

Circular Integration of Electrified Plastic Waste-to-X Systems into Oil Refineries

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The integration of plastic waste-to-X systems into the oil refineries offers a promising solution to the growing problem of plastic waste, while also supporting decarbonization by circulating plastic waste back into its supply chain as alternative feedstock. However, to ensure the environmental sustainability of plastic waste-to-X integration, it is crucial to account for the additional direct and indirect emissions involved. To address this, the potential of implementing electrification strategies must be explored. Therefore, this work presents a P-graph model to assess potential electrification pathways for the plastic waste-to-X system with simultaneous consideration of both economic and environmental aspects. The model focuses on two key aspects – the mode of electrification (i.e., direct or indirect electrification) and technology selection. A case study is presented to demonstrate the model's applicability, revealing that electrification can reduce total cost by 97 % compared to the conventional system. However, the emissions avoidance potential is 33 % lower due to lower throughput. Scale-up analysis shows that achieving the same emissions avoidance as well as further scaling could increase the cost by 0.7 % to 7.8 %. Insights obtained from the analysis are expected to provide valuable guidance for policymakers in the development of strategies to promote transition towards circular economy.

1. Introduction

Global plastic production is projected to reach 1,100 Mt by 2050, with approximately 85 % ending up in landfills or as unregulated waste, posing a significant environmental threat (UNEP, 2025). Resource recovery (or plastic waste-to-X) has gained increasing attention, as it tackles the issue by converting plastic waste into valuable products such as fuel, chemicals, and monomers. These products are compatible with refinery processes, making the strategy of reintegrating plastic-derived products into existing supply chains a promising approach to mitigate the resultant environmental impact. However, the conventional processes employed in these valorisation pathways are often energy-intensive and rely on fossil fuel combustion (Theofanidis et al., 2025), resulting in substantial greenhouse gas emissions. To address this challenge, there is growing interest in transitioning fossil fuel-based valorisation technologies to electrified alternatives. Recent advancements have demonstrated the potential of electrified technologies as viable options for processing plastic waste with reduced carbon footprints. Such includes microwave-assisted depolymerisation (Yuan et al., 2023), microwave pyrolysis (Jiang et al., 2020), and plasma-assisted gasification (Sanlisoy and Carpinlioglu, 2017). Additionally, electrified upgrading technologies for plastic-derived product, such as steam cracking (Kim et al., 2022) and catalytic upgrading (Eschenbacher et al., 2022), further demonstrate the feasibility of integrating electricity-driven process into plastic waste valorisation. Despite these technological developments, the feasibility of integrating such electrified technologies into plastic waste-to-X system remains uncertain. Therefore, a systematic approach to evaluate the economic and environmental implications of electrification is crucial for informed decision-making (Mousa and Al-Mohannadi, 2024). Current optimisation methods (i.e., mathematical and graphical) for plastic waste management, primarily focus on waste sorting (Lim et al., 2023), recycling (Tan et

al., 2022) and waste-to-resources conversion (Pacheco-López et al., 2021). However, these studies overlook the potential of integrating electrified technologies alternatives into the conventional refinery processes. In this context, P-graph offers a robust solution approach for modelling the plastic waste-to-X system. Its ability to generate multiple near-best solutions is crucial for informed decision making (Friedler et al., 2022), particularly in complex systems. While P-graph has been successfully applied across various fields, including carbon trading (How et al., 2024), wastewater treatment network (Pimental et.al, 2022), negative emissions technologies portfolio (Migo-Sumagang et.al, 2024), and circular economy optimisation (Yeo et al., 2020), its potential in optimising electrified plastic waste-to-X system remains unexplored. Therefore, this study incorporated P-graph framework to evaluate the feasibility of electrifying the system considering both economic and environmental performance. The analysis further compares the electrified system with its fuel-based alternative, offering insights into the potential benefits and challenges associated with the transition.

2. Problem Statement

Given mixed plastic waste w , consisting of various plastic type, first undergoes pre-treatment using technology t to produce clean and sorted plastic i . The sorted plastic i is then processed through conversion technologies t' to convert plastic into intermediate i' , which is further upgraded using technology u to meet the specification for direct integration into the refinery. The upgraded product p can follow two routes, either to be (i) integrated into the refinery to full demand d , or (ii) recycled within the system for technology t , t' , and u , which then reduced the need for fresh resources s . Additionally, product p can also be utilised for utility generation e through trigeneration technologies v , to offset external requirements. To evaluate the transition towards electrification, electrical alternatives are integrated for technology t' , u and v . Given that the electricity consumption is expected to rise, renewable energy sources are also considered to enhance the sustainability of the electrified system.

3. Methodology

This work proposes the use of P-graph for the selection of optimal electrified plastic waste-to-X pathway. The mathematical formulation and P-graph representation are covered in this section.

3.1 Mathematical Formulation

Different types of plastic waste entering the system can be converted into various products p depending on the conversion technologies and upgrading process. The product flow F_p is distributed across refinery demand ($F_{p,d}$), utility system for generating utilities via technology v ($F_{p,v}$) and recycling stream ($F_p^{recycle}$):

$$F_p = \sum_d F_{p,d} + \sum_v F_{p,v} + F_p^{recycle} \quad \forall p \in P \quad (1)$$

The supply of product p that can be used in the refinery is capped to a specified range of minimum demand ($F_{p,d}^{Min}$) and maximum demand ($F_{p,d}^{Max}$), ensuring operational stability:

$$F_{p,d}^{Min} \leq F_{p,d} \leq F_{p,d}^{Max} \quad \forall p \in P, \forall d \in D \quad (2)$$

The objective of the model is to minimise the total expenses (C^{Total}), while accounting for environmental benefits through the potential revenue from carbon credit ($C^{C,total}$). The remaining cost factors include expenditure for importing external resources (C^{Import}), capital expenditure ($C^{CX,total}$) based on the processing capacity of selected technology, and operating expenses ($C^{OX,total}$) proportional to material flow. $C^{C,total}$ is calculated based on the system net emissions reduction ($G^{Net\ reduction}$) multiplying with carbon credit price C^C .

$$\min C^{Total} = C^{Import} + C^{CX,total} + C^{OX,total} - C^{C,total} \quad (3)$$

$$C^{C,total} = G^{Net\ reduction} \times C^C \quad (4)$$

The $G^{Net\ reduction}$ is defined as the difference between avoided emissions ($G^{Avoided}$), direct emissions (G^{Direct}), and indirect emissions ($G^{Indirect}$). G^{Direct} represents emissions directly released from the process, while $G^{Indirect}$ accounts for emissions associated with the imported resource based on their respective emissions factor. The sum of G^{Direct} and $G^{Indirect}$ constitutes the total emissions of the system.

$$G^{Net\ reduction} = G^{Avoided} - G^{Direct} - G^{Indirect} \quad (5)$$

$G^{Avoided}$ represents emissions that would be emitted in case when plastic waste is not consumed to produce given products in the process, including (i) emissions attributed to product generation via conventional process,

which are calculated by multiplying $F_{p,d}$ with the emissions factor of the conventional process being replaced (ε_p), and (ii) emissions attributed to landfilling of plastic waste w , which are calculated by multiplying the flow of plastic waste utilised ($F_{w,t}$) with the corresponding landfill emissions factor (ε_w).

$$G^{Avoided} = \sum_p \sum_d (F_{p,d} \times \varepsilon_p) + \sum_w \sum_t (F_{w,t} \times \varepsilon_w) \tag{6}$$

3.2 P-graph Representation

The model outlined in Section 3.1 is translated into a P-graph model (Figure 1) through P-graph Studio v5.2.5.0 (P-Graph Studio, 2019). The P-graph representations consist of nodes that refer to the flow of raw materials (e.g., resources, utility), intermediate and final products across various technologies (e.g., pre-treatment, conversion, upgrading). The upgraded product node can be directed (i) to meet refinery demand, which contributes to emissions avoidance, or (ii) recycle within the system, either directly as a resource or through regeneration in the utility system. Any additional resource or utility input (e.g., electricity, cooling water) is subjected to its respective indirect emissions factor, while direct emissions are accounted for processes within the system.

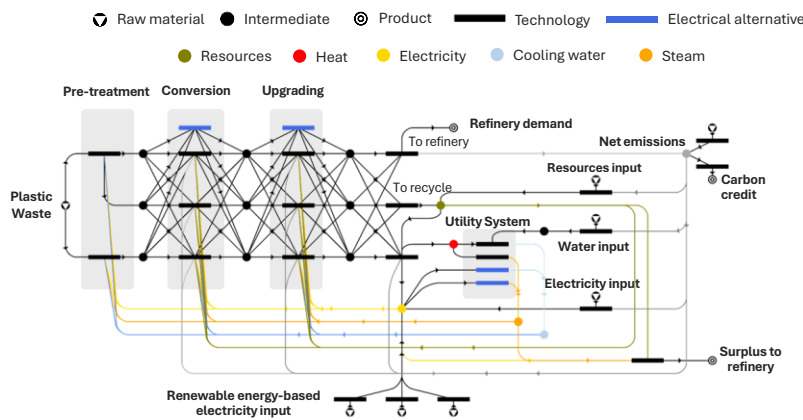


Figure 1: P-graph representation of the plastic waste-to-X system with electrical alternatives

4. Case Study

An oil refinery with crude oil processing capacity of 100,000 barrels/day serves as the case study in this work. Figure 2 illustrates the superstructure of the plastic waste-to-X pathway.

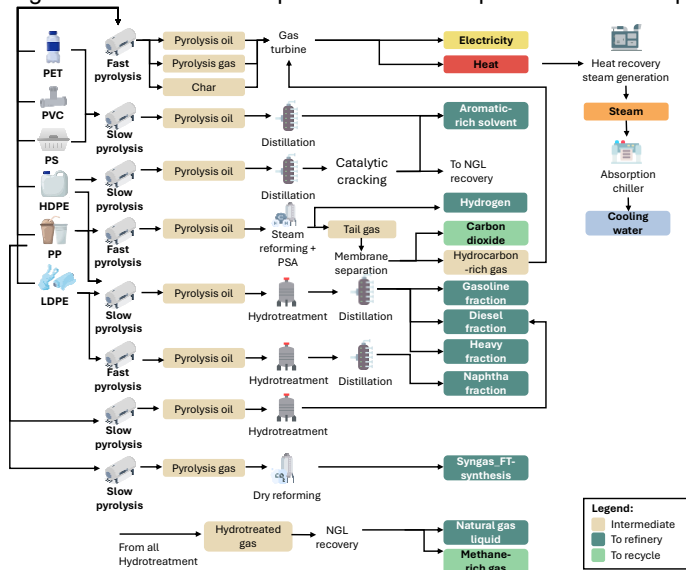


Figure 2: Potential plastic waste-to-X pathway considered.

Mixed plastic waste first undergoes pre-treatment to obtain six primary plastic fractions – polypropylene (PP), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC). These sorted plastics are then directed to pyrolysis for waste conversion, following with upgrading process (e.g., distillation, hydrotreating, reforming). In the electrification scenario, several electric alternatives are introduced. For pyrolysis, microwave pyrolysis is considered alongside the conventional fuel-based pyrolysis. Similarly, electrified reforming is considered as an alternative to conventional reforming. For distillation and hydrotreating, electric heater is proposed to replace the fuel combustor for pre-heating. In terms of the utility system, the steam boiler and absorption chiller can be replaced with electric boiler and electric chiller, respectively. This case study focuses on identifying the most cost-effective plastic waste-to-X pathway by minimising total expenses of the system.

5. Results and Discussion

Using the *Solution Structure Generation* (SSG) algorithm in P-graph, more than 10,000 feasible plastic waste-to-X pathways were generated. The optimal and near-optimal pathways for cost minimisation were then determined using the *Accelerated Branch and Bound* (ABB) algorithm. The top 100 lowest-cost solutions generated by P-graph were evaluated, focusing on the key performance parameters and pathway changes as shown in Table 1 and Table 2, respectively. The analysis compares the base case (without electrification) and the optimised electrification pathway (E1), along with selected near-optimal solutions at rank 5, 63, and 79 (denoted as E5, E63, and E79). The results indicate that the base case has a 17 % higher total cost than that of E1, primarily due to the greater raw material cost required for the plastic-to-syngas synthesis pathway. Specifically, the base case suggests more than ten times higher throughput (21,872 t PP input) on the PP-to-syngas pathway compared to E1 (1,558 PP input). This can be explained as syngas offer the highest emissions avoidance potential among the available plastic-derived products. In base case, given the absence of electrical alternatives, the model prioritises plastic-derived fuel to meet the energy demand internally and externally. In order to offset the emissions associated with fuel combustion, the model then suggests maximising the throughput of the PP-to-syngas pathway to boost the emissions avoidance potential. In contrast, E1, which does not rely on fuel generation can therefore omit the need for high throughput. Although this results in 58 % lower avoided emissions potential compared to the base case, the adoption of electrified alternatives in E1 still demonstrates superior environmental performance. Specifically, emissions generated in E1 constitute only 30 % of the emissions in base case.

Table 1: Comparison of key parameters for base case, optimal electrification pathways (E1) as well as the near-optimal solutions at rank 5 (E5), 63 (E63), and 79 (E79)

Results parameter	Base case	E1	E5	E63	E79
Total cost (USD/y)	43,544,114	37,214,000	37,226,200	37,394,000	37,409,700
Total emissions (t CO ₂ .eq/y)	89,140	36,573	36,567	36,182	36,512
Avoided landfill emissions (t CO ₂ .eq/y)	22,566	22,582	22,652	22,592	22,566
Avoided refinery emissions (t CO ₂ .eq/y)	85,469	50,021	50,021	45,376	50,021
Net emissions reduction (t CO ₂ .eq/y)	22,891	36,014	36,036	31,846	36,101

Table 2: Pathway changes in base case, optimal electrification pathways (E1) as well as the near-optimal solutions at rank 5 (E5), 63 (E63), and 79 (E79)

Product	Technology selected	Base case	E1	E5	E63	E79
Energy generation	PVC-based fuel pyrolysis	✓	-	-	-	-
	PP-based fuel pyrolysis	✓	✓	✓	✓	✓
Cooling water	Absorption chiller	✓	✓	-	✓	✓
	Electrical chiller	-	-	✓	-	-
PVC-based energy generation	Fuel-based pyrolysis	✓	✓	✓	-	✓
	Microwave pyrolysis	-	-	-	✓	-
PS-based aromatic solvent	Fuel-based pyrolysis	✓	✓	✓	✓	-
	Microwave pyrolysis	-	-	-	-	✓

Another notable change in pathway in E1 compared to the base case is the shift from a combination of PVC and PP fuel-based pyrolysis pathway to relying solely on PP-based for energy generation. This change is driven by the integration of electrified alternatives and renewable energy sources, which reduces the overall system

fuel demand from 12,879.5 to 4,685.86 t/y. As a result, the PP-to-energy pathway alone now becomes sufficient, primarily due to its superior pyrolysis oil yield (62 %), which is significantly greater than other plastics ranging from 3.8 % to 45.5 %. Aside from the optimal E1 solution, the near-optimal results offer several alternative pathways aligned with different operational goals. For instance, solution E5 presents another viable entry point for electrification with only a 0.03 % increase in total cost. This solution suggests replacing conventional absorption chiller with an electric chiller for cooling, resulting in a slight increase in operating cost (0.01 %) due to the rise in electricity and water demand. Solution E63 is the first to introduce electrification of the pyrolysis process using microwave pyrolysis, specifically applied to the PVC-based energy generation pathway. This choice is justified by its low electricity requirement (214.8 kWh/t input), making it the most energy-efficient among available pyrolysis options. Integrating this additional pathway alongside the existing PP-based fuel pyrolysis reduces the PP plastic input. Consequently, the combustion fuel required decreases from 4,685.86 to 4,521.39 t/y, leading to lower direct emissions. As a result, E63 emerges as the solution with the lowest total emissions generated. Building on E63, solution E79 applies microwave pyrolysis to the PS-to-aromatic solvent pathway. Among all available pyrolysis options, this pathway operates at the smallest scale, processing only 1,910.03 t/y of plastic input compared to other pathways (5,067 to 104,602 t/y). Despite its smaller scale, E79 achieves the highest net emissions reduction, demonstrating the advantage of electrifying smaller, high-impact pathways to maximise environmental performance without requiring large-scale expansion.

To further study the potential of the electrified system, the model was extended to achieve the same emissions avoidance level as the base case (denoted as case E1*). This model is resolved by introducing $G^{Avoided}$ in Eq(6) as the constraint, which requires the system to achieve. The results show that the target can be achieved with a 24 % increment in total cost from case E1 (Figure 3 (a)), with no changes in technology selection. The increase in emissions avoidance was achieved solely by increasing the system throughput by 41 % of the existing configuration, which increases the production of syngas with high emissions avoidance potential. To assess the scalability, the electrified system was evaluated via a progressive emissions avoidance target ranging from 20 % to 100 %. The results show a corresponding increase in total cost between 1 % and 11 % compared to that of E1, while pathway selection remained consistent. Notably, a shift in emissions behaviour is observed (Figure 3 (b)). Direct emissions from the system increase mainly due to higher system throughput to achieve higher emissions avoidance, leading to greater production of secondary products, such as plastic-derived fuels. These products are primarily utilised for generating energy for internal energy use via combustion, resulting in an increase in direct emissions from 23,468 to 64,601 t CO₂-eq/y while approaching to 100 % emissions avoidance target. Nevertheless, the use of plastic-derived fuels for energy generation reduces the reliance on external electricity, resulting in a net reduction of emissions from 33,361 to 83,648 t CO₂-eq/y. As a whole, with the enhanced emissions avoidance potential, the system can achieve a net reduction in emissions. In fact, the marginal abatement cost is reduced from 631 to 389 USD/t CO₂-eq avoided, indicating emissions removal is getting more cost-effective as the system scales.

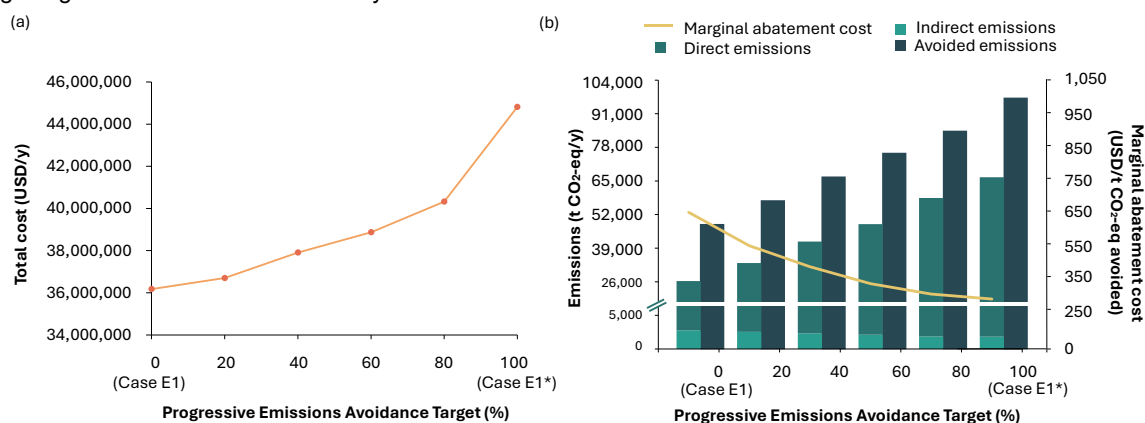


Figure 3: (a) Total cost variation at increasing emissions avoidance target; (b) The Marginal Abatement Cost (MAC) and the system emissions generation of electrified plastic waste-to-X system at increasing emissions avoidance target

6. Conclusion

The optimisation model developed in this study effectively identifies cost-efficient plastic waste-to-X pathways, providing valuable insights into the trade-offs between electrified and non-electrified systems. By incorporating technology selection with simultaneous electrification consideration, the model captures how different

configurations impact the system performance in terms of the economic and environmental aspect, making it a versatile tool for decision-making. Additionally, its capability to generate multiple alternative solutions further supports decision-makers in evaluating various technology combinations, which could ensure flexibility in adapting to different scenarios in real-world applications. Moving forward, future work should focus on expanding the model to include a wider range of valorisation technologies, such as liquefaction, gasification, and liquefaction, providing a more comprehensive assessment of technology selection. Additionally, the incorporation of carbon capture technologies should be explored to address the unavoidable emissions generated from the system, particularly under higher throughput scenarios. Overall, the model offers a practical decision-making tool, guiding stakeholders in evaluating the feasibility of transitioning to an electrified plastic waste valorisation system.

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