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Integrating Chemical Recycling into Brownfield Processes: Waste Polyethylene Pyrolysis and Naphtha Steam Cracking

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ABSTRACT

In this study, we evaluate the economic and environmental impacts of integrating waste polyethylene (PE) pyrolysis with naphtha-based steam cracking for 660 Mt/y ethylene production. We compare six integration scenarios to both business-as-usual (BAU) steam cracking and greenfield waste PE pyrolysis plant. We perform process simulations and equipment design in Aspen Plus® V12, followed by a techno-economic analysis (TEA) and a life-cycle assessment (LCA. The integration capacity we considered corresponds to one full-capacity PE pyrolysis furnace, reducing naphtha feed by 7% in BAU steam cracking. Through the TEA, we identify the most cost-effective scenario by merging the PE pyrolysis gas with the steam cracker furnace outlet after preheating the PE feed. This integration reduces production costs by 6.46MM€/y, improving costs a 0.3% compared to BAU and 30% compared to the pyrolysis greenfield design. LCA results show that the greenfield pyrolysis plant achieves the lowest global warming potential (GWP), reducing emissions by 14% compared to BAU. Among the integration scenarios, lowest GWP occurs when PE pyrolysis gases, also with feed pre-heating, merge before the main compressor train, obtaining a 0.12% GWP reduction compared to BAU. This analysis highlights the potential of introducing circular technologies in existing plants to progressively shift from fossil fuel usage.

Keywords: process integration, circular economy, ethylene, sustainable feedstock, chemical recycling

INTRODUCTION

Circularity in the chemical industry is essential for achieving sustainability, especially as the sector moves away from linear, fossil-based production models. Circular processes aim to minimize waste, optimize resource use, and closing carbon loops by utilizing renewable and waste resources. This approach is a key strategy to address both environmental and economic challenges [1].

Plastics account for the largest share of oil usage outside fuel production [2]. Their widespread use has led to vast global waste accumulation, particularly from single-use packaging. In the European Union, packaging represents approximately 40% of plastic demand, generating large volumes of waste that often escape effective management systems [3].

Compared to disposal methods like landfilling and incineration, recycling faces challenges related to cost and material quality. Mechanical recycling is one of the least energy-intensive options, but it is limited by the number of cycles the material can endure [4]. In contrast, chemical recycling is a more expensive alternative but avoids degradation by breaking plastics down into their monomers [5].

In Europe, the most produced polymer is the polyethylene (PE) families of plastics, with a share of 22% of the production [3]. Given that PE is the most widely produced plastic and is predominantly used in single-use packaging, it represents the most promising candidate for chemical recycling.

Among the diverse chemical recycling methods, pyrolysis is the most researched since it converts plastic into lower molecular weight products [5], which allows the recovery of monomers and the closure of carbon loops.

Waste PE Pyrolysis plants are already existing at a commercial scale, and many companies have announced collaborations between projected pyrolysis plants and their refineries [5]. However, repurposing existing infrastructure for circular processes offers a more cost-

Table 1: Integration scenarios summary

Scenario	Integration concept	Pyrolysis product feed location
1.a	Waste LDPE pyrolysis integrated without the need of additional equipment	Outlet of naphtha furnace reactor
2.a	- Increase the heat recovery of pyrolysis gas to generate power. The absence of heavy component in the product gas, allows more efficient cooling. Heat exchanger(s) EX1-P perform this task. - Duty reduction in primary fractionator (T1), bypassing the unit since pyrolysis gas contains no heavy components	After primary fractionator
3.a	- All from 2.a - Reduce the energy requirements of the distillation units for light components by separating the C_4+ components prior to integration. Flash separator SEP3-P performs this task, with the aid of compressor C2-P to reach the adequate pressure for the integration point, and heat exchanger EX2-P to lower the gas temperature to allow gas to condense in the flash drum.	Intermediate stage compressor and T7 feed
1.b, 2.b, 3.b	Use heat from the pyrolysis gas to preheat waste PE feed in the first pyrolysis (low temperature) reactor	To corresponding scenario (1.a-3.a)

effective and resource-efficient solution [6]. This study explores different integration strategies for incorporating PE pyrolysis into existing ethylene production. The proposed scenarios are compared against both a greenfield design of waste LDPE pyrolysis plant and naphtha steam cracking.

APPROACH AND METHODOLOGY

Integration Strategy

We first replicated the design from Somoza et al. [7] for a greenfield ethylene plant based on waste PE pyrolysis, and the design from Spallina et al. [8] for a brownfield olefins plant based on naphtha steam cracking (SC). As reference for pyrolysis of PE, we used the conversion and yields from Kannan et al. [9], whose experiments focused on maximizing the ethylene yield in the flash pyrolysis of waste low density polyethylene (LDPE).

Both designs share a substantial similarity, due to their comparable main reactor outlets, since both processes' main products are polyolefins. Both plants can be briefly described with their major common elements by having the high-temperature reactor, a following cooling stage, a compressor train to raise the pressure enough to enable the separation of the light hydrocarbons and the consequent distillation column cascade. The SC contains additional processes, such as a removal of water and C_9+ fraction preceding the compression train, and intermediate reaction steps between the cascade distillation, with the aim to increase the ethylene and propylene yields.

Given these similarities, we developed six integration scenarios to incorporate LDPE pyrolysis into an existing steam cracking process. The goal is to achieve a competitive cost compared to the grass-roots design of a standalone pyrolysis plants, and with the second aim to reduce the cost of ethylene production by steam cracking. A brief summary of the proposed integration scenarios is provided in Table 1.

Figure 1 illustrates the SC layout alongside with the proposed integration scenarios, highlighting the similarities between the SC and the greenfield pyrolysis design. The color coding emphasizes the units that perform equivalent tasks in the waste pyrolysis plant design.

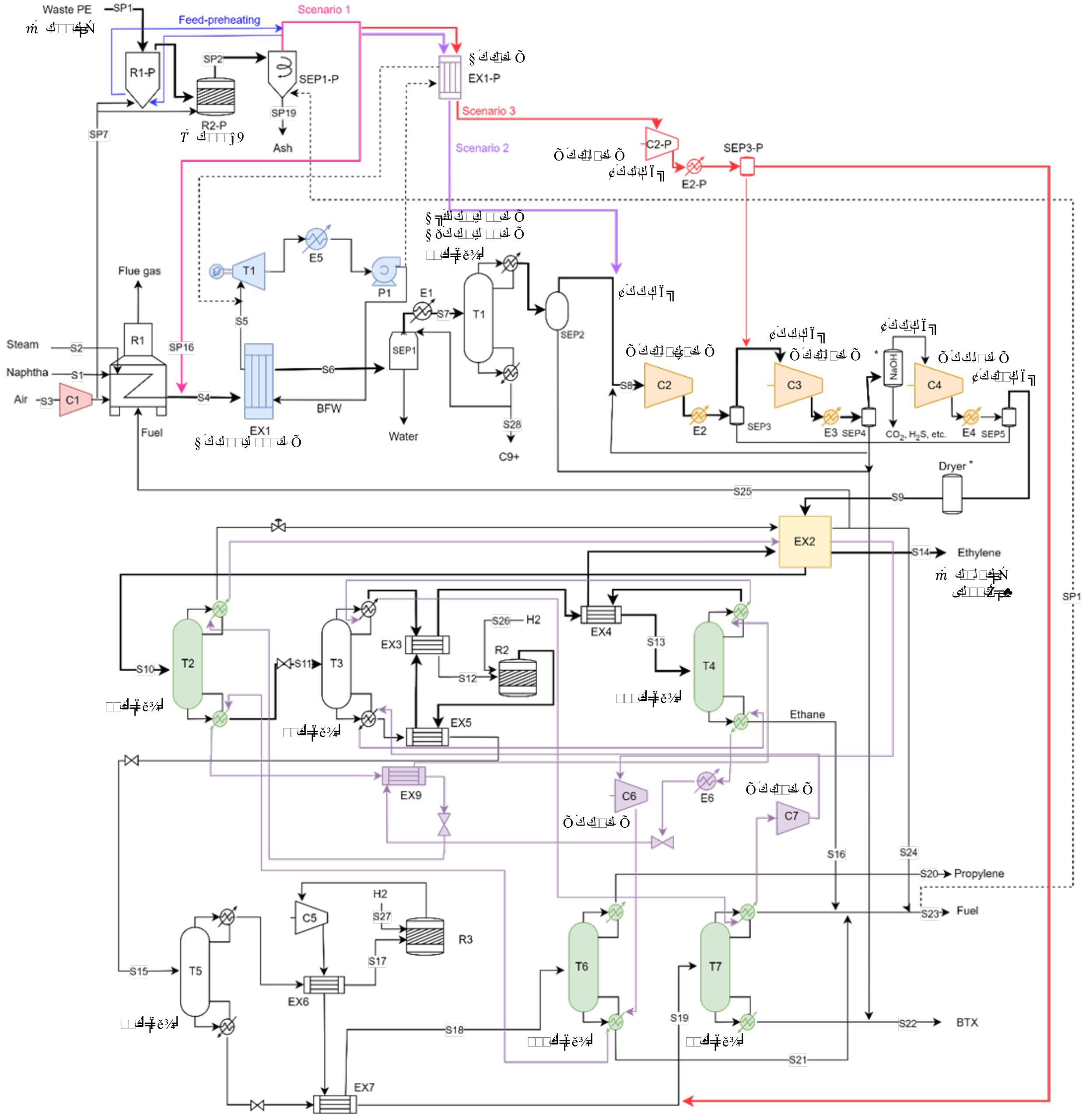
Simulation and Assessment Methods

We performed process simulations and equipment design for both independent plant designs and the integration scenarios, in Aspen Plus® V12, using PolyNRTL as property package, to enable LDPE to be handled in mass and energy balances.

For each integration scenario, we conducted a comprehensive techno-economic assessment (TEA) and life cycle assessment (LCA) to evaluate both the economic viability and environmental impact of incorporating LDPE pyrolysis into the naphtha steam cracking process.

For the TEA, we followed the cost evaluation guidelines from Towler and Sinnott [10], supplementing with additional sources [8] [11] for equipment not covered in [10].

For the LCA, we applied the ISO 14040:2006 standards for life cycle assessment methodology, using the Ecoinvent3 database in SimaPro software to assess environmental impacts, focusing primarily on Global Warming Potential (GWP).



* Not consider in the simulation, economic and environmental analysis

Figure 1: Steam Cracking plant layout with PE pyrolysis integration scenarios. Colored units correspond to the coinciding units in a standalone PE pyrolysis plant, highlighted for similarity.

RESULTS AND DISCUSSION

Techno-Economic Assessment (TEA)

To compare both standalone plants, we allocated the cost of production per kg of ethylene. The feed from the greenfield design for a waste PE pyrolysis plant, corresponds to one full-capacity pyrolysis furnace, representing approximately a 7% of the steam cracking naphtha feed. Using this cost allocation, we estimate that the standalone waste PE pyrolysis plant produces ethylene at 1.045€/kg of ethylene, while the cost at the steam cracking plant is 0.7429€/kg of ethylene. This significant cost difference is what motivated this study.

For the integration scenarios, we set the ethylene production capacity to 660Mt/y. Introducing one LDPE pyrolysis furnace at full capacity, the naphtha feedstock can be reduced by the aforementioned percentage.

Figure 2 illustrates the cost differences between the average of all integration scenarios and the business-as-usual (BAU) standalone steam cracking process. Since ethylene production remains fixed, this output remains unaltered across all scenarios.

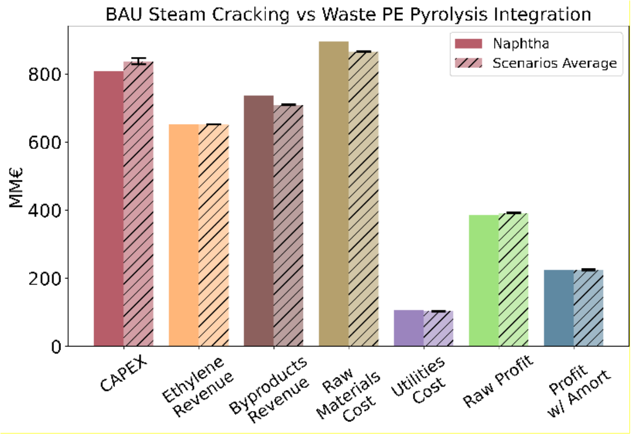


Figure 2. Comparison of business as usual steam cracking vs average of integration scenarios.

Figure 3 breaks down the main costs and revenues for each scenario, using the BAU steam cracking as reference. The ethylene production (and revenue) remains

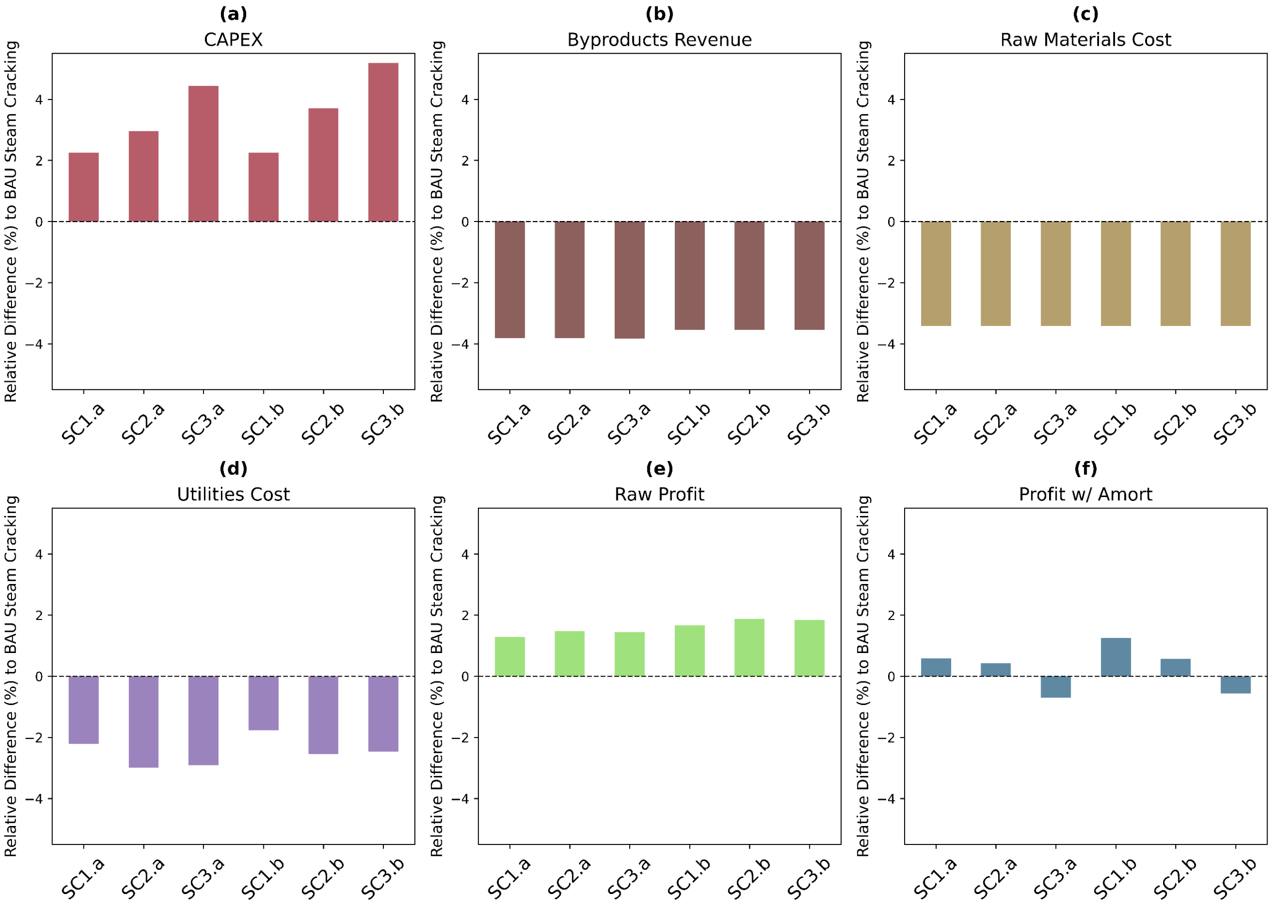


Figure 3: Comparison of economic and operational metrics for naphtha-based steam cracking and waste PE pyrolysis scenarios

constant across all scenarios. However, the revenue from other products decreases in all integration cases. This reduction occurs because (high temperature) flash pyrolysis is targeted towards maximizing ethylene yield [9]. Among the byproducts, propylene production is the least affected, with only a 0.82% reduction (2.4M€/y) from the BAU case. The revenue from C_{9+} stream decreases by 7.5% (2.4M€/y), while the BTX revenue drops by 3.3% (7.7M€/y), with minimal differences between the integration cases. Fuel products experience the largest revenue loss, averaging 11% (12.6M€/y) in cases without feed pre-heating and 10% (10.6M€/year) in cases with pre-heating. Overall, the average reduction in revenue across the scenarios is a 3.6% (27M€/y).

Despite revenue losses, utility expenses decrease by approximately 5% (3M€/y) across all integration scenarios. Scenario 2 achieves greater utility savings than Scenario 1, as expected. The utilities reduction for Scenario 3 are, however, lower than Scenario 2, due to the low substitution ratio that hinders the potential energy savings in distillation. This trend applies to both cases with and without feed pre-heating.

Differences in feedstock prices result in a yearly cost reduction of 3.6% (30M€/y) for a 7% of reduction in naphtha consumption. However, revenue losses offset most of this benefit. In the best-performing scenario (Scenario 1 with feed pre-heating), this translates into an overall raw profit increase of 1.67% (6.5M€/y), primarily due to lower utility costs. After accounting for the CAPEX amortization of the equipment and overhead expenses, the final cost of ethylene production drops minimally to 0.7407€/kg, compared to 0.7429€/kg of BAU case.

Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) evaluates the Global Warming Potential (GWP) across different configurations: BAU steam cracking, greenfield plant of waste LDPE pyrolysis, and six integrated scenarios.

As shown in Figure 4 a), the greenfield pyrolysis process has a lower GWP than the BAU naphtha steam cracking (1.243 vs. 1.441 kg CO_2 eq./kg ethylene), largely due to reduced reliance on fossil naphtha. In the naphtha steam cracking process, the highest emissions are from fossil feedstock (35% of total) and direct emissions from furnace combustion (28%). In contrast, standalone pyrolysis sees direct emissions contribute approximately 54% of its GWP due to higher energy demand, with electricity also a significant factor (26%).

The integration scenarios, which substitute only 7%

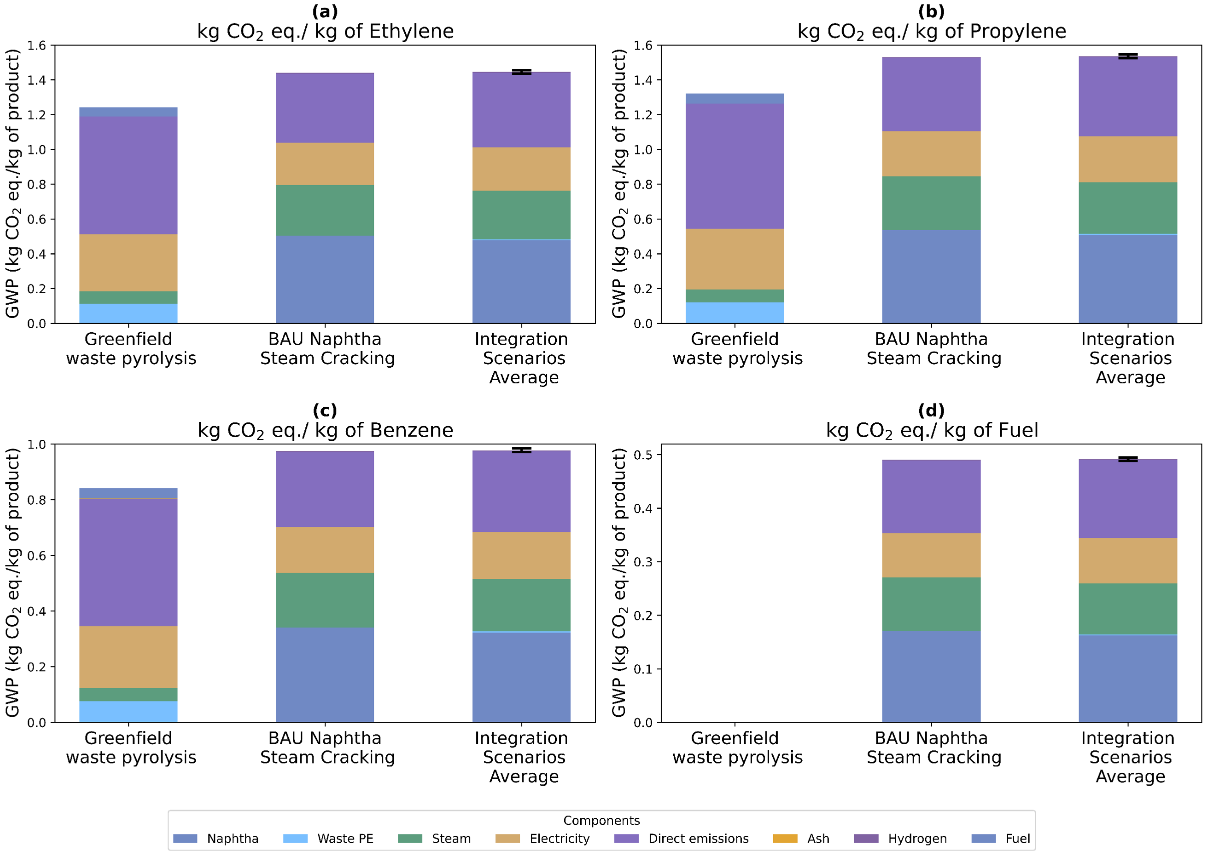


Figure 4: Comparison of LCA results of Standalone plants and average of integration scenarios

of naphtha with pyrolysis gas, yield marginal GWP reductions. Although they reduce GWP contributions from naphtha, steam, and hydrogen, these benefits are partially offset by increased direct emissions and electricity use. Among the integration options, Scenario 2.b achieves the lowest GWP (1.439 kg CO_2 eq./kg ethylene), demonstrating that preheating lowers emissions. Overall, all products—ethylene, propylene, BTX, and fuel—exhibit similar GWP trends across the processes.

From the rest of the mid-point categories we evaluated in the LCA analysis, fossil resource scarcity is the category most positively impacted by pyrolysis integration scenarios. All of them show a reduction respect to BAU steam cracking, with also Scenario 2.b achieving the highest reduction of a 4.8%(from 1.817 kg of oil eq. to 1.729 kg of oil eq.).

CONCLUSION

A 7% of substitution of naphtha with pyrolysis gas offers an economically feasible way for the industry to gradually introduce sustainable technology and gain operational experience, however, the cost improvements remain marginal. However, the key factor that makes pyrolysis of waste plastic attractive is the price gap between naphtha and waste plastic.

In this study, we identified Scenario 1 with feed preheating the most economically viable integration option, achieving annual operating cost savings of 6.5 million euros compared to business as usual operation of steam cracking.

From an environmentally perspective, the pyrolysis process has a lower GWP than both naphtha steam cracking and integration scenarios. Among the integration options, Scenario 2 with feed preheating achieves the lowest GWP at 1.439 kg CO_2 eq./kg C_2H_4, demonstrating that heat integration is key to reduce environmental impact.

The divergence between economic and environmental assessments highlights the challenges of integrating waste plastic pyrolysis at low substitution ratios. Nevertheless, since the factor that determines Scenario 1.b as the best candidate in economic terms is the low CAPEX, a higher substitution ratio might favour Scenario 2.b since it showed the highest raw profits among the integration possibilities.

In addition, LCA indicators support Scenario 2.b as the best candidate, however, since the waste PE pyrolysis is carried at higher temperatures compared to steam cracking, increasing the share of PE pyrolysis integrated might change the preferred integration scenario, and affect sustainability indicators.

Therefore, a study of higher substitution ratios is highly recommended.

REFERENCES

1. J. Slootweg. Sustainable chemistry: Green, circular, and safe-by-design. OneEarth, 7, 5, 754 – 758 (2024).
2. World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company, The New Plastics Economy: Rethinking the future of plastics (2016).
3. European Green Deal, Putting an end to wasteful packaging, boosting reuse and recycling(2022).
4. J. Garcia, M. Robertson. The future of plastics recycling. Science, 358, 6365 (2017).
5. H. Li, et al. Expanding plastics recycling technologies: chemical aspects, technology status and challenges. Green Chemistry, 24, 8899 – 9002 (2022).
6. K. Télessy, L. Barner, F. Holz. Repurposing natural gas pipelines for hydrogen: Limits and options from a case study in Germany. International Journal of Hydrogen Energy, 80, 821 – 831 (2024).
7. A. Somoza -Tornos, A. Gonzalez-Garay, C. Pozo, M. Graells, A. Espuña, G. Guillén-Gosálbez. Realizing the Potential High Benefits of Circular Economy in the Chemical Industry: Ethylene Monomer Recovery via Polyethylene Pyrolysis. ACS Sustainable Chem. Eng., 8,9, 3561 – 3572 (2020).
8. V. Spallina, I. Campos Velarde, J.A. Medrano Jimenez, H. Reza Godini, F. Gallucci, M. van Sint Annaland. Techno-economic assessment of different routes for olefins production through the oxidative coupling of methane (OCM): Advances in benchmark technologies. Energy Conservation and Management, 154, 244 – 261 (2017).
9. P. Kanan, A. Al Shoaibi, C. Srinivasakannan. Temperature effects on the yield of gaseous olefins from waste polyethylene via flash pyrolysis. Energy & Fuels, 28(5): p/ 3363-3366 (2014).
10. G. Towler, R. Sinnott. Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design. Ed: Third edition. Butterworth-Heinemann, Elsevier. (2021).
11. R. Turton, J. Shaeiwith, D. Bhattacharyya,W.B. Whiting. Analysis, Synthesis and Design of Chemical Processes. Ed: Fifth Edition (2018).