
INTEGRATED EXERGETIC–ECONOMIC ASSESSMENT OF THERMAL AND CATALYTIC PYROLYSIS OF HOUSEHOLD THERMOPLASTIC WASTE FOR SUSTAINABLE WASTE-TO- ENERGY APPLICATIONS

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DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

The increasing generation of household thermoplastic waste presents environmental and resource-management challenges while providing an opportunity for energy recovery. This study presents an integrated exergetic–economic assessment of thermal and ZSM-5 catalytic pyrolysis of a modelled mixed household thermoplastic feedstock. Aspen Plus V14.0 was used to simulate a 1,000 kg h⁻¹ process, with thermal pyrolysis at approximately 500 °C and catalytic pyrolysis at 350 °C. Mass and energy balances, exergy analysis, SPECO exergoeconomics, techno-economic evaluation and sensitivity analysis were applied. Thermal pyrolysis produced 65.2 wt% oil, 19.8 wt% gas and 15.0 wt% char, while catalytic pyrolysis produced 58.5 wt% oil, 29.0 wt% gas and 12.5 wt% char. Catalytic operation reduced process-energy input from 3,334.20 to 1,840.62 kW (44.8%) and increased exergetic efficiency from approximately 62% to 71%. The catalytic configuration also reduced CAPEX from US\$5.043 million to US\$4.000 million and annual OPEX from US\$1.859 million to US\$1.206 million. Under a 20-year project life and 10% discount rate, NPV increased from approximately US\$11.34 million to US\$12.34 million, while IRR increased from 38.10% to 47.93% and payback decreased from 2.62 to 2.09 years. Product selling price was the dominant sensitivity variable. The results indicate that catalytic pyrolysis offers the stronger integrated energy, exergy and economic performance under the stated assumptions.

Keywords: household thermoplastic waste; thermal pyrolysis; catalytic pyrolysis; ZSM-5; Aspen Plus; exergoeconomics

1. INTRODUCTION

Plastic waste is an environmental, resource-management and energy challenge because its durability and chemical resistance hinder conventional disposal and recycling. Household plastic streams are heterogeneous and may contain mixtures of polyolefins, polystyrene, polyethylene terephthalate and polyvinyl chloride. Uncontrolled disposal, landfilling and open burning can therefore result in loss of material value and environmental burdens. Thermochemical conversion provides an alternative route for recovering embedded hydrocarbon value as liquid, gas and solid products. Product distribution depends on feed composition, temperature, residence time, reactor configuration and catalyst selection (Al-Salem et al., 2017; Dai et al., 2022; Speight, 2020).

Thermal pyrolysis generally requires relatively high temperatures to cleave polymer chains, whereas catalytic pyrolysis can promote cracking and secondary reactions at lower severity. ZSM-5 is particularly relevant because its acidic and porous structure can influence hydrocarbon selectivity and promote lighter and aromatic products (Chen et al., 2023; Wang et al., 2022; Zhou et al., 2022). However, product yield alone does not reveal the quality of energy utilization or where thermodynamic irreversibility occurs. Exergy analysis identifies useful work potential and exergy destruction, while exergoeconomics assigns economic consequences to thermodynamic losses. The SPECO method provides a systematic basis for component-level cost assessment (Dincer & Rosen, 2013; Tsatsaronis, 1993).

Previous studies have commonly focused on product distribution, process simulation or conventional economic indicators separately. The present study integrates product yields, process energy, exergy efficiency, component-level exergy-destruction costs, SPECO factors and project

economics for thermal and ZSM-5 catalytic pyrolysis of a mixed household thermoplastic feedstock. The aim is to determine which configuration provides the more favorable integrated technical and economic performance. Specifically, the study objectives are to: (i) develop comparative Aspen Plus V14.0 models; (ii) compare oil, gas and char yields; (iii) quantify process-energy requirements and exergetic efficiency; (iv) identify exergoeconomic hotspots; and (v) compare CAPEX, OPEX, NPV, IRR, profitability index and payback period.

2. METHODOLOGY

2.1 Feedstock and Simulation Basis

The feedstock was defined as a modelled mixed household thermoplastic stream rather than a measured Nigerian municipal-waste composition. The assumed composition 3 comprised HDPE (20 wt%), LDPE (10 wt%), PE (15 wt%), PP (30 wt%), PS (10 wt%), PET (10 wt%) and PVC (5 wt%), giving a total feed of $1,000 \text{ kg h}^{-1}$. The conceptual pretreatment sequence comprised sorting, removal of metals and inerts, size reduction and drying. This modelling basis was used consistently for both configurations and is not presented as a statistically measured national composition.

Table 1: Assumed mixed household thermoplastic feedstock composition.

Polymer	Mass fraction (wt%)	Typical household source
HDPE	20	Bottles, containers
LDPE	10	Films, bags, packaging
PE	15	Packaging and consumer products
PP	30	Food containers, caps, household items
PS	10	Disposable packaging and cups
PET	10	Beverage bottles
PVC	5	Household products and packaging
Total	100	—

2.2 Process Simulation and Energy Analysis

Aspen Plus V14.0 was used with the Peng–Robinson/RKS property method. Conventional components were represented together with appropriate hypothetical solid/polymer components using HCOALGEN and DCOALIGT where required. RYield and RCSTR blocks were used to represent decomposition and reaction behaviour. Thermal pyrolysis was evaluated at approximately 500 °C and catalytic pyrolysis at 350 °C with ZSM-5. The steady-state mass balance was expressed as:

$$\Sigma \dot{m}_{in} = \Sigma \dot{m}_{out} \quad (1)$$

For an adiabatic steady-state control volume with negligible shaft work, the energy balance was represented as:

$$\dot{Q}S - \dot{W} + \Sigma \dot{m}_{in} h_{in} = \Sigma \dot{m}_{out} h_{out} \quad (2)$$

Process-energy input was taken from the external heat and utility requirements of the model. Useful energy recovery represents recoverable energy in product streams and defined heat-recovery pathways.

2.3 Exergy and SPECO Analysis

Exergy analysis used an environmental reference temperature of 25 °C and atmospheric pressure. Total stream exergy was considered as the sum of physical, chemical, kinetic and potential components:

$$E_x = E_{x,ph} + E_{x,ch} + E_{x,ke} + E_{x,pe} \quad (3)$$

Chemical exergy is particularly important for hydrocarbon-rich plastic feedstocks.

Exergy efficiency was evaluated from the ratio of useful product exergy to fuel exergy supplied. Component exergy destruction was used to identify thermodynamic hotspots. SPECO was then applied to assign costs to exergy flows and component capital and operating costs. The exergoeconomic factor was interpreted as the relative contribution of investment cost to the combined investment and exergy-destruction cost; low values indicate greater scope for irreversibility reduction, while high values indicate stronger capital-cost dominance.

2.4 Economic Evaluation and Sensitivity

The economic assessment assumed 8,000 operating hours per year, a 20-year project life, a 10% discount rate and 30% corporate tax. CAPEX, OPEX, product revenue, NPV, IRR, profitability index and simple payback were evaluated on the same basis for both configurations. The catalytic base case included annual ZSM-5 replacement. Sensitivity analysis varied product selling price, OPEX, CAPEX and feedstock cost by $\pm 20\%$ using the same after-tax cash-flow formulation and 20-year, 10% discount-rate basis.

2.5 Model Validation

Percentage deviation was calculated as the absolute difference between simulated and literature yield divided by the literature yield and multiplied by 100. The thermal model gave an average absolute relative deviation of 7.90%. For the catalytic model, oil, gas and char/coke deviations were 20.95%, 26.09% and 316.67%, respectively; the high solid-product deviation is strongly influenced by the low 3 wt% reference value and should therefore not be interpreted as a direct overall prediction error.

3. RESULTS AND DISCUSSION

3.1 Product Distribution and Energy Performance

The thermal configuration produced 65.2 wt% oil, 19.8 wt% gas and 15.0 wt% char, equivalent to 652, 198 and 150 kg h⁻¹ at the design feed rate. Catalytic pyrolysis produced 58.5 wt% oil, 29.0 wt% gas and 12.5 wt% char, equivalent to 585, 290 and 125 kg h⁻¹. The catalytic route therefore shifted part of the condensable fraction toward gas while reducing solid formation. This trend is consistent with the role of ZSM-5 in promoting cracking and secondary reactions (Wang et al., 2022; Zhou et al., 2022).

Both configurations achieved positive net energy balances. Thermal pyrolysis required 3,334.20 kW and recovered approximately 4,446 kW, whereas catalytic pyrolysis required only 1,840.62 kW and recovered approximately 3,033 kW. Although absolute useful-energy recovery was lower for the catalytic route, its net energy gain was higher because of the substantially lower external energy requirement. The catalytic configuration reduced process-energy input by approximately 44.8% and increased the energy recovery ratio from 133.24% to 164.78%.

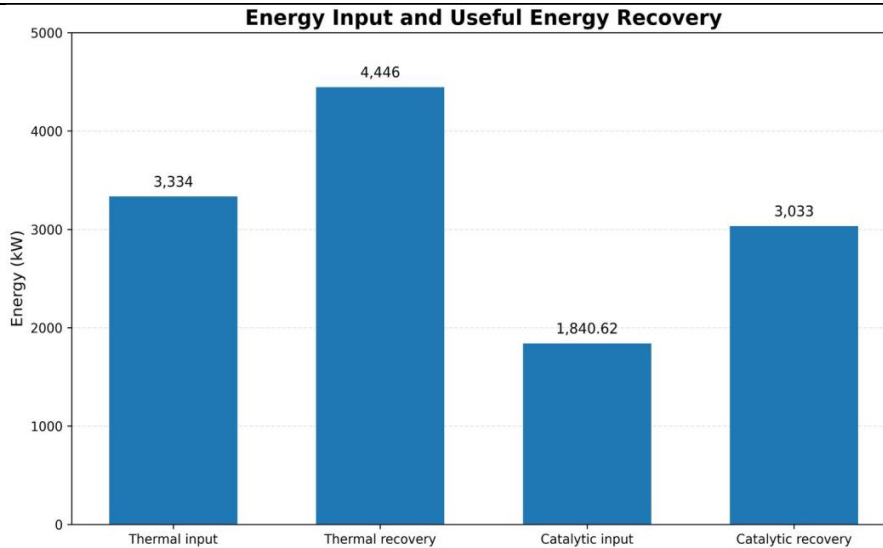


Figure 1: Comparison of process-energy input and useful energy recovered

3.2 Exergy and Exergoeconomic Performance

The consolidated exergy results gave approximately 62% exergetic efficiency for thermal pyrolysis and 71% for catalytic pyrolysis. The improvement indicates that a larger fraction of supplied exergy was converted into useful product exergy under the adopted system boundary. The principal component hotspot was the dryer: its exergy-destruction cost decreased from US\$1,641.66 h^{-1} to US\$1,477.49 h^{-1} . The combustor cost decreased from

US\$63.83 h^{-1} to US\$27.01 h^{-1} , a reduction of approximately 57.7%.

The low dryer factors indicate that thermodynamic inefficiency dominates its combined cost, so heat recovery, insulation and moisture-control improvements are higher priorities than simply increasing equipment investment. The catalytic combustor factor rises from 27.23% to 47.07% while its absolute exergy-destruction cost falls by 57.7%. This represents a shift in cost composition rather than an automatic overall improvement. The pyrolyzer and heat exchanger have intermediate factors and therefore require simultaneous consideration of capital cost and irreversibility. High factors for the separator and compressor indicate greater capital-cost dominance.

3.3 Techno-Economic Performance

The catalytic configuration required approximately 20.7% less CAPEX and 35.1% less annual OPEX than the thermal configuration. Although annual product revenue was lower for catalytic operation (approximately US\$3.860 million yr^{-1} versus US\$4.500 million

yr^{-1}), the lower investment and operating requirements produced stronger overall

profitability. Under the 20-year, 10% discount-rate basis, NPV increased from approximately US\$11.34 million to US\$12.34 million, while IRR increased from 38.10% to 47.93%.

Profitability index increased from 3.25 to 4.08 and simple payback decreased from 2.62 to 2.09 years.

Table 2: Consolidated techno-economic comparison

Economic indicator	Thermal	Catalytic
CAPEX (US\$ million)	5.043	4.000
Annual OPEX (US\$ million)	1.859	1.206
Annual product revenue (US\$ million)	4.500	3.860
NPV (US\$ million)	11.34	12.34
IRR (%)	38.10	47.93
Profitability index	3.25	4.08
Payback (years)	2.62	2.09

Sensitivity analysis showed that product selling price was the dominant economic variable. A 20% increase in product price raised catalytic NPV to approximately US\$16.94 million, while a 20% decrease reduced it to about US\$7.73 million. OPEX, CAPEX and feedstock-cost changes produced smaller NPV responses. The base catalytic case assumes a 12-month ZSM-5 replacement interval; catalyst deactivation and regeneration were not explicitly simulated, so alternative service-life cases are economic sensitivity scenarios rather than predictions of actual catalyst lifetime.

3.4 Safety, Environmental Implications and Limitations

The PVC fraction is 5 wt%, corresponding to approximately 50 kg h⁻¹ in the design feed. On a conservative basis, complete conversion of available chlorine to HCl gives an upper-bound HCl generation estimate of approximately 29.2 kg h⁻¹. This is not an actual emissions prediction because chlorine speciation and an HCl balance were not explicitly simulated. Commercial implementation would therefore require feedstock control, gas cleaning, acid-gas treatment, pressure relief, gas detection and appropriate process-safety systems. Environmental performance also requires future assessment of emissions, catalyst consumption, char utilization, wastewater, auxiliary fuel and life-cycle greenhouse-gas effects. The study is simulation-based; the assumed feed composition, catalyst stability, product quality and economic assumptions require experimental, pilot-scale and market validation before investment decisions.

4. CONCLUSION

An integrated Aspen Plus V14.0 assessment of thermal and ZSM-5 catalytic pyrolysis of a modelled mixed household thermoplastic feedstock was presented. Thermal pyrolysis produced higher liquid yield, whereas catalytic pyrolysis produced more gas and less char.

Catalytic operation reduced process-energy input by approximately 44.8% and increased exergetic efficiency from about 62% to 71%. The dryer was the dominant exergoeconomic hotspot, while the combustor showed a substantial reduction in exergy-destruction cost under catalytic operation. Economically, the catalytic configuration required lower CAPEX and OPEX and achieved higher NPV, IRR and profitability index together with a shorter payback period. Product selling price was the most influential sensitivity variable. Therefore, catalytic pyrolysis provides the stronger integrated performance under the stated 20-year, 10% discount-rate assumptions. Future work should prioritize pilot-scale validation, catalyst-deactivation and regeneration modelling, detailed product characterization, dryer heat- integration optimization, chlorine/emissions management, uncertainty analysis and life-cycle assessment.

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