Optimizing Waste-to-Energy Solutions for Circular Plastic Waste Management

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Abstract

This work explores different waste-to-energy (WTE) technologies, including pyrolysis, gasification, and incineration, to achieve Sustainable development goals. A mixed-integer linear programming model is proposed in this study to identify the viable routes for sustainable energy production. Moreover, a new measure of sustainability is proposed to holistically assess all the technologies multi-dimensionally. The Total Sustainability Metric (TSM) encompasses several metrics: energy efficiency, material consumption, water usage, waste generation, emissions, etc. Through a case study comparing various WTE scenarios, initial outcomes spotlight a promising combination of pyrolysis and gasification, delivering sustainable energy with 56% more profitability and over 41% higher sustainability than the base case of incineration. In conclusion, the model offers a swift, systematic approach to pinpointing optimal WTE technologies and holds the promise of resolving plastic waste management and circularity concerns while generating profitable energy solutions.

**Keywords**: Plastic Waste Management, Sustainability, Chemical recycling

* 1. Introduction

The urgency to achieve the Sustainable Development Goals (SDGs) drives the escalating emphasis on energy and environmental sustainability. Solid waste management, particularly plastics, is crucial to environmental sustainability due to their nonbiodegradability. The growing plastic production resulted in 139 million metric tons of plastic waste in 2021 (UNEP, 2023). Addressing these concerns, waste-to-energy (WTE) offers a dual benefit by alleviating waste burdens and providing alternative energy sources that align with sustainability objectives. WTE technology presents an eco-friendly avenue to address waste management and energy challenges. The SDGs encompass optimizing lifecycle stages for reuse and recycling using Process System Engineering (PSE) principles for enhancing circularity and energy efficiency while mitigating costs, emissions, and environmental impact (Avraamidou et al., 2020).

* 1. Literature Review

Energy recovery through incineration is a promising solution for plastic waste, given its high calorific value and suitability for end-of-life treatment. However, it raises concerns about depleting valuable carbon resources and emitting harmful air pollutants (Nikiema & Asiedu, 2022). Mechanical recycling, while eco-friendly, faces challenges like material quality degradation and labor-intensive processes, hindering plastic circularity (Schyns & Shaver, 2021). Chemical or molecular recycling, including pyrolysis and gasification, gains attention for a circular plastics economy due to their high technology readiness levels (Uekert et al., 2023). Exploring plastic waste management, especially through chemical recycling, supports the transition to a circular economy, reducing costs and pollution. Effective screening methods are crucial for waste-to-energy approaches, with studies employing techno-economic and life cycle assessments for feasibility evaluations. Limited research has delved into optimization models for plastic waste recycling, such as the framework proposed by (Somoza-Tornos et al., 2021) and the superstructure introduced by (Zhao & You, 2021). (Lim et al., 2022) present an optimal strategy for sorting and recycling mixed plastic waste. While previous studies focused on the feasibility of converting plastic waste, there is a need for further exploration, particularly in optimizing primary products from chemical recycling processes such as pyrolysis oil or synthesis gas. Moreover, to measure and design a circular economy, it's essential to establish a metric considering recovered materials' environmental, economic, and social value. Commonly used indicators include the Linear Flow Index (LFI), Material Circularity Indicator (MCI), and Product Circularity Indicator (PCI) based on material flow analysis precisely measuring material circulation but lacks consideration of life cycle emissions and avoided impacts, limiting its ability to represent product sustainability fully. Additional indicators such as material and energy efficiency, feedstock flexibility, and co-product utilization are crucial to individual processes (Supply Chain School, 2019).

This work introduces an innovative screening model that comprehensively evaluates various pathways for plastic waste recycling. Specifically, WTE approaches. This employed framework facilitates sophisticated decision-making by fostering a well-balanced assessment of different plastic recycling technologies. Moreover, to comprehensively assess the sustainability of all alternatives multi-dimensionally, the model introduces a novel metric that integrates various supplementary metrics such as material, energy, and water efficient utilization, waste generation, carbon footprint, economic viability, recyclability, co-product utilization, product quality, and TRL.

* 1. Methodology

The approach to screening the different plastic waste-to-energy pathways is illustrated in Figure 1.

Figure 1. Methodology

* 1. Mathematical model Formulation

This work focuses on investigating plastic waste in energy technologies. A screening model based on mixed-integer linear programming (MILP) was developed to assess all the alternatives while considering multiple factors. The model's primary objective is maximizing overall profitability and is subjected to various equality and inequality constraints, including material and energy balance, capacity limits, economics considerations, and circularity constraints. The model proposes a set P of possible pathways. The model equations are presented as follows:

(1)

Subject to:

(2)

(3)

The net profit and income of the technology is determined as follows:

(4)

(5)

The income is calculated using the output mass flowrate ( of the specific product i and the price () of the product (electricity in this case in $/kWh). Capex is estimated through regression modeling with piecewise linearization to handle nonlinear data. Opex depends on each pathway’s requirements including material, energy, utilities, etc. The overall sustainability is measured by incorporating supplementary metrics such as Material Utilization Indicator (MUI), Energy Utilization Indicator (EUI), Water Utilization Indicator (WUI), Solid-Waste Generation Indicator (WGI), Carbon Footprint Indicator (CFI), Economic viability Indicator (EVI), Co-product Utilization Indicator (CUPI), Recyclability Indicator (RI), Product Quality Indicator (QPI), and Technology Readiness Level Indicator (TRLI). All these indicators are given a specific weight factor () and collectively form the Total Sustainability Metric (TSM), as shown in Eq. (6) to Eq. (15), respectively. Each individual indicator and the final metric are all normalized on a scale of 0-1, where zero represents the worst-case scenario, and one represents the best-case scenario.

|  |  |
| --- | --- |
|  | (6) |
|  | (7) |
|  | (8) |
|  | (9) |
|  | (10) |
|  | (11) |
|  | (12) |
|  | (13) |
|  | (14) |
|  | (15) |

* 1. Case Study

Products of waste-to-energy technologies for circular plastic waste management can vary depending on the technologies and processes employed. Generally, waste-to-energy solutions aim to produce energy through electricity generation, heat production, synthetic fuels, steam production, and combined heat and power. The case study considers the production of electricity and fuels through three pathways: pyrolysis, gasification, and energy recovery by direct incineration. The model aimed at achieving maximum economic profit and contribution to the circular economy through the proposed sustainability metric.

Table 1. Case Study Data in $M/y.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| No. | Technology | Products | Income | Capex | Opex |
| P1 | Incineration - Base case | Electricity | 15.9 | 1.36 | 3.6 |
| P2 | Gasification + Methanol Synthesis + MTG | Gasoline  Propylene | 49.7 | 4.97 | 23.8 |
| P3 | Gasification+ Incineration | Electricity | 12.8 | 6.33 | 18.6 |
| P4 | Pyrolysis | Pyrolysis oil | 26.4 | 3.11 | 5.5 |
| P5 | Pyrolysis + Incineration | Electricity | 11.1 | 4.46 | 9.0 |

The case study is scaled based on sources that generate 275 tons per day of mixed plastic waste. Detailed technical are provided in Table 1. Further data and constraints may be formulated and included with the core model as needed for a specific case study to retain the class of the optimization model. The model has been solved with Python 3.10.2 - Pyomo 6.4.0, Gurobi solver 10.0.1. Optimal solutions have been consistently obtained within a few seconds.

* 1. Results and Discussion

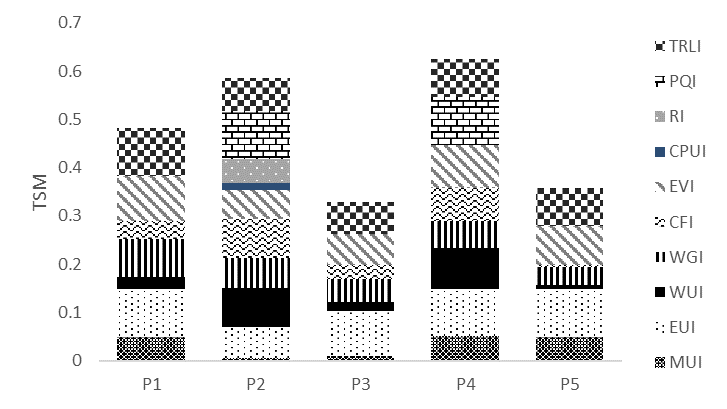


Figure 2. Contribution of Individual Indicators in TSM.

The waste-to-energy pathways (P1 to P5) are evaluated based on a comprehensive set of sustainability metrics, as illustrated by Figure 2, emphasizing that the higher the value is, the better. Among these pathways, P4 (Pyrolysis) stands out as the most sustainable WTE technology, as reflected by the value of TSM, indicating superior overall sustainability and circularity. P2 follows closely, showing strong performance across various indicators. P1 and P5 demonstrate moderate sustainability, while P3 means an overall negative impact. Regarding MUI, P2 demonstrates superior efficiency, while P1 and P5 show higher material usage.

Figure 3. Net profit and TSM for Different Pathways.

Pathway 3 exhibits the most efficient energy utilization (EUI). The most efficient pathways in terms of water are P2 and P4. P3 generates the most waste, while P4 and P2 represent a better performance. CFI is lowest in P3 and P5, indicating the most negligible environmental impact, while EVI is highest in P2, reflecting the lowest cost. P2 is the only pathway that encompasses a valuable co-product, propylene. And that also reflects the better performance in the recyclability metric compared to all alternatives. Lastly, it is noticeable that Incineration for energy recovery is the most mature pathway reflected by the higher TRL value. Figure 3 illustrates the net profit compared to the sustainability metric for all the pathways before using the optimization model and reflecting the trade-offs between economic feasibility and sustainability. Particulary, although P2 is the highest profitable route, it shows lower performance in terms of sustainability compared to P4. Also, although P5 is more sustainable than P3, neither of them is economically feasible.

Figure 4. Optimization results

Figure 4 illustrates the optimization results compared to the base case of energy recovery by incineration (P1) for maximizing profitability and sustainability. The base case yields an annual profit of $11 million, whereas combining the P2 and P4 outperforms, with a total net profit of $M17.2 annually, enhancing the base case's net profit by 57% and improving the base case sustainability by more than 41% offering the highest contribution to the circular economy.

* 1. Conclusion

The findings of this screening approach suggest that selling pyrolysis fuel oil, represented by P4 and gasoline fuel in P2, holds promise for achieving higher sustainability and circularity in waste-to-energy technologies. Furthermore, assessing individual indicators can provide insights into specific strengths and weaknesses of each pathway. This analysis helps identify pathways that excel in certain aspects, aiding in informed decision-making for sustainable waste-to-energy solutions. This work clarifies the role of technology in the circular economy for authorities to foster a cleaner and more sustainable global economy or, in other words, a sustainable trash-to-cash economy.

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