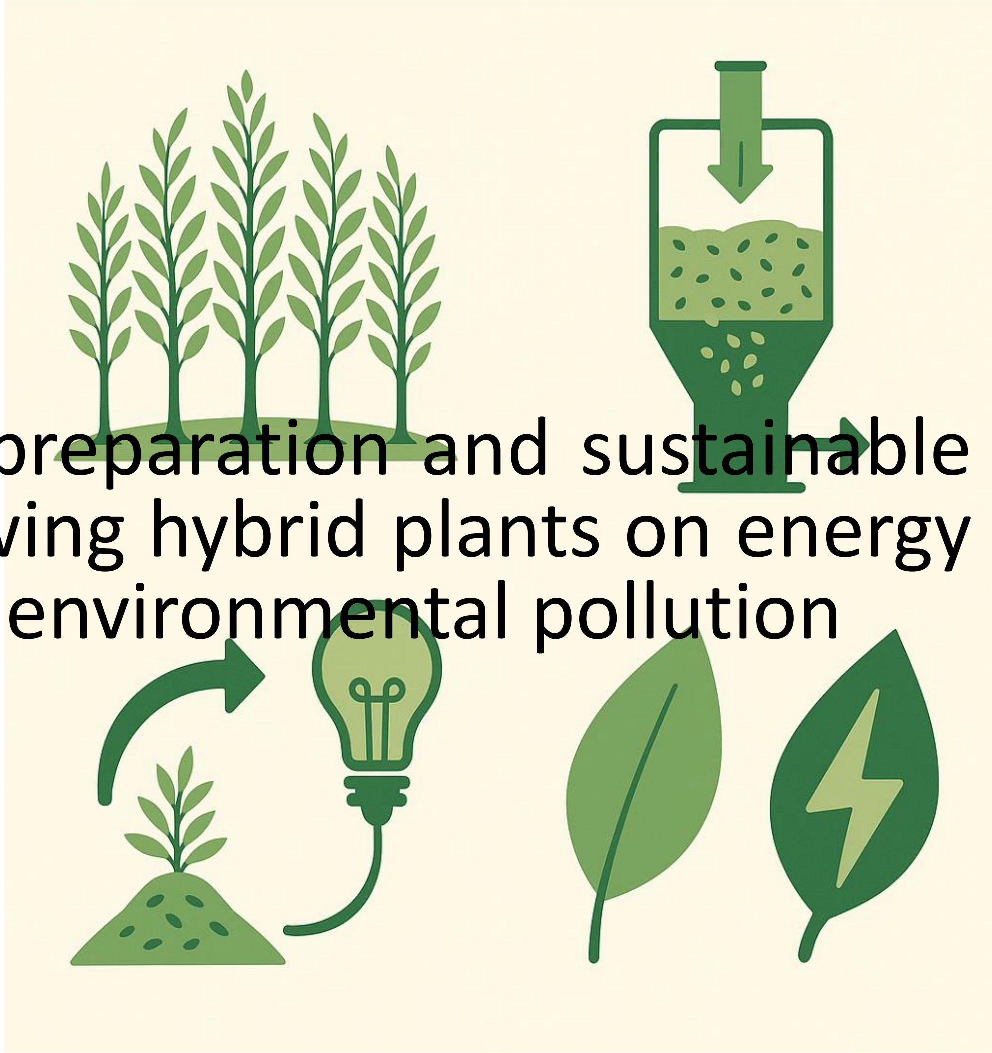

The impact of preparation and sustainable use of fast-growing hybrid plants on energy conversion and environmental pollution

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Hypothesis

Optimising the process parameters and engineering design of small-scale gasification and combustion systems for fast-growing woody biomass and cereal straw will raise overall conversion efficiency by ≥20 % and cut specific emissions of CO, NO_x and unburned hydrocarbons by ≥30 %, enabling mixed-farming enterprises to move toward energy self-sufficiency and climate-neutral operation.

Goal

To develop and experimentally validate an integrated technological and design framework that converts both hybrid woody crops (e.g., Salix Viminalis, Hybrid Poplar) and cereal straw into electricity and heat with high efficiency and low emissions, providing a technically and economically feasible route to decentralised energy autonomy for small and medium agricultural enterprises.

Main tasks

1. Quantify the physico-chemical properties, seasonal yields and supply-chain logistics of the selected hybrid crops for thermochemical conversion; establish optimal preprocessing (chopping, pelleting) routes.
2. Multi-Fuel Gasifier Design Optimisation: Design, model and build a downdraft gasifier, optimise reduction-zone geometry and staged airflow to maximise syngas calorific value and minimise tar.
3. Extend and validate the theoretical gasification-rate model to predict fuel consumption and syngas quality, particle-size distributions and air supply. Produce scale-up guidelines.
4. Refine air distribution, fuel-feeding and control strategies for a top-combustion boiler burning hybrid-wood chips to reach ≥85 % thermal efficiency and comply with EU Eco-design emission limits.
5. Couple the optimised gasifier to an engine-generator set, implement real-time control of syngas–air mixing for variable straw/wood gas compositions.
6. Perform energy-balance and cost-benefit analyses for diversified agroecosystems using local biomas and energy-crop plantations, determine break-even capacity, payback period and GHG-mitigation potential.

Object and Subject of Research

Object: Thermochemical energy conversion processes of woody biomass in small-scale gasification and combustion systems.

Subject: Coupled physicochemical phenomena in the recovery (reduction) zone of downdraft gasifiers and in top-combustion boilers, as well as the influence of generated syngas on engine-based electricity production.

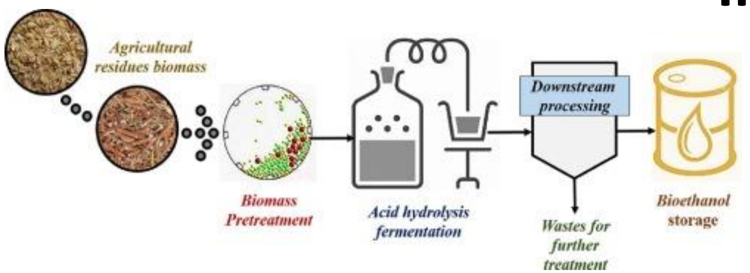
Introduction I

Agricultural production allows to receive a great amount of biomass available for energy conversion. 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. Therefore, the choice of a raw material is an important efficiency factor in the energy conversion of biomass.

One such species can be fast-growing plants, in particular, hybrid poplar, hybrid willow, and hybrid aspen.

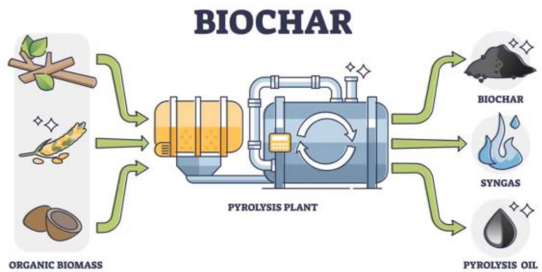
One of the widespread and promising fast-growing plants for energy conversion is the hybrid willow Salix Viminalis. The fast-growing willow is mainly used in the processes of direct combustion as it has a high heating value (from 17 to 19.5 MJ/kg).

Introduction II



https://www.sciencedirect.com/science/article/pii/S0048969723017771

Bioethanol production



https://www.fastechus.com/blog/pyrolysis-the-future-of-hydrogen-production

Pyrolysis

Own research – https://doi.org/10.3390/en15207721

Gasification technologies

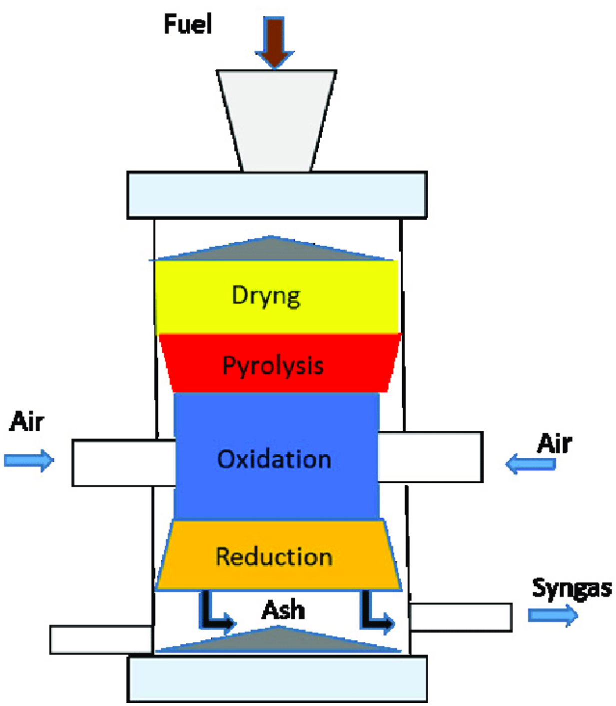
Own research – https://doi.org/10.22616/ERDev.2024.23.TF071

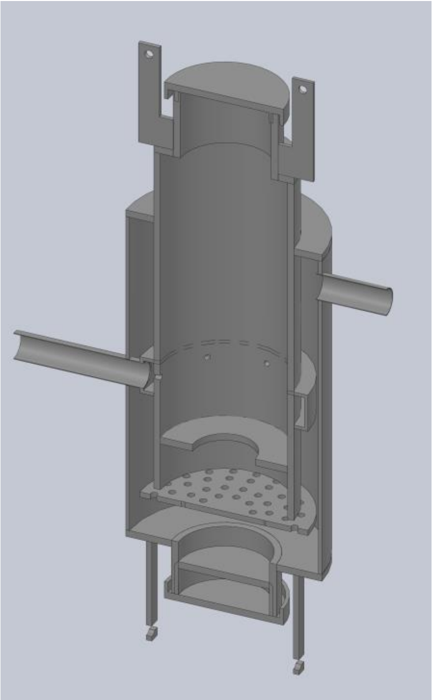
Direct combustion

The biomass is also suitable for biofuel production by biochemical transformation, for example, for bioethanol production, or by thermochemical transformation—pyrolysis. 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 and direct combustion.

Introduction III

In the process of biomass gasification, it is appropriate to 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. However, when using a small gasifier 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.





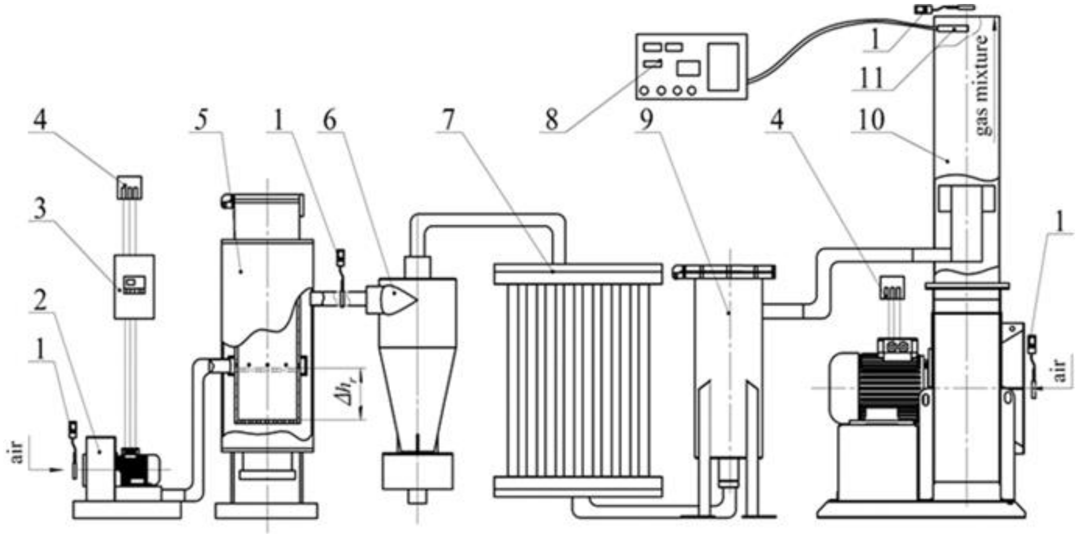
Introduction IV

When burning Salix Viminalis biomass, some problems may arise related to the heterogeneity of the fuel, high moisture level, large yield of ash formation and the formation of solid conglomerates, as a result of ash melting. In addition, incorrectly selected operating modes of the boilers can significantly increase the emissions of pollutants produced as a result of burning biomass in the boiler. This can have a harmful effect on human health, cause disruption of the chemical composition of the atmosphere and affect the deterioration of the climate. Studies show that burning biofuel in boilers with top-down combustion improves the combustion process and reduces the amount of pollutant emissions.

However, this happens only with correctly selected operating parameters of the boiler.

Main research equipment and methodology I

The impact of fuel fractions and parameters of the gasifier recovery zone on the quality of the generated generator gas



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.

The impact 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. The plant was built on the basis of the experimental downdraft gasifier. 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. 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.

Main research equipment and methodology II

The gasifier's 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).
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

Fuel (biomass) fraction characteristics

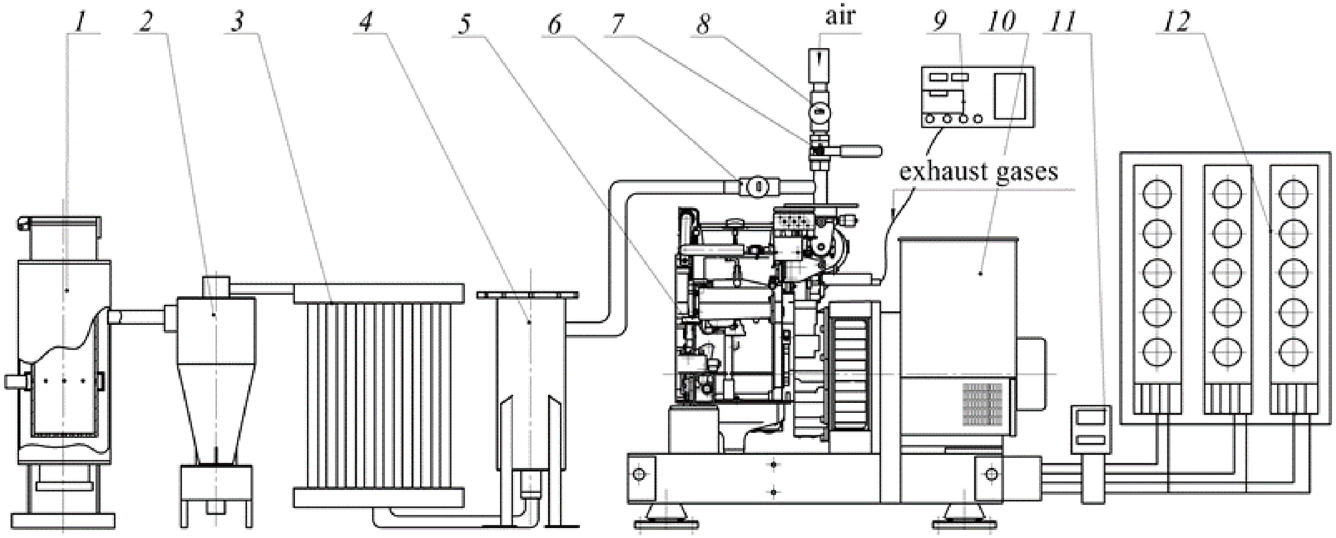
Fraction	№	Average Sizes, mm			Average Area of a Full Surface S, mm^2	Average Volume V, mm^3	SVR, S/V mm^{-1}
		Length	Width	Thickness			
Large	1	40	15	12	2520	7200	0.35
Medium	2	30	12	8	1392	2880	0.48
Small	3	20	9	5	650	900	0.72
Very small	4	10	4	4	192	160	1.20
Fuel pellets	5	10	4 (diameter)		192	160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

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

In the research, a fuel biomass of a fast-growing willow Salix Viminalis and Hybrid Black Poplar was divided into four fractions according to the geometrical sizes. The fuel pellets that were made of the ground biomass of a fast-growing willow were used as well.

Main research equipment and methodology III

The impact of generator gas on electricity generation

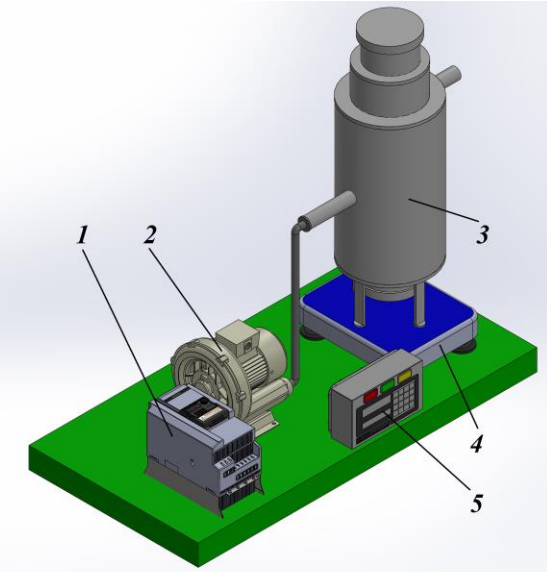


1—a downdraft gasifier; 2—a filter for intermediate gas purification; 3—a refrigerator; 4—a filter for a final gas purification; 5—an internal combustion engine; 6—a gas meter; 7 –a mixer for regulating the air supply into the engine; 8—an air meter; 9—an analyzer of the chemical composi-tion of exhaust gases; 10—an electric generator; 11—wattmeter; and 12—a standard electrical load consumer

Main research equipment and methodology IV

A Theoretical Model of the Gasification Rate of Biomass and Its Experimental Confirmation

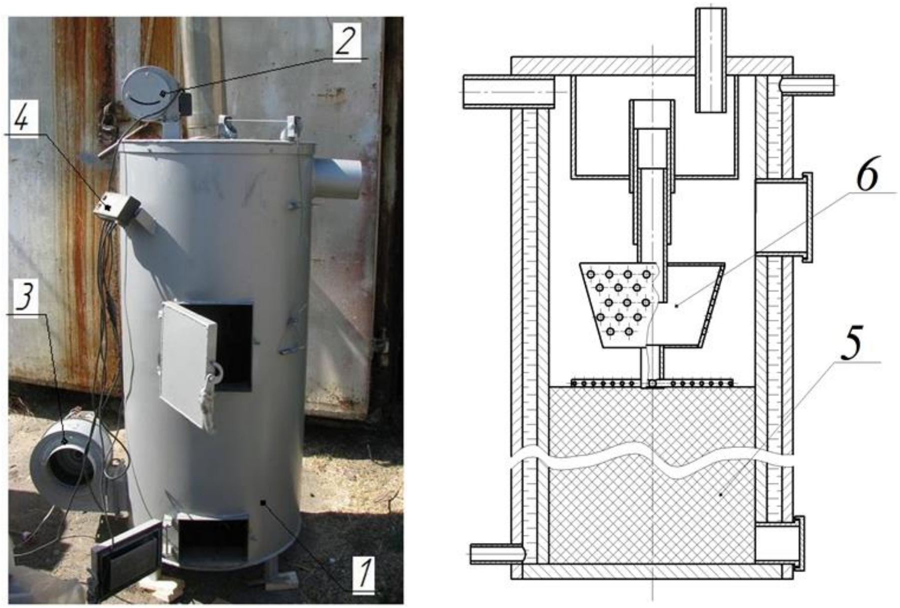
The parameters of a gasifier were chosen to ensure the highest quality of genetator gas. In particular, the diameter of the working area is 200mm, the height of the working area is 110 mm. The air supply to the gasifier varied from 0.00088 m^3/s to 0.01169 m^3/s. A gasifier was installed on the scales. In the process of conducting the research was recorded some change in a gasifier mass.



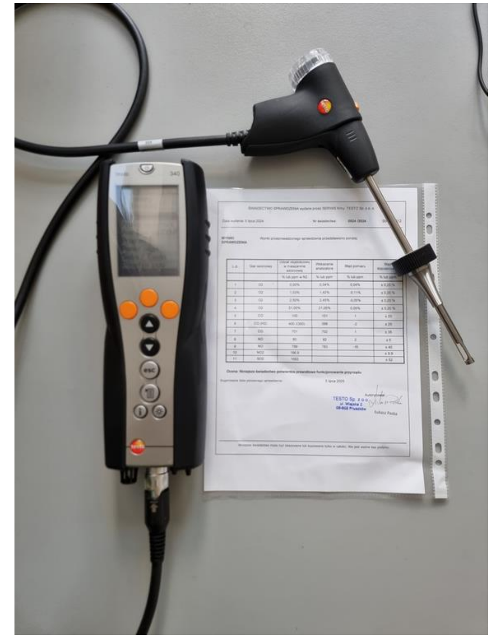
1 – frequency converter Hitachi-3G3JX-A4075-EF; 2 – blower Goorui GHBH-0D5-34-1R2; 3 – downdraft gasifier; 4 – weight scales; 5 - weight scales indicator

Main research equipment and methodology V

The impact of the parameters of a top-combustion boiler on the energy and environmental efficiency of biomass combustion



1 – boiler, 2 –fan WPA-06, 3 – fan OBR-200M-2K,
4 – electronic control system ATOS, 5 – fuel, 6 – air supply system



Gas analyzer Testo 340

In the realm of sustainable energy production, converting biomass from fast-growing plants into thermal energy stands out as a promising avenue. To actualize this concept, we propose the utilization of a top-fired boiler that incorporates innovative features to enhance its performance. This boiler comprises two distinct working areas, namely the combustible gas formation area and the combustible gas combustion area. The segregation of these zones facilitates a more controlled and efficient biomass-to-energy conversion process. Central to the improved efficiency of this proposed boiler is the incorporation of an air distributor in its design. This crucial element optimizes the combustion process by facilitating air distribution within the system. The air distributor plays a pivotal role in enabling the boiler to operate in the biomass gasification mode. This mode allows for the efficient burning of the resulting combustible gas, thereby maximizing energy output and minimizing waste.

Main research equipment and methodology VI

Fuel groups by size

Groups		
I	II	III
		
Average linear dimensions of a piece of fuel (length, width, thickness), mm		
40x15x12 (±5%)	30x12x8 (±5%)	20x9x5 (±5%)
Full area of the external surface of a piece of fuel, mm^2		
2520	1392	650
Volume of a piece of fuel, mm^3		
7200	2880	900
The ratio of the total area of the external surface of a piece of fuel to its volume *SVR*, mm^{-1}		
0.35	0.48	0.72

Main research equipment and methodology VII

Plan of the experiment type 3^2

№ of research	The ratio of the total area of the external surface of a piece of fuel to its volume *SVR*, mm^{-1}	Volume of air intake into a combustion zone *Q*, $m^3 \cdot s^{-1}$	№ of research	The ratio of the total area of the external surface of a piece of fuel to its volume *SVR*, mm^{-1}	Volume of air intake into a combustion zone *Q*, $m^3 \cdot s^{-1}$
1	(-1) – 0.35	(-1) – 0.0015	6	(+1) – 0.72	(0) – 0.0208
2	(0) – 0.48	(-1) – 0.0015	7	(-1) – 0.35	(+1) – 0.0400
3	(+1) – 0.72	(-1) – 0.0015	8	(0) – 0.48	(+1) – 0.0400
4	(-1) – 0.35	(0) – 0.0208	9	(+1) – 0.72	(+1) – 0.0400
5	(0) – 0.48	(0) – 0.0208			

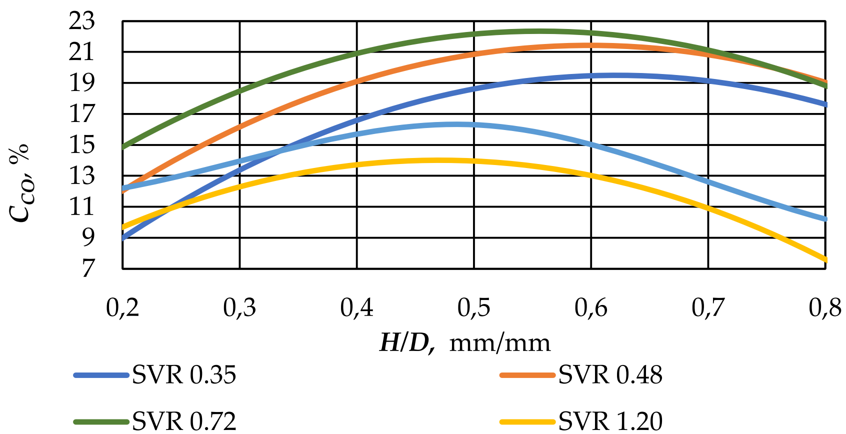
Numerical values of research results

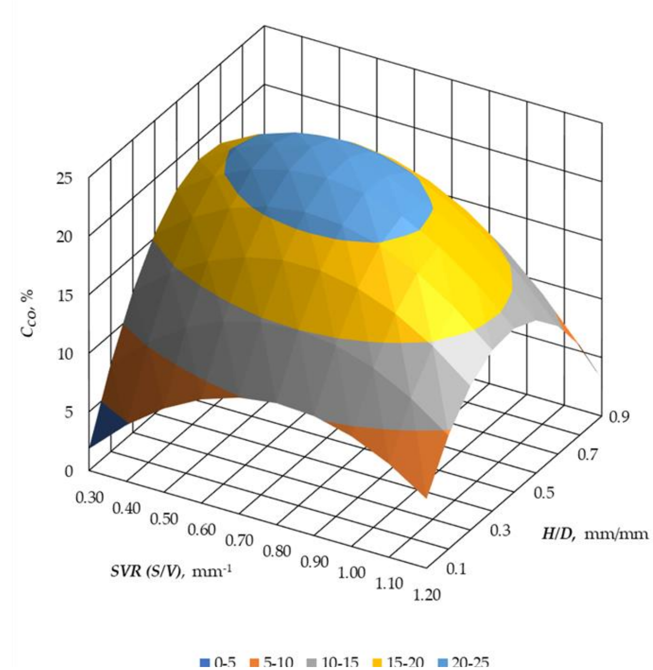
№ of the research	The ratio of the total area of the external surface of a piece of fuel to its volume *SVR*, mm^{-1}	Volume of air intake into a combustion zone *Q*, $m^3 \cdot s^{-1}$	Specific content of CO in flue gases *CO*, $mg \cdot m^{-3}$	Thermal power of a boiler *P*, kW
1	0.35	0.0015	502	13.4
2	0.48	0.0015	492	14.0
3	0.72	0.0015	480	14.8
4	0.35	0.0208	389	17.4
5	0.48	0.0208	385	17.5
6	0.72	0.0208	362	17.8
7	0.35	0.0400	635	17.0
8	0.48	0.0400	632	17.0
9	0.72	0.0400	620	17.4

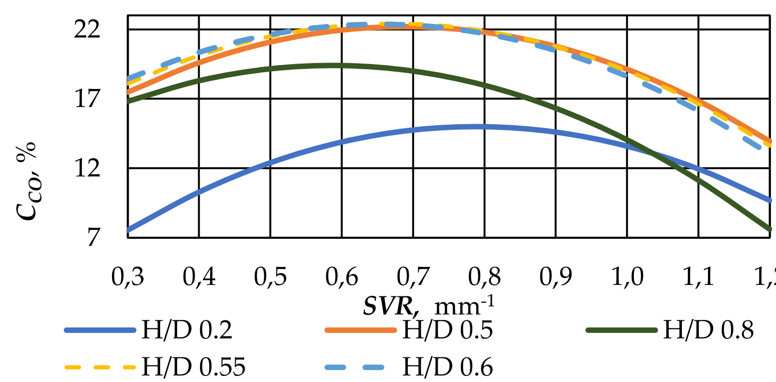
Research results I

The impact of fuel fractions and parameters of the gasifier recovery zone on the quality of the generated generator gas.

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)







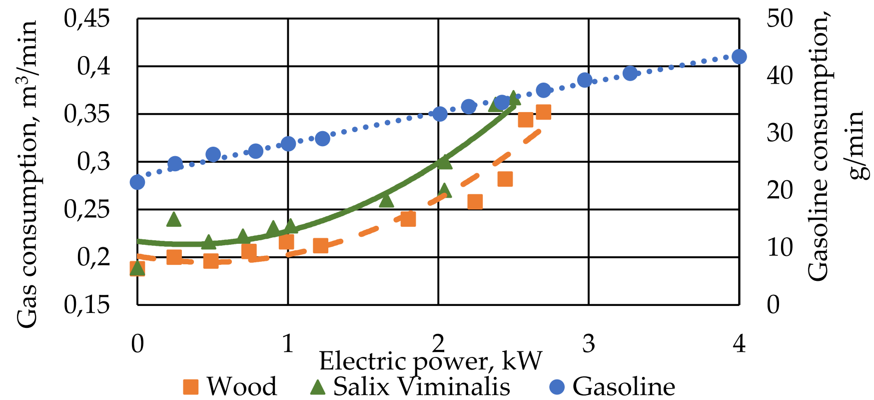
In the process of gasification of a fast-growing willow Salix Viminalis in a downdraft gasifier, the maximum CO concentration in a producer gas equals 22.2–22.3%. The maximum calorific value of gas is observed when using a small fraction of fuel SRV—0.7–0.72 mm^{-1} and when keeping to the ratio of height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

Research results II

The impact of generator gas on electricity generation

Power generator capacity

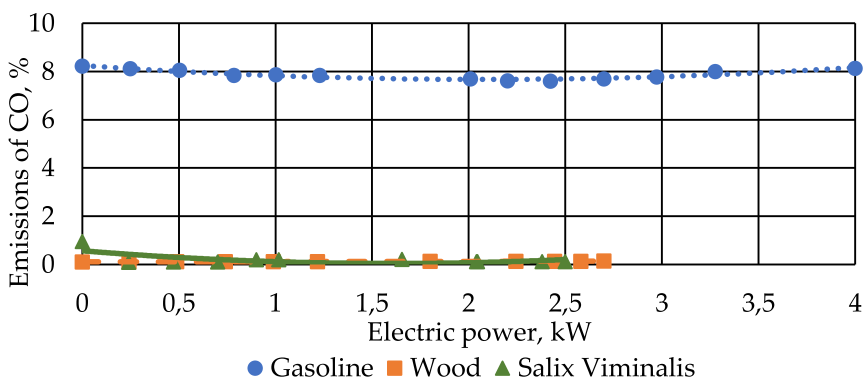
Fuel consumption



$$Q_2 = 0.031N^2 - 0.020N + 0.22$$

Q_2—gas consumption, m^3/min; and
N—electric power, kW

Emissions of CO



Emissions of CxHy

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 CxHy. The studies testify to the expediency of energy conversion of the fast-growing willow biomass by the gasification processes.

Research results III

A Theoretical Model of the Gasification Rate of Biomass and Its Experimental Confirmation

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Biomass gasification rate theoretical equation, which purpose is to establish the non-gasified fuel amount at the current moment:

$$m = m_1 + (m_0 - m_1)\ \exp(-k\tau)$$

where *m* – fuel that was not gasified (turned into gas) at the current moment, kg;
m_0 –the initial volume of fuel, kg;
m_1 – the volume of ash, kg;
k – the gasification rate coefficient, s-1;
τ – the gasification duration, s.

The mass of fuel m_g, that has been gasificated at the given moment of time:

$$m_g = m_0 - (m + m_1)$$

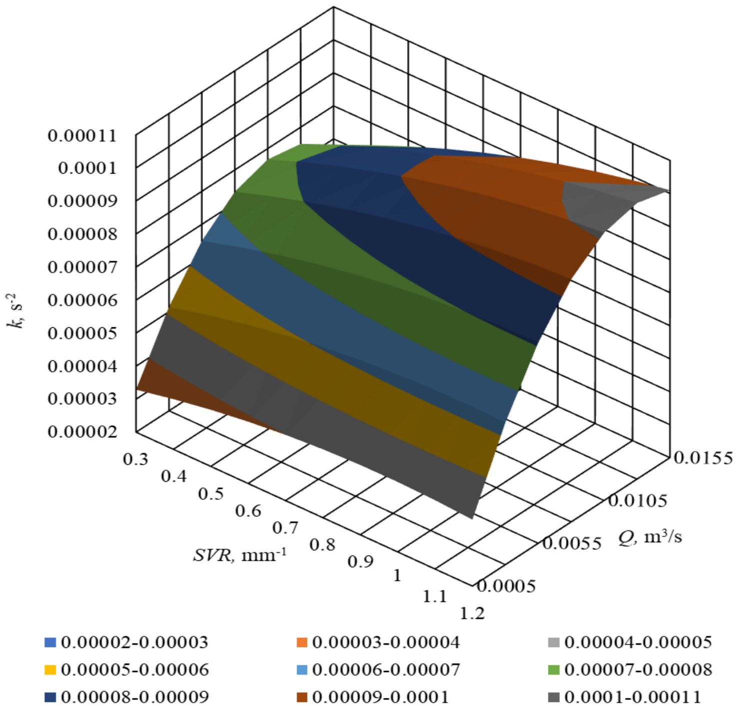
And the gasification rate coefficient can be determined from the dependence:

$$k = \frac{1}{\tau} \ln \frac{m_0 - m_1}{m - m_1}$$

Research results IV

A Theoretical Model of the Gasification Rate of Biomass and Its Experimental Confirmation

Change in the coefficient of gasification rate depending on air supply and fuel sizes



With an increase of air supply to the working area of a gasifier, the gasification rate coefficient also increases, in particular for the fuel pellets. The change in the coefficient can be described by the dependence:

$$k = -0.6077Q^2 + 0.0129Q + 3 \cdot 10^{-5}$$

where Q – air supply, m^3/s.

For the fractions of wood in pieces the gas rate coefficient depends not only on the air supply, but also on the size of the fraction:

$$k = 1.953 \cdot 10^{-5} + 3.576 \cdot 10^{-5} SVR + 0.008Q - 1.909 \cdot 10^{-5} SVR^2 + 0.002SVRQ - 0.408Q^2$$

Obtaining of the biomass gasification rate provides a possibility to determine the fuel consumption level while using downdraft gasifier with different geometric sizes during the process of receiving gas. Moreover, the biomass (fuel) consumption calculation makes it possible to evaluate technical and economic aspects of using gasifiers and biomass gasification technologies.

Research results V

The impact of the parameters of a top-combustion boiler on the energy and environmental efficiency of biomass combustion

$$CO = 534.40 - 3.84SVR - 16992.52Q - 58.62SVR^2 + 490281.70Q^2 + 428.87SVR \cdot Q,$$

$$P = 12.09 + 2.54SVR + 334.02Q + 0.78SVR^2 - 5296.53Q^2 - 66.90SVR \cdot Q.$$

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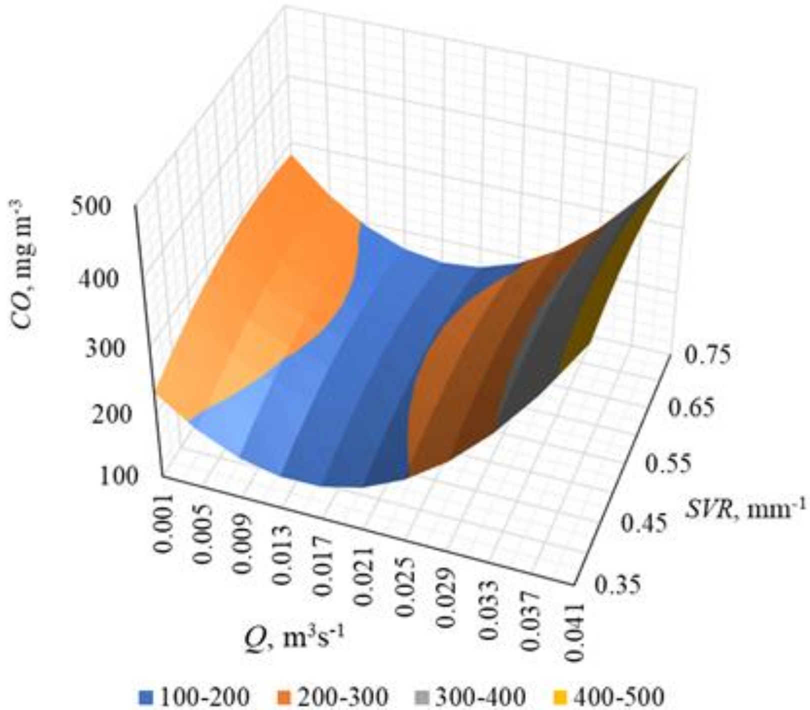
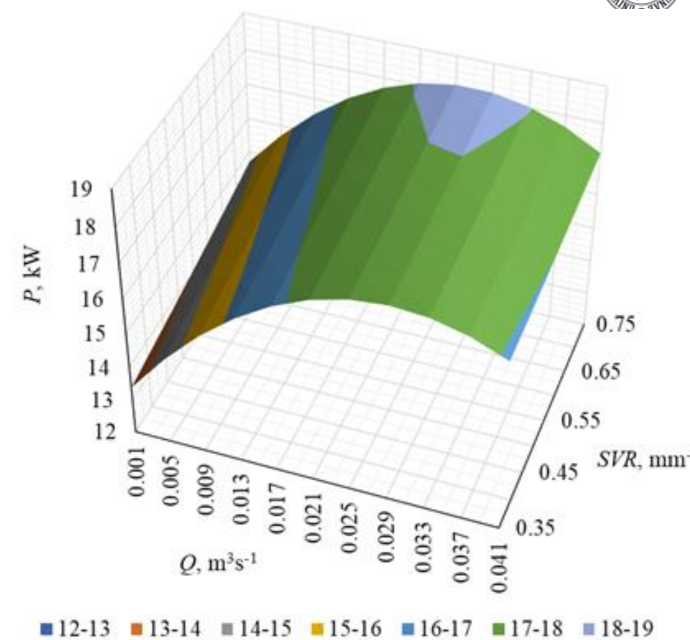


The impact of geometric dimensions of fuel particles and the amount of air entering the combustion zone on the content of CO in flue gases



The impact of geometric dimensions of fuel particles and the amount of air entering the combustion zone on the thermal power of the boiler

During the course of experimental investigations, several key parameters were explored to evaluate the performance of the boiler. One such parameter was the size of fuel pieces fed into the boiler. The size of fuel pieces was found to have a little effect on the overall efficiency of the system. Additionally, the air supply to the boiler furnace was identified as another critical factor influencing efficiency. Proper control and management of the air supply contribute to the combustion process, impacting the overall efficiency of the boiler as well as the level of harmful gas emissions, was determined.

Conclusion

In the process of gasification of a fast-growing wood biomass in a downdraft gasifier, the maximum CO concentration in a producer gas equals 22.2–22.3%. The maximum calorific value of gas 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. Gasification of other types of fast-growing woody plants yielded similar results.

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Obtaining of the biomass gasification rate provides a possibility to determine the fuel consumption level while using downdraft gasifier with different geometric sizes during the process of receiving gas. Moreover, the biomass (fuel) consumption calculation makes it possible to evaluate technical and economic aspects of using gasifiers and biomass gasification technologies.

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