# Streszczenie w języku angielskim

The analysis in this PhD dissertation is centred on the operation of the waste management system within the present legal and market frameworks. The main aim of the study was established as: assessment of the possibility of implementing technology for gasification of fuel fractions of municipal waste and sewage sludge and effective energy production in technical and organizational integration with the existing waste management model based on mechanical and biological processing of municipal waste.

Moreover, the following supplementary objectives were defined: :

- Indication of the optimal technological configuration of the waste gasification plant for seamless integration with municipal plants operating based on the technology of mechanical-biological processing of municipal waste
- Organizing, defining and proposing an environmental legal framework for the implementation of commercial waste gasification plants
- Proposal for determining optimal technical and environmental solutions for waste gasification technology on a scale corresponding to integration with municipal plants

And finally, thesis of the study was defined:

Waste gasification technology in the new legal conditions of the IED directive, technical and market conditions of MBP in Poland may constitute a real (technically and economically) alternative to building integrated waste management systems within municipal plants.

As civilization advances, the issue of escalating waste generation and its consequential adverse environmental impact continues to grow. The generation of excessive waste is attributed to the irrational management of resources and a delay in implementing legal regulations within the realm of waste management. The current pursuit of sustainable resource utilization and environmental protection is epitomized by the circular economy, where a pivotal element involves energy recovery from waste.

In Chapter 3, the study delves into EU and Polish policies in the waste management sector, exploring the legal aspects related to the thermal processing of waste. Thermal processing of waste is regulated by the provisions of the IED Directive (DIRECTIVE 2010/75/EU), according to which the thermal treatment of municipal waste is classified as an R1 recovery process. It was also assumed that part of the energy recovered from thermal processing of waste containing biodegradable fractions may constitute energy from a renewable energy source if the technical conditions set out in the regulation are met.

In Chapter 3, an effort is made to establish connections between current regulations on the thermal processing of waste and gasification technology, a method that yields low-calorie process gas (syngas) exhibiting parameters akin to natural gas. The regulations on waste incineration and co-incineration (including the over-sieve fraction of municipal waste) are regulated, among others, by: Directive 2010/75/EU on industrial emissions and the BAT (Best Available Technologies) conclusions, which were introduced into Polish law, among others, through the Environmental Protection Law (Journal of Laws 2022.2556) and the Waste Act (Journal of Laws 2023.1587).

The provisions of the IED Directive introduced a conditional exemption from the technical requirements for the thermal processing of waste for **waste gasification or pyrolysis technologies**, which are mandatory for waste incineration processes.

Art. 42 section 1. points out that the special provisions for waste incineration plants and waste co-incineration plants do not apply to gasification or pyrolysis plants if the gases resulting from this thermal processing of waste are purified to such an extent that they are no longer waste before incineration and are not likely to cause emissions higher than those resulting from the combustion of natural gas.

Moreover, meeting the indicated condition for process gas from waste gasification under the regulation on emission standards (Journal of Laws 2020.1860) indicates that there is no obligation to apply emission standards, as for waste incineration or co-incineration plants. Under these provisions, emissions from the combustion of purified process gas should be related to the emission standards for the combustion of natural gas in energy units.

The Regulation of the Minister of Development of January 21, 2016 on the requirements for conducting the thermal processing of waste and methods of dealing with waste generated as a result of this process does not apply to waste gasification processes.

The legislative changes indicated above have significantly increased the possibilities of using waste gasification technology and their energy use in more energy-efficient high-efficiency cogeneration systems.

The rest of Chapter 3 discusses the types of waste that can be subjected to thermal processing with energy recovery, with particular emphasis on the over-sieve fraction (preRDF) of municipal waste originating from mechanical-biological waste processing plants. Attention was drawn to the fact that this fraction remains waste with a high calorific value, hence it is rational to use it for the production of alternative fuel and thermal energy recovery (Waste to Energy).

Waste-to-Energy (WtE) is the transformative process of converting waste into energy, primarily in the form of heat and electricity. WtE is considered one way to reduce waste, increase the use of renewable energy sources and improve air quality by reducing greenhouse gas emissions.

Nevertheless, WtE remains a contentious subject, marked by apprehensions regarding the potential release of harmful substances into the atmosphere and the utilization of raw materials that could, in theory, be reclaimed through alternative means. It must be emphasized that thermal waste processing is one of the most technically and technologically advanced recovery methods, meeting the legal standards specified in the BAT conclusions, including extremely restrictive emission levels.

The rest of Chapter 3 discusses thermal waste processing technologies, including technical conditions and chemistry of processes such as combustion, pyrolysis and gasification. The high potential of the over-sieve fraction (preRDF) of municipal waste was also highlighted. Considering the scale and objectives of the proposed gasification plant for the preRDF fraction in this PhD dissertation, the scope was confined to outlining the fundamental principles of processes occurring in the gas generator, namely pyrolysis and gasification. . The dissertation also outlines the types of gasification reactors and their fundamental technical characteristics. This is essential as the choice of gasifier for the gasification of the preRDF fraction of municipal waste, combined with sewage sludge, necessitates consideration of both the diverse composition of the feed concerning the technical aspects of the gasification process and the environmental conditions, along with ensuring process safety. Furthermore, its characteristics make it well-suited for energy recovery from waste and the high-efficiency production of electricity. .

The composition, quality requirements and methods of purifying syngas, along with its fuel potential. Purified syngas proves to be a viable fuel for energy use.

Technological variants of syngas energy management, including piston engines, gas turbines and fuel cells, were briefly discussed. In specific solutions, hydrogen can also be generated for use in other plants e.g. in transport. Taking into account the fuel potential of syngas derived from waste, the possibilities of applications are unlimited, and the only barrier may be economic aspects.

In conclusion, the study examined the municipal waste management system in operation in Poland, centred around municipal plants using Mechanical-Biological Processing (MBP).

Due to the escalating volume of generated waste, the legal regulations mentioned earlier, and the prohibition on landfilling waste with a combustion heat exceeding 6 MJ/kg introduced in 2016, the current state of the Polish waste management system falls short of being adequately effective both environmentally and economically. Additionally, there exist ambiguities in the precise interpretation of legal regulations, particularly concerning the management of fractions exceeding 80mm. Hence, it becomes imperative to seek solutions that guarantee the management of this specific waste fraction in

alignment with the principles of sustainable development, especially considering its estimated quantity of 4 million tons/year.

Hence, a critical aspect lies in accurately characterizing the preRDF over-sieve fraction and, consequently, establishing a standardized methodology for examining the morphology of this waste fraction. In Poland, the method traditionally employed is the Polish Standard PN-93/Z-15006, which was withdrawn in September 2015 (without a direct replacement, though it remains permissible for use). However, it pertains to mixed (untreated) municipal waste, and its scope does not encompass the preRDF waste stream. Therefore, the research methodology aimed at determining the distinctive features of the preRDF waste stream of municipal origin should be appropriately directed and tailored to align with the utility functions of this stream.

Moreover, it is important to acknowledge that the separated over-sieve fraction stream (preRDF) is contingent upon the technical standards of waste sorting plant equipment, as well as market conditions and the demand for materials earmarked for recycling purposes. Hence, in the strategic planning of a facility for the energy transformation of the preRDF over-sieve fraction within a system based on Mechanical-Biological Processing (MBP) as part of a circular economy initiative, due consideration should be given to all the legal and market trends mentioned above. As part of the study, tests of the morphological composition and physicochemical tests of the preRDF waste fraction were carried out. The aim of the study was to determine energy properties and their stability in four seasons and spatial standardization.

The tests were conducted during representative months of each of the four seasons, encompassing two campaigns in 2014 and in 2023 (as the control campaign). Due to the nature of waste management and the increased awareness of waste segregation, the campaign carried out in 2023 was aimed at examining the validity of the previously observed trends in the composition and fuel potential of the over-sieve waste fraction (preRDF).

Five locations were carefully chosen for the research, spanning the Silesian and Opole voivodeships, and encompassing three distinct types of environments: mixed buildings, multi-family buildings, and single-family buildings. Research focused on municipal plants from five representative locations. The technical equipment of all municipal plants was systematically analysed. A total of 12 waste samples (2014 campaign) and 6 waste samples (2023 campaign) were tested.

Moreover, the aim of the research was to develop a universal methodology for testing the morphological composition of the over-sieve waste fraction (preRDF) originating from the MBP plant and to standardize the method of collecting waste samples for testing.

Following the established research methodology, the morphological composition of the material was assessed across 13 distinct fractions. The samples were also used to prepare representative samples for laboratory tests to examine the physical and chemical properties of the waste and to determine its energy potential.

Based on the research results, a detailed analysis was carried out to determine the energy properties in the tested seasons and types of buildings. Additionally, analyses were conducted to examine the correlation between the proportion of essential elements influencing the fuel quality of the tested preRDF fraction.

The presented test results indicate high calorific value of waste samples in all seasons. They are characterized by qualitative stability in particular seasons, which confirms their increased standardization.

The test results of the preRDF fraction indicate good energy properties, increased calorific value in relation to mixed municipal waste, quality standardization in all seasons of the year and standardization according to the sources of their generation.

The high calorific value of the tested samples and visible qualitative standardization in seasonal and spatial terms indicate the distinctive, valuable fuel characteristics of the preRDF over-sieve fraction of municipal waste.

In the following part of the study , the waste management model was examined with a focus on proposals for implementing the optimal technology for waste gasification plants.First and foremost, a legal and technological model for gasification technology in the conditions of Polish legal regulations was proposed. The following aspects were analysed: energy efficiency, emission of pollutants into the air according to emission standards, monitoring of environmental impact, monitoring of process parameters, operation of the plant in conditions other than normal, post-process waste and sewage from technological processes.

Based on the above legal conditions, the recommended technological variant of preRDF waste gasification in integration with the waste management system based on MBP was proposed and described in detail based on the LIFEcogeneration.pl project.

For the purposes of this analysis, waste streams were balanced in waste management regions serving 120,000 inhabitants. Then, the amount of the preRDF stream produced in the municipal plant was calculated at the level of 12000 tons/year and the amount of sewage sludge produced in the region with a conventional water content of 20% at the level of 3000 tons/year. Therefore, the capacity of the recommended model waste gasification plant was determined to be 15,000 tons/ year. The following section describes and analyses the technological system of the plant consisting of four basic technological units:

- Homogenization unit - mechanical processing, mixing and thickening of solid fuel (result: formed fuel intended for gasification in a gas generator),
- Gasification and syngas production unit,
- Deep syngas purification unit,
- Combined heat and power unit.

Technical parameters and the specificity of their operation were specified for each of the technological units. The required supporting systems were also defined, such as: sewage treatment plant and recirculation system, and syngas after-combustion system.

Next, calculations were made and the mass and energy balance were presented. Separate analyses of the mass balance and energy balance of the plant were performed.

On the basis of the energy balance, the energy efficiency of the waste gasification plant was determined in three approaches: energy efficiency of waste processing, energy efficiency of recovery of chemical energy contained in waste, efficiency of renewable energy production.

The energy efficiency index for waste processing was set at 0.83, which is a very good result.

The energy efficiency of chemical energy recovery in waste was calculated, revealing a total efficiency of 56.1% and an electricity generation efficiency of 15.8%.The efficiency of renewable energy production was determined based on the analysis of the share of biodegradable fractions in the morphological composition of preRDF waste.

The average content of this biodegradable fraction was 40%. At the same time, tests carried out using the sample digestion method for the 2023 campaign showed a much higher share of the biodegradable fraction at the level of 62%.

The next part of the study analysed the environmental conditions of waste gasification technology according to the recommended technological variant. All emissions and waste and sewage generation streams were defined and discussed.

The recommended technological model of the waste gasification plant was analysed for its integration possibilities with the municipal waste management system.

The most optimal scheme for connecting the waste gasification plant with the municipal plant was presented and described, and the characteristic parameters of this integration were determined.

Finally, the feasibility of implementing waste gasification technology in the Polish waste management model based on MBP was assessed.

The analysis was based on three key criteria: technical, environmental and economic.

The technical criteria analysed general technical requirements, energy efficiency and process safety.

The environmental criterion assessed the impact of a model waste gasification plant on the environment.

Finally, the economic criterion assessed the profitability of building a model waste gasification plant under market conditions. A financial model was built and revenues and costs were modelled over an operational period of 18 years. Three basic financial assessment indicators were determined: NPV, IRR and the discounted capital payback period. The assessment was made based on various financial scenarios and an analysis of sensitivity to market conditions variability.

The final chapter provides a summary, formulates key conclusions, and references the thesis, substantiating its evidence.

Key words: waste gasification, waste research, municipal waste morphology, cogeneration, waste to energy, energy efficiency, waste management models

Słowa kluczowe: zgazowanie odpadów, badania odpadów, morfologia odpadów komunalnych, kogeneracja, energia z odpadów, efektywność energetyczna, modele gospodarki odpadami,