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ACCELERATING PLASTIC WASTE CIRCULARITY

The growing plastic waste crisis and the limitations of traditional recycling methods have driven the search for innovative and scalable solutions. Converting plastic waste into olefins presents a promising pathway to close the materials loop, reduce environmental impact, and support the transition to a circular economy. Plastic-to-olefins (PTO) conversion enables the transformation of post-consumer waste into high-value petrochemical feedstocks, aligning with regulatory pressures, market dynamics, and global decarbonisation efforts.

This article outlines the closed-loop PTO process, detailing critical steps including plastic pyrolysis, hydroprocessing, and steam cracking. It highlights critical technical challenges such as feedstock variability, furnace adaptability, and process optimisation. To address these complexities, a simulation-based methodology was employed, leveraging advanced software to model process units, predict operational challenges, and optimise key parameters for improved efficiency and sustainability.

The plastic waste crisis and the increasing demand for sustainable solutions have driven the development of innovative methods for recycling and reusing plastics. With nearly 380 million t of plastic produced annually[1] and the majority ending up in landfills, oceans, or incinerators, the need for scalable and sustainable recycling solutions has never been more urgent. Traditional mechanical recycling techniques struggle with mixed or contaminated feedstocks, limiting their effectiveness. In response, chemical recycling methods – especially those leveraging pyrolysis and advanced hydroprocessing – have emerged as transformative technologies for closing the loop on plastic use.

One of the most promising advancements in this field is the closed-loop plastic waste-to-olefins process. By chemically converting post-consumer plastic waste into olefins, which are the fundamental building blocks for new plastic products, this technology enables circularity at scale. It also reduces the carbon footprint associated with virgin olefin production. This approach focuses on converting waste plastics into valuable olefins, which serve as the building blocks for producing new plastics and other petrochemical products. This article explores the technological advancements, operational case studies, and best practices in plastic waste recycling using simulation, optimisation, and decarbonisation techniques.

Importance of plastic waste to olefins conversion

Plastic pollution has reached alarming levels worldwide, with millions of tons of waste accumulating in landfills and oceans. Traditional recycling methods have limitations in processing mixed and contaminated plastics, leading to inefficiencies in waste management. Additionally, the olefin industry faces significant energy consumption and carbon emissions challenges, with CO_2 emissions ranging from 0.85 to 1.8 t per ton of ethylene produced.[2] Finding an economically viable and sustainable alternative is crucial for reducing the industry's carbon footprint while maintaining production efficiency.

Several key drivers are accelerating the adoption of PTO conversion technologies, positioning them as a critical solution in the transition toward a circular and low-carbon economy. One of the primary forces is regulatory pressure, as governments worldwide introduce increasingly stringent environmental regulations. These policies are aimed at reducing landfill dependence, cutting greenhouse gas emissions, and promoting resource efficiency – effectively encouraging industries to adopt circular economy practices.

In parallel, market dynamics are reinforcing this shift. The global recycled plastics market is experiencing robust growth, with a compound annual growth rate (CAGR) of approximately 9.5%.[3] This surge is particularly notable in the Asia-Pacific region, where rising demand for sustainable materials and strong manufacturing activity are driving investment in recycling and chemical conversion technologies.

Additionally, corporate and national decarbonisation commitments are influencing strategic decision-making across sectors. As more industries align their operations with net zero targets, the conversion of plastic waste into olefins emerges as a viable and scalable pathway for reducing carbon footprints while recovering valuable resources and advancing sustainability objectives.

Overview of closed-loop plastic waste to olefins

A closed-loop system ensures that plastic waste is continuously processed and reused without loss of material value. Unlike traditional linear models that result in plastic disposal, this approach reintegrates waste-derived olefins back into the supply chain.

The process of converting plastic waste into valuable olefins involves a series of integrated steps designed to maximise waste recovery and ensure product quality, as shown in Figure 1. Initially, plastic waste undergoes collection and sorting, where materials are categorised according to polymer type and contamination levels to ensure feedstock consistency. Following this, the sorted plastics enter the chemical recycling phase, typically through pyrolysis, where thermal cracking breaks down the polymers into pyrolysis oil under controlled conditions. Pyrolysis is a mature thermochemical process increasingly applied to mixed plastic waste (MPW), polyethylene (PE), polypropylene (PP), polystyrene (PS),

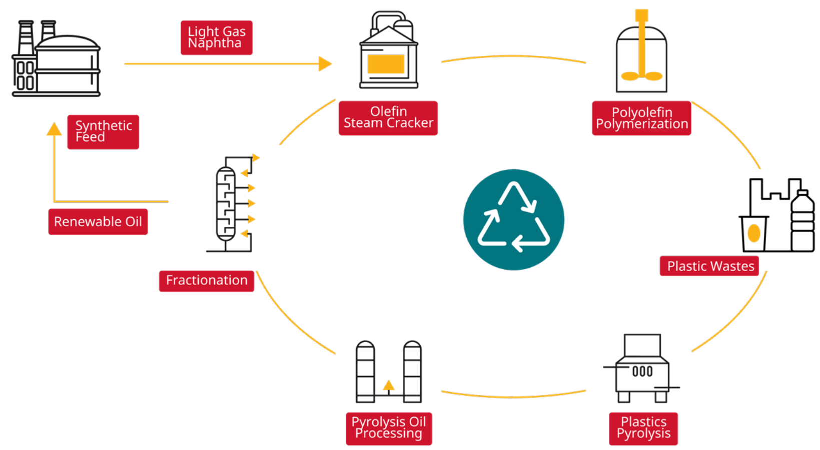

Figure 1. Lifecycle process of plastic waste into olefins and polyolefins.

and polyethylene terephthalate (PET).[4] The feedstock composition strongly influences product yields.

To maintain desirable product yields, it is important to monitor and optimise the pyrolysis reactor's key operational variables, including temperature, residence time, and pressure.

The second step is hydroprocessing the pyrolysis oil. The pyrolysis oil contains impurities that require refining. Advanced hydrotreatment and hydrocracking methods remove contaminants, improving the pyrolysis oil quality.

The third step of the process is steam cracking the naphtha for olefin production. Synthetic naphtha is fed into steam crackers, where it is thermally cracked into valuable olefins such as ethylene and propylene. The efficiency of this process is enhanced by simulation-driven optimisation, which predicts reactor behaviour, coking rates, and energy consumption.

The olefin can be sent for further fractionation and finally to the polyolefin unit for polymerisation. The olefins produced are separated and polymerised to form new plastics, completing the closed-loop cycle. Integrating carbon capture and utilisation (CCU) technologies minimises the overall CO_2 footprint of the process.

The integration of recycled plastic-derived pyrolysis oil into olefin production represents a promising pathway toward more sustainable operations, yet it also presents significant challenges that technologists and operators must address, as summarised in Figure 2.

These challenges include the complex analysis and variability of pyrolysis oil, which consequently affects decisions around necessary downstream processing and feed preparation. Understanding how this unconventional feed affects steam cracker performance – particularly product yield, coking behaviour, and equipment compatibility – is critical to ensuring reliable, efficient operation, including potential burner and convection section upgrades. The performance of the crackers' convection section and the long-chain olefinic content in the pyrolysis oil can impact ethylene and propylene yields, reduce radiation duty, and increase coke formation. Strategies such as blending pyrolysis oil with naphtha and designing furnaces capable of processing wide boiling range feeds help mitigate these challenges.

One of the foremost concerns is the variability and complexity of pyrolysis oil composition. To assess its suitability, a detailed characterisation is essential. This includes analysing boiling point distribution, density, impurity levels, and hydrocarbon composition using paraffins, isoparaffins, olefins, naphthenes, and aromatics (PIONA) analysis. These factors influence how the feedstock behaves during thermal cracking and directly affect product yield, process stability, and fouling tendencies.

A key consideration in the transition to pyrolysis oil is the capability of existing steam cracker furnaces. Many furnaces operating today are designed for traditional light naphtha feedstocks, raising concerns about whether these units can handle the preheating and evaporation requirements of heavier or olefin-rich pyrolysis oils. The convection section's heat transfer efficiency, susceptibility to coking, and the behaviour of the transfer line exchanger under new conditions must all be re-evaluated. If the current design proves inadequate, options include upgrading the existing furnace, introducing feedstock pre-treatment systems, or developing entirely new furnace configurations tailored to the characteristics of pyrolysis oil.

These technical complexities directly impact plant performance. For example, long-chain olefinic content in the pyrolysis oil can reduce ethylene and propylene yields, lower radiant heat duty, and accelerate coke deposition – ultimately shortening furnace run lengths and increasing maintenance frequency. Moreover, blending strategies, such as adjusting the ratio of pyrolysis oil to naphtha, require careful optimisation to maintain desired product slates without compromising equipment integrity.

In this evolving landscape, the technologist's role is central. These experts evaluate how pyrolysis oil will affect overall plant operation and guide decision-making processes that align with both environmental targets and operational constraints. By interpreting complex feedstock behaviour, modelling process impacts, and proposing viable integration pathways, they provide critical insights that support the development of sustainable olefin production systems. In doing so, they help bridge the gap between the ambition of circular economy initiatives and the technical realities of refinery operations.

Successfully integrating recycled pyrolysis oil into olefin production requires a holistic view of feed characterisation, furnace adaptability, and product optimisation under sustainable operation targets.

Figure 2. Plastic-derived pyrolysis oil into olefin.

Methodology

In the pursuit of enhanced process efficiency, simulation and optimisation play a critical role in processing the PTO conversion pathway. Advanced process simulation tools, such as Petro-SIM®, enable precise control and optimisation of key parameters like temperature, pressure, and residence time, ensuring high efficiency, optimal yields, and consistent product quality. By leveraging platforms like Petro-SIM and other advanced modelling environments, operators can proactively address performance limitations and monitor key performance indicators (KPIs) that are often difficult to measure in real-time operations, helping to quickly identify and correct process deviations.

Additionally, decarbonisation strategies, including carbon capture integration and energy recovery techniques, are increasingly incorporated into process models to support low-emission or net zero production goals. This holistic approach not only improves economic viability but also advances environmental sustainability in the PTO transformation process.

A leading petrochemical company implemented a process simulation tool, like Petro-SIM, to enhance the performance of its steam crackers. Applying optimisation strategies, it investigated and analysed the effect of different scenarios related to the energy efficiency and CO_2 emissions reduction of the steam cracker, as follows: changing hydrocarbon feed ratio (S/C), coil outlet temperature (COT), excess air, fuel composition (fuel switching). Optimisation results show energy savings of about 4.6% and emission reduction by 44%, while achieving a marginal gain of about 3.7%.

In this study, the impact of various feed types on KPIs was investigated. To accurately analyse the effect of different feed types on steam cracker performance across various scenarios, individual optimisation was performed, as cracker performance varies with changing process conditions.

Table 1. KPIs for steam cracker

Steam Cracker KPI	Definition	Unit
Severity (P/E ratio)	Ratio of propylene to ethylene production rate	wt./wt.
Energy intensity	Total energy consumption per ethylene + propylene production rate. Total energy consumption = total furnace fuel + electrical consumption – steam export	GJ/m.t. $_{(C2,\ C3)}$
Emission intensity	CO_2 emission generation per ethylene + propylene production rate	t CO_2/t $_{(C2,\ C3)}$

Results

Four different feed scenarios were evaluated to assess the impact of plastic waste integration into olefin production: Case 1: conventional naphtha, Case 2: atmospheric gas oil (AGO), Case 3: (PE + VGO) pyrolysis oil (conversion blending of PE and vacuum gas oil (VGO) to pyrolysis oil), Case 4: (PE + VGO) pyrolysis oil upgraded via hydrocracking (HDC) to naphtha.

The KPIs for each case are summarised in Table 1, with results shown in Table 2.

Ethylene and propylene yields are crucial metrics for evaluating cracker performance under various feed types. Case 4, involving hydrocracked pyrolysis oil upgraded to naphtha, achieved the highest ethylene + propylene yield at 40.2 wt%, outperforming both traditional fossil-based feeds (naphtha and AGO) and untreated pyrolysis oil. In contrast, Case 3 (direct pyrolysis oil) showed a lower yield of 35.3 wt%, indicating that upgrading significantly enhances olefin production efficiency.

Severity, expressed as the propane-to-ethylene (P/E) ratio, reflects cracking severity and feedstock reactivity. Case 3 demonstrated the lowest severity at 0.43 wt/wt, suggesting a lower severity requirement when using untreated pyrolysis oil. In comparison, traditional naphtha and AGO required higher severity levels (0.55 - 0.558 wt/wt), while the hydrocracked case (Case 4) exhibited slightly higher severity (0.57 wt/wt) relative to untreated pyrolysis oil.

Radiation efficiency, a measure of furnace heat transfer performance, was relatively consistent across the cases, ranging from 38.63% to 41.7%. The highest radiation efficiency was observed with conventional naphtha (41.7%), whereas hydrocracked pyrolysis oil in Case 4 had the lowest radiation efficiency (38.63%), likely due to differences in feed physical properties affecting heat transfer characteristics.

Energy intensity, defined as the energy consumption per unit of product, varied across feedstocks. Case 2 (AGO) demonstrated the lowest energy intensity at 18.36%, followed closely by Case 1 (naphtha) at 19.39%. Plastic-derived feeds exhibited slightly higher energy intensities, with Case 3 at 19.25% and Case 4 at 19.25%, reflecting the additional energy demands associated with processing pyrolysis-derived materials.

Emission intensity followed a similar trend to energy intensity. AGO (Case 2) achieved the lowest emission intensity at 0.71, while naphtha exhibited the highest at 0.78. Cases 3 and 4, representing the pyrolysis oil routes, fell in between, with emission intensities of 0.74 and 0.70, respectively. The slight reduction in emissions for Case 4 indicates that upgrading pyrolysis oil not only improves product yields but can also contribute to lower carbon intensity compared to traditional fossil feeds.

The results demonstrate that incorporating plastic waste-derived pyrolysis oils – particularly after upgrading

Table 2. Impact of feedstock type on steam cracker furnace KPIs

KPIs	Naphtha	AGO	(PE + VGO) pyrolysis oil	(PE + VGO) pyrolysis oil + HDC → naphtha
Ethylene + propylene yield	36.3	36.8	35.3	40.2
Severity P/E	0.55	0.558	0.43	0.57
Radiation efficiency	41.7	39.85	40.0	38.63
Energy intensity	19.39	18.36	19.25	
Emission intensity	0.78	0.71	0.74	0.70

– offer a promising pathway toward sustainable olefin production. Upgraded pyrolysis oil (Case 4) outperformed traditional feeds in olefin yield while maintaining competitive energy and emission intensities. However, achieving comparable furnace performance and managing feed properties remain important considerations for successful large scale implementation.

Challenges and future directions

Despite its promise, PTO pyrolysis faces several challenges. One major hurdle is the complexity of feed combinations and the intricate reaction network involved. Converting mixed plastic waste into monomers and pyrolysis oil requires a deep understanding of the underlying reaction mechanisms. Another challenge is the uncertainty surrounding technology adoption. The absence of a universally accepted pyrolysis technology introduces investment risks for industry players. Finally, economic viability remains a significant concern. The cost of producing recycled olefins must be competitive with that of fossil-derived alternatives for the technology to gain broader traction.

Outlook

As the European Climate Law targets carbon neutrality by 2050 and emphasises improved plastic waste management, tomorrow's refineries and petrochemical plants will increasingly shift to non-fossil feedstocks – including plastic and municipal waste, biomass, and captured CO_2.[5] Within this transition, plastic pyrolysis is positioned as a core process integrated alongside CO_2 capture, Fischer-Tropsch synthesis, and biomass gasification.

Conclusion

The PTO process presents a viable solution for tackling plastic pollution while enhancing sustainability in the petrochemical industry. By leveraging advanced simulation and process optimisation technologies, industries can improve efficiency, reduce emissions, and contribute to a more sustainable future. With continued research, policy support, and investment in innovative recycling technologies, plastic waste can be transformed from an environmental burden into a valuable resource for the global economy.

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