.M.; Yarosh, Y.D.; Kukharets, V.V. Integrated use of bioenergy conversion technologies in agroecosystems. *INMATEH Agric. Eng.* **2017**, *51*, 93–100.
3. Mathur, S.; Waswani, H.; Singh, D.; Ranjan, R. Alternative Fuels for Agriculture Sustainability: Carbon Footprint and Economic Feasibility. *AgriEngineering* **2022**, *4*, 993–1015. [CrossRef]
4. Tryhuba, A.; Hutsol, T.; Kuboń, M.; Tryhuba, I.; Komarnitskyi, S.; Tabor, S.; Kwaśniewski, D.; Mudryk, K.; Faichuk, O.; Hohol, T. Taxonomy and Stakeholder Risk Management in Integrated Projects of the European Green Deal. *Energies* **2022**, *15*, 2015. [CrossRef]
5. Johansson, R.; Meyer, S.; Whistance, J.; Thompson, W.; Debnath, D. Greenhouse gas emission reduction and cost from the United States biofuels mandate. *Renew. Sustain. Energy Rev.* **2020**, *119*, 109513. [CrossRef]
6. Cavalaglio, G.; Cotana, F.; Nicolini, A.; Coccia, V.; Petrozzi, A.; Formica, A.; Bertini, A. Characterization of Various Biomass Feedstock Suitable for Small-Scale Energy Plants as Preliminary Activity of Biocheaper Project. *Sustainability* **2020**, *12*, 6678. [CrossRef]
7. Saravanan, A.; Senthil Kumar, P.; Jeevanantham, S.; Karishma, S.; Vo, D.N. Recent advances and sustainable development of biofuels production from lignocellulosic biomass. *Bioresour. Technol.* **2022**, *344*, 126203. [CrossRef]
8. Golub, G.; Skydan, O.; Kukharets, V.; Yarosh, Y.; Kukharets, S. The estimation of energetically self-sufficient agroecosystem's model. *J. Cent. Eur. Agric.* **2020**, *21*, 168–175. [CrossRef]
9. Golub, G.; Chuba, V.; Lutak, V.; Yarosh, Y.; Kukharets, S. Researching of indicators of agroecosystem without external energy supply. *J. Cent. Eur. Agric.* **2021**, *22*, 397–407. [CrossRef]
10. Kukharets, S.; Hutsol, T.; Glowacki, S.; Sukmaniuk, O.; Rozkosz, A.; Tkach, O. Concept of biohydrogen production by agricultural enterprises. *Agric. Eng.* **2021**, *25*, 63–72. [CrossRef]
11. Umakanth, A.V.; Datta, A.; Reddy, B.S.; Bardhan, S. Chapter 3—Biomass feedstocks for advanced biofuels: Sustainability and supply chain management. In *Advanced Biofuel Technologies*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 39–72. [CrossRef]
12. Vaish, S.; Kaur, G.; Sharma, N.K.; Gakkhar, N. Estimation for Potential of Agricultural Biomass Sources as Projections of Bio-Briquettes in Indian Context. *Sustainability* **2022**, *14*, 5077. [CrossRef]
13. Petlickaitė, R.; Jasinskas, A.; Mieldažys, R.; Romaneckas, K.; Praspaliauskas, M.; Balandaitė, J. Investigation of Pressed Solid Biofuel Produced from Multi-Crop Biomass. *Sustainability* **2022**, *14*, 799. [CrossRef]
14. Verdade, L.M.; Piña, C.I.; Rosalino, L.M. Biofuels and biodiversity: Challenges and opportunities. *Environ. Dev.* **2015**, *15*, 64–78. [CrossRef]
15. Hunt, N.D.; Gower, S.T.; Nadelhoffer, K.; Lajtha, K.; Townsend, K.; Brye, K.R. Validation of an agroecosystem process model (AGRO-BGC) on annual and perennial bioenergy feedstocks. *Ecol. Model.* **2016**, *321*, 23–34. [CrossRef]

16. Kurowska, K.; Marks-Bielska, R.; Bielski, S.; Kryszk, H.; Jasinskas, A. Food Security in the Context of Liquid Biofuels Production. *Energies* **2020**, *13*, 6247. [CrossRef]
17. Gomiero, T. Large-scale biofuels production: A possible threat to soil conservation and environmental services. *Appl. Soil Ecol.* **2018**, *123*, 729–736. [CrossRef]
18. Ahamer, G. Why Biomass Fuels Are Principally Not Carbon Neutral. *Energies* **2022**, *15*, 9619. [CrossRef]
19. Mockshell, J.; Villarino, M.E. Agroecological intensification: Potential and limitations to achieving food security and sustainability. *Encycl. Food Secur. Sustain.* **2019**, *3*, 64–70. [CrossRef]
20. Kazemi, H.; Klug, H.; Kamkar, B. New services and roles of biodiversity in modern agroecosystems: A review. *Ecol. Indic.* **2018**, *93*, 1126–1135. [CrossRef]
21. Jasinskas, A.; Šiaudinis, G.; Martinkus, M.; Karčauskienė, D.; Repšienė, R.; Pedišius, N.; Vonžodas, T. Evaluation of common osier (*Salix viminalis* L.) and black poplar (*Populus nigra* L.) biomass productivity and determination of chemical and energetic properties of chopped plants produced for biofuel. *Balt. For.* **2017**, *23*, 666–672.
22. Dimitriou, I.; Mola-Yudego, B. Poplar and willow plantations on agricultural land in Sweden: Area, yield, groundwater quality and soil organic carbon. *For. Ecol. Manag.* **2017**, *383*, 99–107. [CrossRef]
23. Alian, S.; Maclean, A. Assessing Site Availability of Aspen and Northern Hardwoods for Potential Feedstock Development in Michigan: A Case Study. *Land* **2015**, *4*, 413–435. [CrossRef]
24. Lutter, R.; Stål, G.; Arnesson Ceder, L.; Lim, H.; Padari, A.; Tullus, H.; Nordin, A.; Lundmark, T. Climate Benefit of Different Tree Species on Former Agricultural Land in Northern Europe. *Forests* **2021**, *12*, 1810. [CrossRef]
25. Nilsson, D.; Rosenqvist, H. Profitability of Crop Cultivation in Small Arable Fields When Taking Economic Values of Ecosystem Services into Account. *Sustainability* **2021**, *13*, 13354. [CrossRef]
26. Ochieng, R.; Gebremedhin, A.; Sarker, S. Integration of Waste to Bioenergy Conversion Systems: A Critical Review. *Energies* **2022**, *15*, 2697. [CrossRef]
27. Tropea, A. Biofuels Production and Processing Technology. *Fermentation* **2022**, *8*, 319. [CrossRef]
28. Baba, T.; Nomura, H.; Srean, P.; Than, T.; Ito, K. Effects of Mechanization and Investments on the Technical Efficiency of Cassava Farms in Cambodia. *Agriculture* **2022**, *12*, 441. [CrossRef]
29. Banerjee, N.; Sukichandran, P.; Chaudhari, P.; Thakur, A.K.; Kumar, R. Energy analysis and feasibility studies for algal biomass and biofuels. *Mater. Today Proc.* **2022**, *57*, 1448–1454. [CrossRef]
30. Gao, J.; Jebrane, M.; Terziev, N.; Daniel, G. Evaluation of Wood Quality Traits in Salix viminalis Useful for Biofuels: Characterization and Method Development. *Forests* **2021**, *12*, 1048. [CrossRef]
31. Abreu, M.; Silva, L.; Ribeiro, B.; Ferreira, A.; Alves, L.; Paixão, S.M.; Gouveia, L.; Moura, P.; Carvalheiro, F.; Duarte, L.C.; et al. Low Indirect Land Use Change (ILUC) Energy Crops to Bioenergy and Biofuels—A Review. *Energies* **2022**, *15*, 4348. [CrossRef]
32. Stolarski, M.J.; Krzyżaniak, M.; Warmiński, K.; Załuski, D.; Olba-Zięty, E. Willow Biomass as Energy Feedstock: The Effect of Habitat, Genotype and Harvest Rotation on Thermophysical Properties and Elemental Composition. *Energies* **2020**, *13*, 4130. [CrossRef]
33. Bala-Litwiniak, A.; Musiał, D. Computational and Experimental Studies of Selected Types of Biomass Combustion in a Domestic Boiler. *Materials* **2022**, *15*, 4826. [CrossRef]
34. Jasinskas, A.; Streikus, D.; Šarauskis, E.; Palšauskas, M.; Venslauskas, K. Energy Evaluation and Greenhouse Gas Emissions of Reed Plant Pelletizing and Utilization as Solid Biofuel. *Energies* **2020**, *13*, 1516. [CrossRef]
35. Romanowska-Duda, Z.; Szufa, S.; Grzesik, M.; Piotrowski, K.; Janas, R. The Promotive Effect of Cyanobacteria and Chlorella sp. Foliar Biofertilization on Growth and Metabolic Activities of Willow (*Salix viminalis* L.) Plants as Feedstock Production, Solid Biofuel and Biochar as C Carrier for Fertilizers via Torrefaction Process. *Energies* **2021**, *14*, 5262. [CrossRef]
36. Golub, G.; Kukharets, S.; Skydan, O.; Yarosh, Y.; Chuba, V.; Golub, V. The Optimization of the Gasifier Recovery Zone Height When Working on Straw Pellets. *Int. J. Renew. Energy Res.* **2020**, *10*, 529–536.
37. Greinert, A.; Mrówczyńska, M.; Grech, R.; Szefner, W. The Use of Plant Biomass Pellets for Energy Production by Combustion in Dedicated Furnaces. *Energies* **2020**, *13*, 463. [CrossRef]
38. Pan, P.; Zhang, M.; Xu, G.; Chen, H.; Song, X.; Liu, T. Thermodynamic and Economic Analyses of a New Waste-to-Energy System Incorporated with a Biomass-Fired Power Plant. *Energies* **2020**, *13*, 4345. [CrossRef]
39. Patra, T.K.; Sheth, P.N. Biomass Gasification Models for Downdraft Gasifier: A State-of-the-art Review. *Renew. Sustain. Energy Rev.* **2015**, *50*, 583–593. [CrossRef]
40. Golub, G.; Kukharets, S.; Yarosh, Y.; Chuba, V. Method for Optimization of the Gasifier Recovery Zone Height. *J. Sustain. Dev. Energy Water Environ. Syst.* **2019**, *7*, 493–505. [CrossRef]
41. Nunes, L.J.R. Biomass gasification as an industrial process with effective proof-of-concept: A comprehensive review on technologies, processes and future developments. *Results Eng.* **2022**, *14*, 100408. [CrossRef]
42. Anukam, A.; Mamphweli, S.; Reddy, R.; Meyer, E.; Okoh, O. Pre-processing of Sugarcane Bagasse for Gasification in a Downdraft Biomass Gasifier System: A Comprehensive Review. Renew. *Sustain. Energy Rev.* **2016**, *66*, 775–801. [CrossRef]
43. Sarker, S.; Nielsen, H.K. Assessing the gasification potential of five woodchips species by employing a lab-scale fixed-bed downdraft reactor. *Energy Convers. Manag.* **2015**, *103*, 801–813. [CrossRef]
44. Hai, I.U.; Sher, F.; Yaqoob, A.; Liu, H. Assessment of biomass energy potential for SRC willow woodchips in a pilot scale bubbling fluidized bed gasifier. *Fuel* **2019**, *258*, 116143. [CrossRef]

45. Valin, S.; Ravel, S.; Pons de Vincent, P.; Thiery, S.; Miller, H.; Defoort, F.; Grateau, M. Fluidised Bed Gasification of Diverse Biomass Feedstocks and Blends—An Overall Performance Study. *Energies* **2020**, *13*, 3706. [CrossRef]
46. Thomasson, T.; Kiviranta, K.; Tapani, A.; Tähtinen, M. Flexibility from Combined Heat and Power: A Techno-Economic Study for Fully Renewable Åland Islands. *Energies* **2021**, *14*, 6423. [CrossRef]
47. Allesina, G.; Pedrazzi, S. Barriers to Success: A Technical Review on the Limits and Possible Future Roles of Small Scale Gasifiers. *Energies* **2021**, *14*, 6711. [CrossRef]
48. Petrillo, A.; Travaglioni, V.; Di Fraia, S.; Vanoli, L.; Cirillo, D.; La Villetta, M. Experimental study and Life Cycle Assessment of biomass small-scale trigeneration plant. *J. Clean. Prod.* **2021**, *326*, 129234. [CrossRef]
49. Golub, G.; Kukharets, S.; Tsyvenkova, N.; Yarosh, Y.; Chuba, V. Experimental study into the influence of straw content in fuel on parameters of generator gas. *East. Eur. J. Enterp. Technol.* **2018**, *5*, 76–86. [CrossRef]
50. Jia, J.; Xu, L.; Abudula, A.; Sun, B. Effects of operating parameters on performance of a downdraft gasifier in steady and transient state. *Energy Convers. Manag.* **2018**, *155*, 138–146. [CrossRef]
51. Maneerung, T.; Li, X.; Li, C.; Dai, Y.; Wang, C.-H. Integrated downdraft gasification with power generation system and gasification bottom ash reutilization for clean waste-to-energy and resource recovery system. *J. Clean. Prod.* **2018**, *188*, 69–79. [CrossRef]
52. Yarosh, Y.; Golub, G.; Kukharets, S.; Chuba, V. Experimental study of wood gas-operated power plant operation. *Eng. Rural. Dev. Proc.* **2019**, *18*, 1337–1343. [CrossRef]
53. Kukharets, S.; Sukmaniuk, O.; Yarosh, Y.; Kovalchuk, V. Investigational study of environmental performance of power generator operating on generator gas. *Eng. Rural. Dev. Proc.* **2021**, *20*, 444–450. [CrossRef]
54. Pradhan, P.; Arora, A.; Mahajani, S.M. A semi-empirical approach towards predicting producer gas composition in biomass gasification. *Bioresour. Technol.* **2019**, *272*, 535–544. [CrossRef] [PubMed]
55. Szufa, S.; Piersa, P.; Junga, R.; Błaszczuk, A.; Modlinski, N.; Marczak-Grzesik, M.; Sobek, S.; Adrian, Ł.; Dzikuc, M. Numerical modeling of the co-firing process of an in situ steam-torrefied biomass with coal in a 230 MW industrial-scale boiler. *Energy* **2023**, *263*, 125918. [CrossRef]
56. Piersa, P.; Unyay, H.; Szufa, S.; Lewandowska, W.; Modrzewski, R.; Ślężak, R.; Ledakowicz, S. An Extensive Review and Comparison of Modern Biomass Torrefaction Reactors vs. Biomass Pyrolysis—Part 1. *Energies* **2022**, *15*, 2227. [CrossRef]