Systems & Control Transactions

Research Article - Peer Reviewed Conference Proceeding
ESCAPE 35 - European Symposium on Computer Aided Process Engineering
Ghent, Belgium. 6-9 July 2025
Jan F.M. Van Impe, Grégoire Léonard, Satyajeet S. Bhonsale,
Monika E. Polańska, Filip Logist (Eds.)

PSE PRESS

Techno – Economic Evaluation of Incineration, Gasification, and Pyrolysis of Refuse Derived Fuel

Matej Koritár[a], Maroš Križan[a], and Juma Haydary[a]*

[a] Slovak University of Technology, Department of Chemical and Biochemical Engineering, Bratislava, Slovakia
* Corresponding Author: juma.haydary@stuba.sk.

ABSTRACT

New ways of reducing environmental impact of solid waste are constantly developed. Thermochemical conversion with focus on material or energy recovery is one of the viable options. To make the feedstock properties more suitable for such a process, refuse derived fuel (RDF) is created. Although several studies have focused on thermochemical conversion in recent years, only few have comprehensively compared the main aspects of incineration, gasification, and pyrolysis processes from multiple aspects. This study focuses on mathematical modeling of these three processes in the Aspen Plus environment. Comparison from economic, safety, and environmental viewpoints was performed. As a base for the calculations, 10 t/h of RDF was selected. All three processes demonstrated the suitability to be used for energy recovery. Pyrolysis showed the greatest potential for material recovery. Payback period was used as a parameter of economic comparison with pyrolysis being the most profitable process. Based on the calculated Dow Fire and Explosion Index (F&EI) and Chemical Exposure Index (CEI) gasification was identified as the most hazardous process. In summary, based on this extensive techno-economic analysis, the ranking of processes from an economic standpoint is as follows: pyrolysis, incineration, gasification. From an environmental perspective, the ranking is: gasification, pyrolysis, incineration. In terms of safety, the order is: incineration, pyrolysis, gasification.

Keywords: refuse derived fuel, incineration, gasification, pyrolysis

INTRODUCTION

Waste generation presents environmental challenges that require direct attention. Within the European Union, generation of waste remains a significant problem with the amount of municipal solid waste increasing each year. Landfilling emerges as the primary environmental consequence of MSW [1]. However, shifts in legislative require the decrease of landfill disposal. Sustainable solutions are being explored, emphasizing the optimization of recyclable material and energy recovery. Solid waste not suitable for material recycling still contains high calorific value and can serve as a partial replacement of fossil fuels. This waste can be transformed into refuse derived fuel (RDF), which has more suitable properties for thermochemical conversion. Heating value of MSW is around 8-12 MJ/kg [2], which is significantly lower than that of RDF reaching as high as 27 MJ/kg [3]. The most common method of energy recovery from MSW is incineration. Alternative processes of thermochemical conversion are gasification and pyrolysis, which provide higher efficiency of energy and material recovery compared to incineration. The main drawback of waste feedstock processing is that it contains contaminants. Common contaminants in MSW and RDF include sulfur and chlorine containing compounds and heavy metals, these are carried into the products of the treatment process, where they cause damage to the equipment. Moreover, they are environmental pollutants. Therefore, it is necessary to minimize their production and decrease their concentration in the products to acceptable levels by purification. This work aims to compare three processes of thermochemical conversion of RDF: incineration, gasification, and pyrolysis. Due to their complex nature, studies comprehensively comparing the techno-economic aspects of the processes using mathematical models are quite rare.

SIMULATION

Aspen Plus simulation software was used to create mathematical models of all three processes. As a base for the calculations, 10 000 kg/h of non-pretreated RDF was chosen. Peng-Robinson equation of state was used as the main thermodynamic model in all calculations. Equilibrium thermodynamic model, minimizing free Gibbs energy of the entire system, was employed to simulate thermochemical conversion of feedstock with the following assumptions [4]:

- Steady state flow in the reactor.
- No temperature or concentration gradients.
- Infinite residence time, chemical equilibrium is reached.
- Only chosen compounds are evaluated.

Equilibrium model is not suitable for processes where the deviation from the chemical equilibrium is too large, e.g. pyrolysis. Therefore, a mathematical model applying experimentally determined yields of the main products and composition of gaseous and solid products was used. To calculate the exact composition of liquid pyrolysis product, elemental balance of representative compounds was applied.

Feedstock properties

Proximate and ultimate composition of RDF pellets was determined in previous experimental work [5] and is shown in **Table 1**. Lower heating value (LHV) of the RDF sample was determined to be 23.89 MJ/kg [5].

Table 1: Proximate and ultimate composition of RDF [% mass]

C	55.6	Moisture	0.73
H	7.83	Volatile matter	77.10
N	0.63	Fixed carbon	7.78
S	0.35	Ash	15.12
Cl	0.88		
O	19.58		

Incineration

Incineration was the least complicated of the three processes studied. Incineration generates heat, part of which is turned into electricity. Material outlet steams are

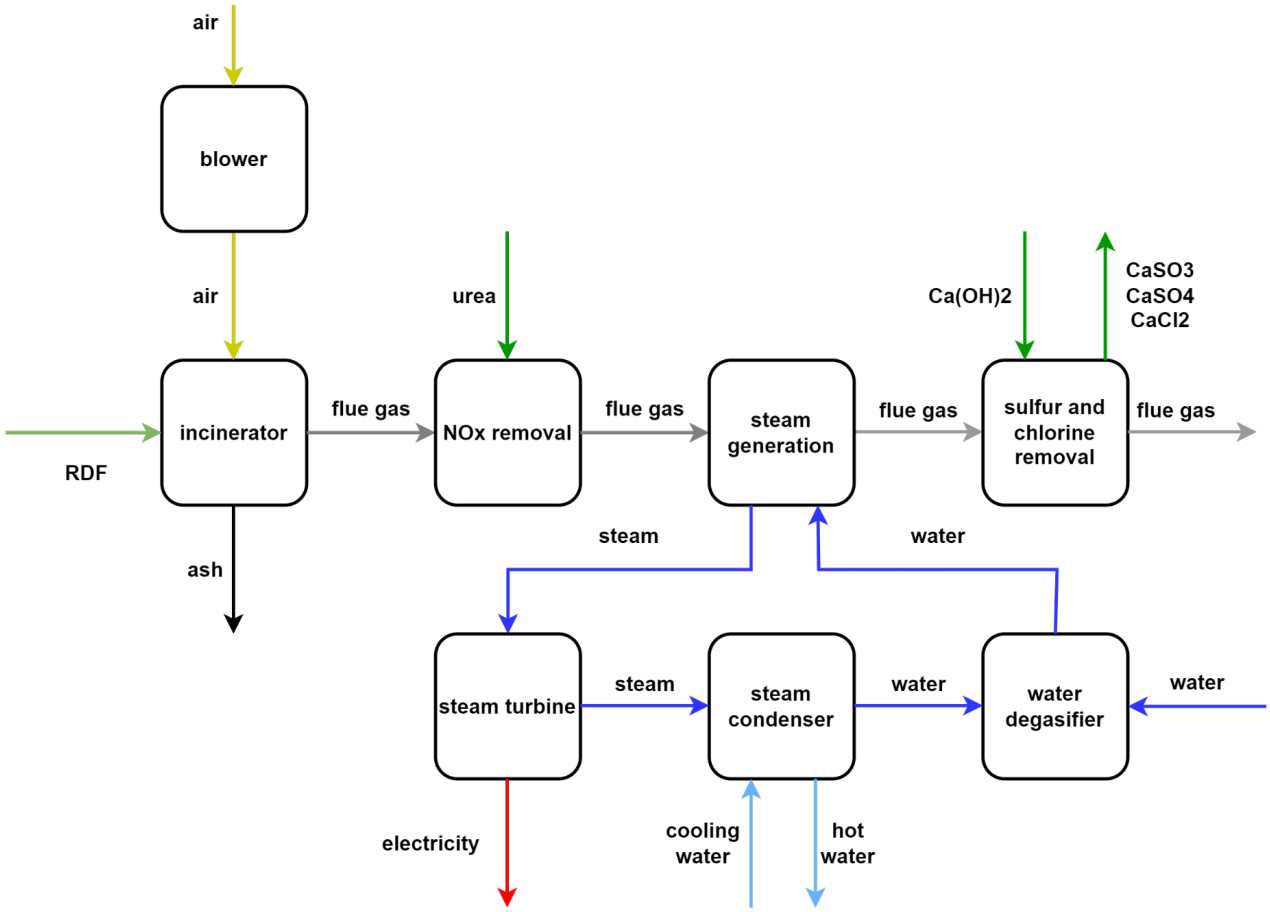

Figure 1: Simplified incineration flowsheet

flue gas and ash. Flue gas contained contaminants, such as NO_x, SO_2, SO_3, Cl_2 and HCl, and thus its purification was necessary. In **Figure 1**, a simplified flowsheet of this process is shown. Raw RDF enters the incinerator, where it burns in an excess of oxygen. Hot flue gas exiting the incinerator is purified to remove NO_x contaminants by selective non-catalytic reduction (SNCR). NO_x is reduced to N_2 via the reaction with urea in water solution. The still hot flue gas is then used for the generation of steam, which generates electricity in the steam turbine. From the cooled flue gas, sulfur, and chlorine contaminants are removed by adsorption using $Ca(OH)_2$.

The amount of incineration air was controlled to maintain 11% of oxygen in the flue gas [6]. Temperature of the exiting flue gas was 1 057°C and it was regulated by the temperature of the combustion air, which was preheated to 135°C. The amount of dry air required was 133 706 Nm^3/h. The process generated 1 361 kg/h of ash and 140 190 Nm^3/h of flue gas.

Composition of flue gas exiting the incinerator is shown in **Table 2**. To purify it from NO_x components, 758 kg/h of 9% urea aqueous solution was required. When the flue gas was cooled to 130°C, it was purified from SO_2 and HCl by the wet process using 140 kg/h of $Ca(OH)_2$. Flue gas purification processes were simulated using a stoichiometric reactor model with defined conversion [8]. Concentrations of contaminants in the purified syngas in **Table 2** were below the required values for the waste incineration, which are 200, 250, 250 and 10 mg/Nm^3 for SO_2, NO_x, CO, and HCl, respectively, for incinerators with nominal power below 100 MW [7].

Table 2: Composition of flue gas and contaminants concentrations in [mg/Nm^3] at 6% reference of O_2

	Vol. fraction	Concentration in raw syngas	Concentration in purified syngas
H_2O	0.065	-	-
O_2	0.114	-	-
N_2	0.754	-	-
CO	0.067	-	-
CO_2	$5.35x10^{-4}$	0.51	0.51
NO	$3.77x10^{-4}$	3 870.60	193.78
NO_2	$2.57x10^{-6}$	40.50	40.50
SO_2	$1.52x10^{-4}$	3 333.80	50.25
SO_3	$5.08x10^{-6}$	139.26	139.26
HCl	$3.57x10^{-4}$	4 458.03	8.96
Cl_2	$3.84x10^{-8}$	0.93	0.93

Superheated steam (600°C, 9 MPa) was generated by flue gas cooling. This steam expanded to 0.25 MPa in the isentropic steam turbine with isentropic efficiency of 0.8, generating 9.5 MW of electric energy. Part of which was spent by the equipment in the process, mainly the air blower, which required 880 kW. To condense the steam exiting the turbine, water for district heating was generated with the heat content of 29.2 MW.

Gasification

Simulation of RDF gasification was significantly more complicated than that of incineration due to the nature of the process. **Figure 2** shows a simplified

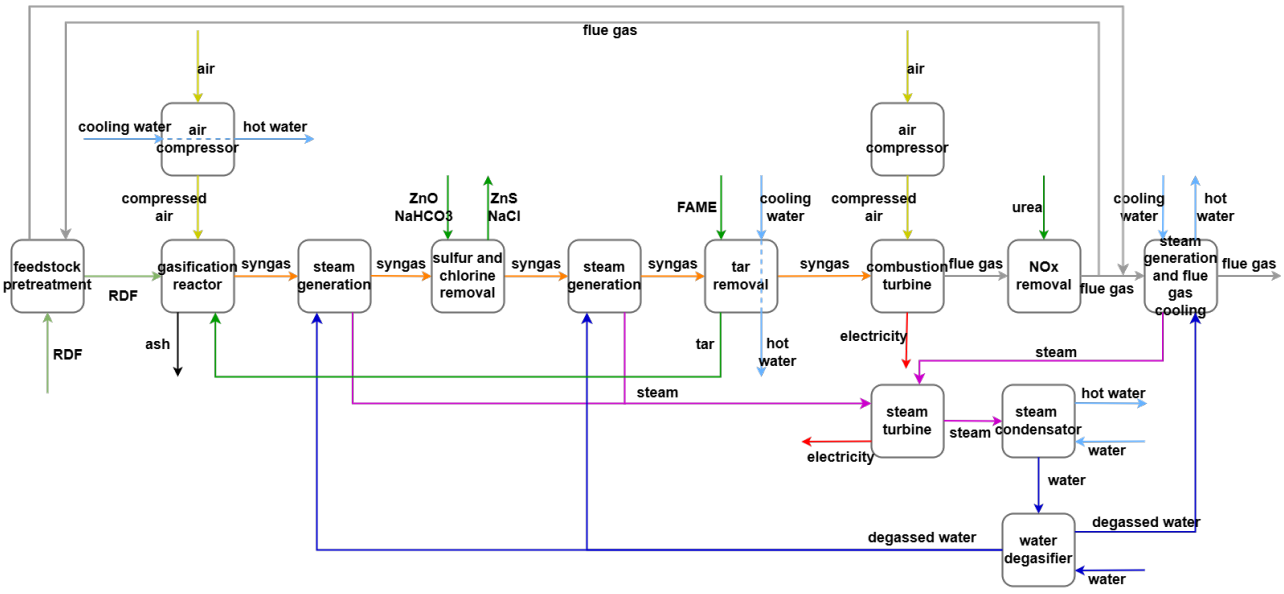

Figure 2: Simplified gasification flowsheet

gasification flowsheet. Before entering the gasification reactor, RDF was pretreated by drying using hot flue gas. Air, as the gasification medium, was compressed by a three-stage compressor with intercooling. Tar removed from syngas was recycled back into the reactor. Hot syngas exiting the reactor was purified from H_2S, HCl, and tar, while its energetic content was used for steam generation. Purified syngas was led into the combustion turbine to generate electricity. Hot flue gas from the turbine was purified only from NO_x contaminants and used for steam generation.

To simulate the gasification reactor, an equilibrium model including tar generation was used. Concentration of tar in syngas was 3.15 g/Nm^3 [2], and tar was represented by naphthalene. Air entered the gasification reactor at 36 bars and 227°C. Such high pressure ensures that no additional syngas compression is required before the combustion turbine. Sub-stoichiometric amount of air was used in the process, which is 25 148 Nm^3/h. Gasification conditions were controlled by the amount of air led into the reactor so that 100% carbon conversion was achieved and LHV of syngas was maximized. The amount of syngas exiting the reactor was 37 690 Nm^3/h, with LHV of 4.38 MJ/Nm^3 and temperature of 902°C.

Table 3: Syngas composition and contaminants concentrations in [mg/Nm^3]

	Vol. fraction	Concentration in raw syngas	Concentration in purified syngas
H_2O	0.049	-	-
H_2	0.163	-	-
O_2	0.000	-	-
N_2	0.531	-	-
NO	$1.35x10^{-13}$	$1.81x10^{-7}$	$1.81x10^{-7}$
SO_2	$3.60x10^{-11}$	$1.03x10^{-4}$	$1.03x10^{-4}$
Cl_2	$1.03x10^{-14}$	$3.23x10^{-8}$	$3.23x10^{-8}$
HCl	$1.34x10^{-3}$	2 139.32	1.06
CO	0.206	-	-
CO_2	0.048	-	-
H_2S	$5.88x10^{-4}$	879.34	4.34
NH_3	$3.70x10^{-4}$	275.06	275.06
tar	$5.51x10^{-4}$	3 098.00	3.45

In **Table 3** syngas composition and contaminants' concentrations are shown. Dry method of purification was used to remove H_2S and HCl from syngas by high temperature adsorption to 80 kg/h of ZnO and 191 kg/h of $NaHCO_3$ mixed with 2 707 kg/h of water. The process was simulated by the same method as in RDF incineration. Tar was removed by absorption into 124 kg/h of fatty acid methyl esters (FAME); methyl oleate was selected as a representative absorbent. Concentrations in the purified syngas met the requirements for combustion turbine fuel, which are 30, 20, and 1.5 mg/Nm^3 for tar, H_2S, and HCl, respectively [9].

Table 4: Concentrations of contaminants in purified flue gas

	Concentration [mg/Nm^3]
NO	213.58
NO_2	17.95
SO_2	3.43
SO_3	0.03
HCl	0.45
Cl_2	$2.31x10^{-6}$
CO	73.30

Purified syngas, along with 44 938 Nm^3/h of air (36 bars, 697°C), entered the combustion turbine. Its amount was regulated so that 3% of O_2 was present in the flue gas exiting the turbine at 768°C. Turboexpander generated 30.5 MW of power, a portion of which was spent to power air compressors in the system. Hot flue gas was purified from NO_x contaminants by the same process as in RDF incineration using 2580 kg/h of 9% aqueous urea solution. After purification (**Table 4**), flue gas met the purity requirements. In summary, 20.7 MW of electric energy was generated in the process and 24.3 MW of heat in form of hot water for district heating was generated using heat from steam condensation and cooling process streams.

Pyrolysis

RDF pyrolysis was focused on recovery of material products, such as pyrolysis oil or activated carbon (AC) adsorbent, while the excess heat was used for district heating. **Figure 3** shows a process flowsheet of pyrolysis. Raw RDF was pretreated in the same way as in RDF gasification. Two streams exit the pyrolysis reactor: gas together with oil, and char. Char is upgraded to AC by steam gasification while pyrolysis oil is separated from the gas and upgraded by distillation into three fractions (**Table 6**). Gases from the pyrolysis and steam gasification reactors are mixed and combusted to generate heat required for the process. Flue gas is purified from the contaminants.

Table 5: Pyrolysis product yields [12]

Product	Yield [%]	Mass flow [kg/h]
Char	25	2 267.6
Oil + water	43	3 898.5
Gas	32	2 901.2

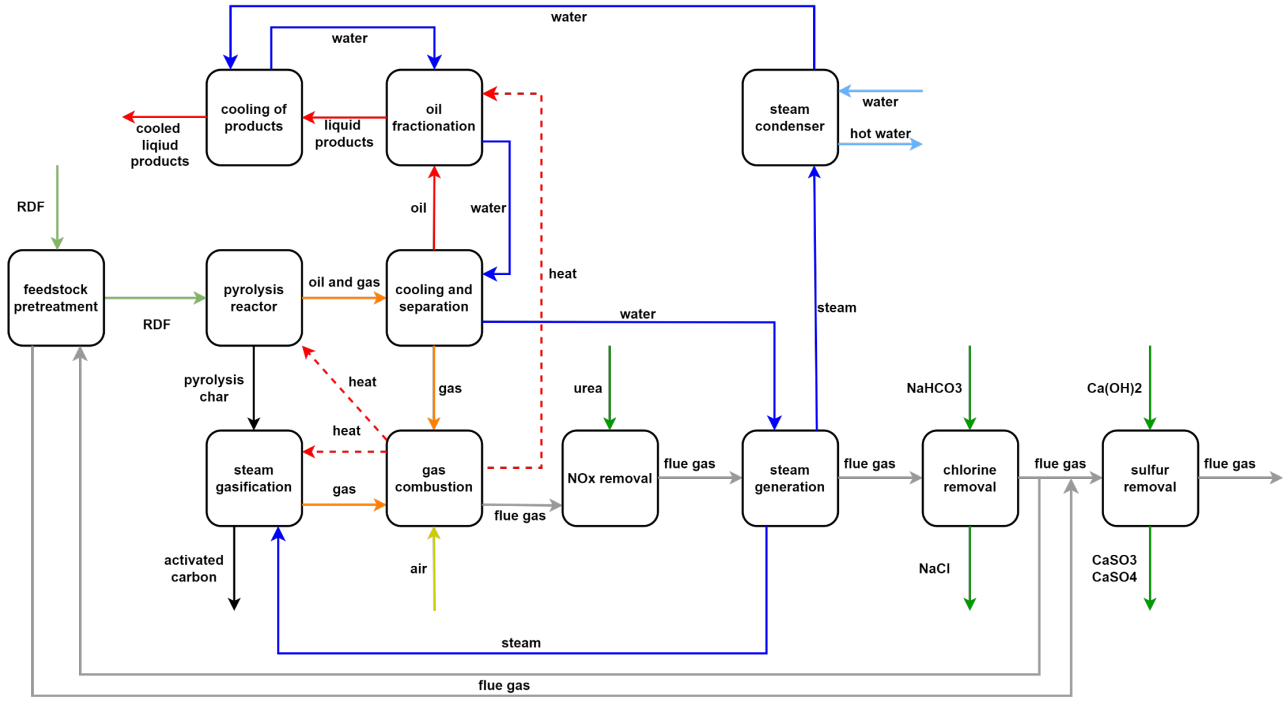

Figure 3: Simplified pyrolysis flowsheet

Table 6: Separated pyrolysis oil fractions

Fraction	Mass flow [kg/h]	BP range [°C]
Light	841	100 – 218
Medium	952	218 – 340
Heavy	1 781	340 – 438

Pyrolysis took place at 600°C. For these conditions, yields of the products (**Table 5**), composition of the gas phase and char [10], and representative molecules for the liquid phase [5], [11] were chosen. No oxidation medium was used in this process. The exact composition of pyrolysis oil was calculated from the elemental balance. For the pyrolysis process, 9.3 MW of heat was required. Steam gasification of char took place at 6 bars and 900°C, with the supply of 1140 kg/h of steam (1 MPa, 250°C) to the reactor at the rate of 0.0279 mol/g/h [13]. The reactor required an additional 3.2 MW of heat to produce 1 655 kg/h of AC. Following assumptions were made when calculating the yield and composition of AC:

- All volatile matter is converted into gas
- All ash stays in the AC
- Yield of AC is 73% [13]

Then, 4 980 kg/h of gas created in the process was combusted in the presence of 28 380 Nm^3/h of air. This process was regulated to maintain 5% of O_2 in purified flue gas (**Table 7**). The same purification processes were employed as in RDF incineration and gasification. To achieve the desired purity, 134 kg/h of urea, 172 kg/h of $NaHCO_3$, 66 kg/h of $Ca(OH)_2$, and 8 330 kg/h of water were required and 10.5 MW of heat in form of hot water for district heating was exported from the process.

Table 7: Concentrations of contaminants in raw and purified flue gas in [mg/Nm^3]

	Concentration in raw syngas	Concentration in purified syngas
CO	47.96	47.96
NO	4 335.6	207.0
NO_2	5.84	5.57
SO_2	1 967.4	187.8
SO_3	3.65	3.49
HCl	2553.6	9.75
Cl_2	0.12	0.12

Economic and safety analysis

Complex economic analysis was performed for all three processes of thermochemical conversion; results are provided in **Table 8**. Payback period (PBP) was used to compare economic feasibility of processes. The shortest PBP was in case of pyrolysis due to low EC and relatively high sales. However, this assumes that there is demand for the material products at the set price. Gasification was not economically feasible due to the high cost of equipment and operational costs. Incineration seemed less feasible than pyrolysis, however there will be always demand for electricity.

To compare the safety of the processes, Dow fire and explosion index (F&EI) as well as chemical exposure index (CEI) were used (**Table 9**). Equipment with the highest values was chosen as representative. Gasification had the highest risk of fire due to the high pressure in the process and handling of large amounts of flammable oils (FAME). The results for incineration and pyrolysis were similar.

Table 8: Economic parameters: equipment cost (EC) [$]; total capital investment (TCI) [$]; annual sales (AS) [$], and payback period (PBP) [years]

	Incineration	Gasification	Pyrolysis
EC	$1.07x10^7$	$4.93x10^7$	$8.24x10^6$
TCI	$5.66x10^7$	$2.25x10^8$	$4.86x10^7$
AS	$1.32x10^7$	$2.07x10^7$	$1.79x10^7$
PBP	11.4	43.5	5.3

Table 9: Results of safety analysis

	Incineration	Gasification	Pyrolysis
F&EI	67.64	159.32	81.00
Risk	Moderate	Severe	Moderate
CEI	12.45	17.10	15.15
Risk	Severe	Severe	Severe

CONCLUSION

In this work, RDF incineration, gasification and pyrolysis were compared considering technical, economic, safety, and environmental aspects. A mathematical model of each process was created in the Aspen Plus environment. Incineration is the simplest process focusing on energy recovery. In this process, 8.6 MW of electric energy and 29.2 MW of heat for district heating is generated. Gasification is more complicated from the technical point of view, providing 20.7 MW of electric energy and 24.3 MW of heat. Pyrolysis is focused mainly on material recovery, producing three fractions of pyrolysis oil with different boiling point ranges and 1 655 kg/h of activated carbon adsorbent, as well as 10.5 MW of excess heat exported as hot water for district heating. From the economic aspect, pyrolysis is the most feasible process, with a payback period of 5.3 years, assuming that there is a demand for its material products. From the safety aspect, incineration is the safest, followed by pyrolysis, and gasification. From the process and environmental point of view, requirements for the contaminants' concentration in syngas and flue gas were satisfied in all three processes. However, pyrolysis produces the most byproducts of gas purification and wastewater, followed by incineration, and gasification.

ACKNOWLEDGEMENT

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-19-0170 and by the program for supporting young researchers funded by the Slovak University of Technology.

REFERENCES

1. G. Gałko, I. Mazur, M. Rejdak, B. Jagustyn, J. Hrabak, M. Ouadi, H. Jahangiri, M. Sajdak, Evaluation of alternative refuse-derived fuel use as a valuable resource in various valorised applications, Energy 263 (2023). https://doi.org/10.1016/j.energy.2022.125920
2. M. Alfè, V. Gargiulo, M. Porto, R. Migliaccio, A. Le Pera, M. Sellaro, C. Pellegrino, A.A. Abe, M. Urciuolo, P. Caputo, P. Calandra, V. Loise, C.O. Rossi, G. Ruoppolo, Pyrolysis and Gasification of a Real Refuse-Derived Fuel (RDF): The Potential Use of the Products under a Circular Economy Vision, Molecules 27 (2022). https://doi.org/10.3390/molecules27238114
3. O.A. Osibote, A. Hlaba, A. Rabiu, A. Otolorin, O. 2+, Refuse Derived Fuel Pellets as a Renewable Energy Source, (2017). https://doi.org/10.7763/IPCBEE
4. J. Haydary, Gasification of Refuse-Derived Fuel (RDF), GeoScience Engineering 62 (2016) 37–44. https://doi.org/10.1515/gse-2016-0007
5. M. Polakovič, Purification of synthesis gas produced by thermo-catalytic gasification of mixed waste, Master Thesis, STU Bratislava, 2023
6. A. Sitka, W. Jodkowski, P. Szulc, D. Smykowski, B. Szumiło, Study of the properties and particulate matter content of the gas from the innovative pilot-scale gasification installation with integrated ceramic filter, Energies (Basel) 14 (2021). https://doi.org/10.3390/en14227476
7. Slov – Lex, Špecifické požiadavky na spaľovacie zariadenia. available January 28, 2025
8. E. Jannelli, M. Minutillo, Simulation of the flue gas cleaning system of an RDF incineration power plant, Waste Management 27 (2007)
9. V. Marcantonio, E. Bocci, J.P. Ouweltjes, L. Del Zotto, D. Monarca, Evaluation of sorbents for high temperature removal of tars, hydrogen sulphide, hydrogen chloride and ammonia from biomass-derived syngas by using Aspen Plus, Int J Hydrogen Energy 45 (2020) 6651–6662. https://doi.org/10.1016/j.ijhydene.2019.12.142
10. M. Zajemska, A. Magdziarz, J. Iwaszko, M. Skrzyniarz, A. Poskart, Numerical and experimental analysis of pyrolysis process of RDF containing a high percentage of plastic waste, Fuel 320 (2022). https://doi.org/10.1016/j.fuel.2022.123981

11. I.H. Hwang, J. Kobayashi, K. Kawamoto, Characterization of products obtained from pyrolysis and steam gasification of wood waste, RDF, and RPF, Waste Management 34 (2014) 402–410. https://doi.org/10.1016/j.wasman.2013.10.009
12. V. Cozzanij, C. Nicolella, L. Petarcaj, M. Rovatti, L. Togno, A Fundamental Study on Conventional Pyrolysis of a Refuse-Derived Fuel, 2006
13. W.K. Buah, P.T. Williams, Activated carbons prepared from refuse derived fuel and their gold adsorption characteristics, Environ Technol 31 (2010) 125–137. https://doi.org/10.1080/09593330903386741