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Techno-Economic Analysis of Polypropylene Recycling Through Catalytic Pyrolysis: FCC Catalysts in Batch Reactors

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ABSTRACT

The short lifespan of plastics, particularly in the packaging sector, results in rapid accumulation of plastic waste, with polypropylene being a major contributor. Chemical recycling is gaining increasing attention as a strategy in managing plastic waste, facilitating the transition from a linear to a circular economy. This study presents a comprehensive techno-economic analysis (TEA) of a polypropylene recycling process via pyrolysis designed for a facility in the Southern United States, processing 300 kt of waste annually. The process was modeled using Aspen Plus for energy and mass balance and Aspen Process Economic Analyzer for capital cost estimations, with additional manual calculations for operating costs. Economic viability was assessed through net present value (NPV), internal rate of return (IRR), and Minimum Fuel Selling Price (MFSP). Results show that recycling polypropylene via catalytic pyrolysis is economically viable, with a NPV exceeding $330 million and an IRR of 29.6% over a 30-year lifespan. The base case (300 kt/year) demonstrates the most promising financial viability, with high IRR and favorable ROI. Sensitivity analysis highlights the impact of market factors and operational costs on the economic viability of the process. Equipment cost breakdown shows that the "Storage" area, particularly the costs associated with hydrogen storage, is a significant contributor to the total capital investment. This finding highlights the importance of on-site hydrogen production to further reduce capital investments and operational costs.

1 | Introduction and Motivation

Polypropylene (PP) is a widely used thermoplastic polymer with diverse applications in packaging, textiles, automotive components, and various consumer products. As the global production of plastic continues to rise, there is a growing concern about its environmental impact, particularly due to the challenges posed by plastic waste, with over 60 million tons generated annually worldwide [1]. Recycling offers a promising solution to mitigate these issues, and PP recycling, in particular, has gained attention due to the material's prevalence in everyday items.

Currently, the plastic waste processing sector predominantly relies on mechanical recycling for its operational simplicity. Although theoretically this method should be applicable to all types of thermoplastics, polyolefins and polystyrenes face challenges in practical implementation [1]. Mechanical recycling often leads to downcycling. Thermal-mechanical degradation during the recycling process, along with the presence of contaminants, adversely impacts the mechanical properties and quality of recycled plastics, thereby limiting the utilization of recycled material and making them less suitable for high-quality applications [2–4]. To overcome these challenges associated with mechanical recycling

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of polyolefins, chemical routes are being studied and developed extensively to enable the production of value-added chemicals from plastic wastes and among various chemical/thermal recycling methods, pyrolysis is the most widely studied approach due to its ability to process mixed and contaminated plastics and produce valuable fuels and chemicals [5].

Techno-economic analysis (TEA) plays a crucial role in evaluating the feasibility and economic sustainability of recycling processes. In this study, we conducted a thorough TEA of the catalytic pyrolysis process for PP recycling while investigating the influential economic factors including production costs, market dynamics, and potential revenue streams. This study aims to provide a comprehensive perspective on the economic limitations, advantages, disadvantages, hotspots, and guidelines for policymakers and researchers in the field of the plastic circular economy.

2 | Review of Related Work

Economic calculations have indicated that the transformation of waste high-density polyethylene into monomers, liquid fuels, and aromatics can yield an Internal Rate of Return (IRR) exceeding 31% [6]. Bora et al. determined that the transformation of waste PP into fuel through fast pyrolysis has the potential to yield a cumulative Net Present Value (NPV) of $149 million while the economic performance of the system was primarily influenced by feedstock price, discount rate, and plant lifespan [7]. Scaling up the plant capacity has been shown to substantially reduce the production cost of fuels, improving the overall process economics [8]. Several studies also highlighted the impact of product distribution, plastic type, and other operating conditions on the process economic [9–11].

Numerous studies with a focus on product distribution and thermogravimetric analysis have been conducted on the pyrolysis of PP, in virgin or waste form, either as a single stream or in plastic blends [12–18]. Table 1 provides a summary of experimental studies on PP pyrolysis. Pyrolysis can be conducted over a wide range of operating temperatures (from 400°C to above 700°C). While higher temperatures yield more valuable aromatics, this study focuses on producing liquid oil as the primary product and operates at lower temperatures. Future studies will explore the process economics of maximizing chemical production and compare these scenarios with the current baseline that prioritizes oil production. As a starting point in this analysis, we used the operating conditions and product distributions reported by Achilias [12] as the baseline for our process since the solid fraction value falls in the middle of the range found in the literature. This approach allows us to investigate the impact of operating conditions and product distributions on the economic sustainability of the process in later stages of our study. Additionally, the reaction temperature in this study was at the lower end of the range observed in the literature, resulting in the lowest reaction energy requirement and potentially the lowest environmental impact.

With growing interest in evaluating the economic aspects of plastic recycling through pyrolysis, there is a requirement for more comprehensive Techno-Economic Analysis (TEA) studies. To fulfill this need, we have designed an in situ catalytic pyrolysis process for PP recycling and performed a comprehensive techno-economic analysis (TEA) to evaluate the viability of the process. This analysis also illustrates the impact of various contextual parameters (plant size, operating time, transportation, storage time, etc.) on the plant's economic feasibility.

3 | Technology Approach

For plant capacity and location, we have considered a grassroots, centralized facility located in the Southern United States where approximately 300 kt (kt) of waste PP are generated annualy [19, 20]. The feedstock for this process is assumed to be the single stream waste PP bales, sourced from Material Recovery Facilities (MRFs). Although these bales may contain various impurities, ranging from organic matter to other polymers and metals found in multilayer packaging, which can affect product distribution, we relied on the product distributions reported in the literature regarding the pyrolysis of PP. This process consists of six main areas: feedstock handling, pyrolysis, separation and purification, hydrotreatment, refrigeration, and storage (Figure 1). The products include ethylene and propylene monomers, gasoline-range and diesel-range blend stocks, and combustible gas. Pyrolysis is conducted in three parallel batch reactors containing fluid catalytic cracking (FCC) catalyst at 450°C and 1 bar, following the operating conditions (in pyrolysis area) and product distribution specified in Achilias' work [12]. Offsite natural gas, along with combustible gas generated onsite, is used to provide the required energy in the reactors for PP pyrolysis. The resulting hydrocarbon vapors are cooled and separated using flash separators and distillation columns. Light

TABLE 1 | Summary of studies on PP pyrolysis.

References	Temperature	Catalyst	Sample size/ throughput	Carrier/fluidizing/ reactive gas	Products
Achilias et al. [12]	450°C	FCC catalyst	1.5 g	Nitrogen	6% gas, 67% oil, 27% char
Kassargy et al. [13]	500°C	USY zeolite	3.1 kg/h		19% gas, 80% oil, 1% char
Predel et al. [14]	510°C	—	1–3 kg/h	Cycled pyrolysis gases	7% gas, 36% oil, 57% wax+char
Williams et al. [15]	500°C	—	30–40 g	N_2—H_2	5% gas, 95% oil

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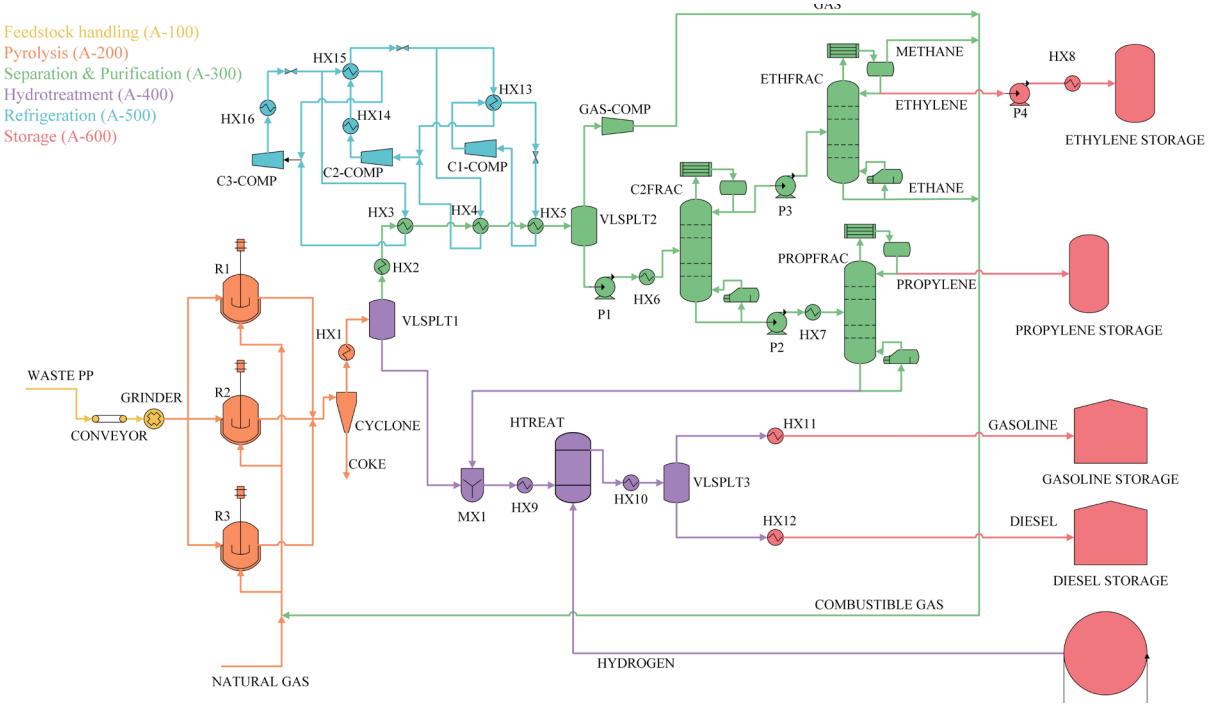


FIGURE 1 | Process flow diagram of polypropylene waste recycling through catalytic pyrolysis.

and heavy fuel blends are further upgraded through hydrotreating. The process schematic is shown by Figure 1.

Aspen Plus was used for process synthesis, equipment sizing, and energy and mass balance calculations. Solid components in this simulation were modeled as "conventional solid component", while the remaining hydrocarbons were modeled as conventional chemicals using the Aspen database. It is assumed that the energy required for cracking PP is similar to that of polyethylene due to their approximately equal bond dissociation energies and relatively similar thermal degradation characteristics and mechanisms [21]. Using literature data with minor modifications based on the heat capacity differences of the two polymer types and their different operating temperatures, the total required energy for reaction is estimated to be approximately 1.1 MJ/kg of PP, following the approach detailed by Gao [22].

Aspen Process Economic Analyzer (APEA) was used for capital cost estimations. To calculate operating costs, fixed operating costs (such as maintenance costs, overhead charges, etc.) were estimated using APEA, while utility costs, feedstock price, and transportation costs were determined manually. All capital and operational costs in this TEA analysis were updated by cost indices. The profitability was assessed using three indicators including NPV, IRR, and Minimum Fuel Selling Price (MFSP).

4 | Discussion

4.1 | Process Simulation and Economics Results

Table 2 shows the mass balance of the base case using Aspen Plus. The flow rates utilized in the simulation were selected to ensure that, over a 7920-h operational year (24 h × 330 days), the plant's processing capacity would consistently maintain at 300 kta of waste PP. The ASPEN simulation shows that, under the selected operating conditions, the primary oil products, gasoline and diesel, account for 38.6 wt% and 59.8 wt% of the total production, respectively. Ethylene, propylene, and combustible gas together make up only 1.6 wt% of the total production. The combustible gas produced during the process mainly consists of CH4 and C2H6, serving as an internal source for heat generation. In addition to the organic contamination, the coke formed during the process contains heavy metals [23]. This is primarily due to two main reasons: firstly, heavy metals such as arsenic, cadmium, chromium (VI), and lead are widely utilized in additives and catalysts during polymer manufacturing [24]. Secondly, aluminum, although not a heavy metal, is included in some lists of toxins and is directly used in packaging as a barrier layer [25]. Consequently, heavy metals become an inherent

TABLE 2 | Baseline process input and output.

Stream	Type	Flow rate (k ton/year)
Waste PP	Feedstock	300
Hydrogen	Feedstock	1.7
Chemical grade ethylene	Product	0.05
Chemical grade propylene	Product	3.1
Gasoline	Product	85.9
Diesel	Product	133
Combustible gas	Product	0.35
Coke	Waste	79.3

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part of the feedstock, accumulating in the coke formed during pyrolysis. Therefore, in this study, we categorized coke as hazardous waste, necessitating special handling and disposal measures to ensure environmental safety, which imposes additional operational costs rather than providing a credit in the process. Ethylene and propylene have chemical grade purities higher than 95%, making them suitable substitutes for crude oil-derived counterparts. The average molecular weights of gasoline and diesel streams in this process are 114.9 g/mol and 213.5 g/mol, respectively, within the range typical of gasoline and diesel fuels [26].

Results show that with a total equipment cost (which also includes costs associated with installation) of $188 million, the "Storage" area, which includes hydrogen and final products storage, has the highest contribution to the total equipment cost (Figure 2A). Designed for a 4-week storage duration, based on design heuristics [27], the three spherical hydrogen storage tanks alone cost more than $180 million. This suggests the importance of incorporating on-site hydrogen production in future plant designs, particularly for centralized large-capacity recycling plants. This would not only eliminate the need to purchase hydrogen, but also reduce the required storage duration and size, leading to substantial reductions in capital investments. While "Storage" section has the highest contribution to the total capital investment, "Pyrolysis" and "Hydrotreatment" areas are the major contributors to the annual operational cost (overall utility and catalysts costs), as shown in Figure 2B.

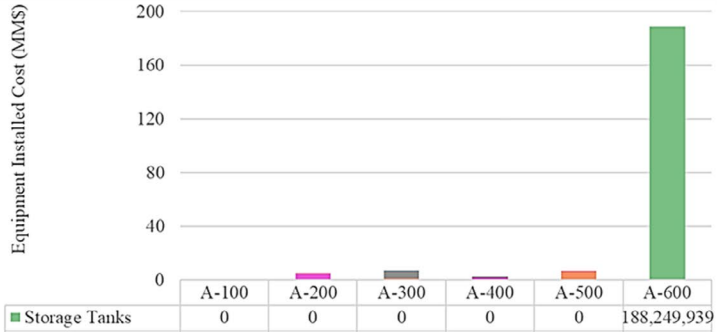
Figure 3A shows the annual operational cost breakdown. The "Raw material & waste" category, which includes the purchase costs of feedstocks (waste PP and hydrogen) and catalysts (FCC for pyrolysis and sulfided Co-Mo for hydrotreating), and waste (coke) handling expenses. "Transportation" cost includes the shipping expenses of hydrogen and waste PP to the production sites. These two categories account for approximately 87% of the total operational costs. The transportation costs for hydrogen and waste PP were determined by assuming a delivery and dispensing cost of $11.6/kg for hydrogen and $0.42/(ton.mile) for hauling waste PP [28–30], assuming an hauling distance of 150 miles. Meanwhile, the "Raw material & waste" cost breakdown revealed that waste PP purchase cost dominates this category with more than $54 million (out of ~80 million), as shown in Figure 3B. Figure 3C presents an overview of the utilities in the process. Natural gas, electricity, and high-pressure steam are responsible for 31.3%, 29.9% and 23.9% of total utility costs, respectively.

Table 3 shows the summary of economic calculations for the base case capacity of 300 kta. For this analysis, the purchase cost of waste PP was assumed to be $181/ton [31] in the baseline economic calculation, aligning with the average market price reported in 2022 [32, 33]. Discounted cash flow analyses were used to estimate profitability. A tax rate of 26% with a 7-year MACR [34] (Modified Accelerated Cost Recovery) depreciation method was used for cash flow analysis. The results indicate that over the 30-year lifespan, the plant has the potential to generate revenue with an NPV over $330 million while having an IRR as high as 29.6%. For the refinery described here, the MFSP is $2.4/GGE (GGE: Gasoline Gallon Equivalents [35]).

4.2 | Sensitivity Analysis

Figure 4 illustrates how variations in major parameters impact the economics of the process. Priority was given to economically and operationally significant variables, such as feedstock purchase and transportation costs, product prices, and main product yields (Figure 5), since these factors commonly drive uncertainty in TEA studies [10, 36–38]. Additionally, parameters such as utility costs were included for their potential to offer valuable insights, even though their variability is low and their impact on profitability is minimal. The IRR is particularly sensitive to the sale prices of liquid fuels (diesel and gasoline) and capital investment, with a% ± 20% variation

(A) Total equipment cost breakdown based on process area



	A-100	A-200	A-300	A-400	A-500	A-600
Storage Tanks	0	0	0	0	0	188,249,939
Flash drums	0	0	251,114	499,986	0	0
Pumps	0	0	204,707	0	0	373,764
Grinder	238,497	0	0	0	0	0
Heat exchangers	0	190,913	754,804	280,937	723,325	326,947
Conveyors	191,940	0	0	0	0	0
Reactor and cyclon	0	4,119,473	0	1,598,928	0	0
Distillation columns	0	0	3,740,642	0	0	0
Compressors	0	0	1,425,890	0	6,064,264	0

(B) Variable operational costs breakdown based on process area

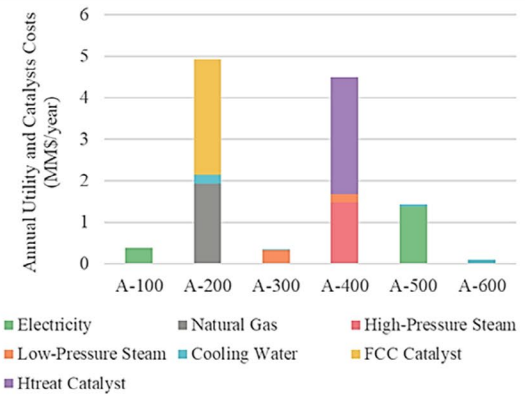
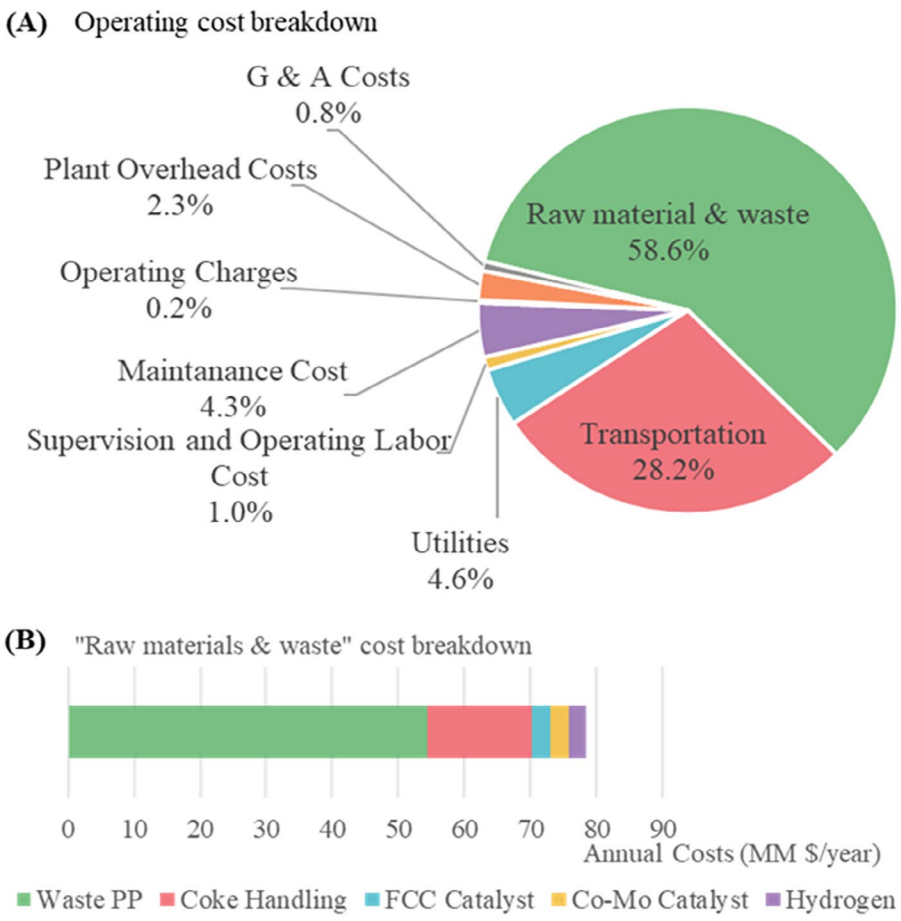


FIGURE 2 | Breakdown of contributions to total equipment cost and variable operational costs based on process area.

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(C) Utility consumption rates and costs

	Rate	Annual cost
Electricity	2193 kW	$1,845,741/year
Cooling Water	1148 m^3/h	$395,348/year
Steam @100PSI	2665 kg/h	$519,339/year
Steam @400PSI	5263 kg/h	$1,475,567/year
Natural gas	39.9 GJ/h	$1,930,975/year

FIGURE 3 | (A) annual operational cost breakdown, (B) "Raw material & waste" cost breakdown, and (C) overview of the utilities.

TABLE 3 | Summary of economic calculations for base case scenario (300 kta capacity, waste PP price of $181/ton).

Total capital investment (MM$)	**374.4**
Annual Operational Cost (MM$/year)	133.7
Annual income (MM$/year)	270
NPV (MM$)	330.7
IRR (—)	29.6%
Minimum Fuel Selling Price ($/GGE)	2.4

causing considerable changes in the IRR, varying from 23% to 36%. Although not as dominant, the purchase cost of waste PP, feedstock transportation cost, and tax rates (which is assumed to be 26%) also influence the profitability of the process as well. Another key economic indicator used in this study is the MFSP on a Gasoline Gallon Equivalents (GGE) basis. For this calculation, the flow rates of liquid fuel streams (gasoline and diesel) were converted to gasoline gallon equivalents using the U.S. Department of Energy's conversion factors: 1.155 for diesel and 1 for gasoline [35]. By calculating the MFSP at the point where the NPV equals zero, a value of $2.4/GGE has been determined which is ~20% lower than the current market price of gasoline in the southern region (~ $3/gal) [33]. Impacts of changes in fuel production rate and waste PP price on MFSP can be seen in Figure 5. As operating a large-scale centralized recycling plant can substantially boost the demand for waste PP bales in the region, it is considered plausible that the price of waste PP bales could potentially rise to twice the average price of $181 per ton observed in 2022 [31]. The calculations

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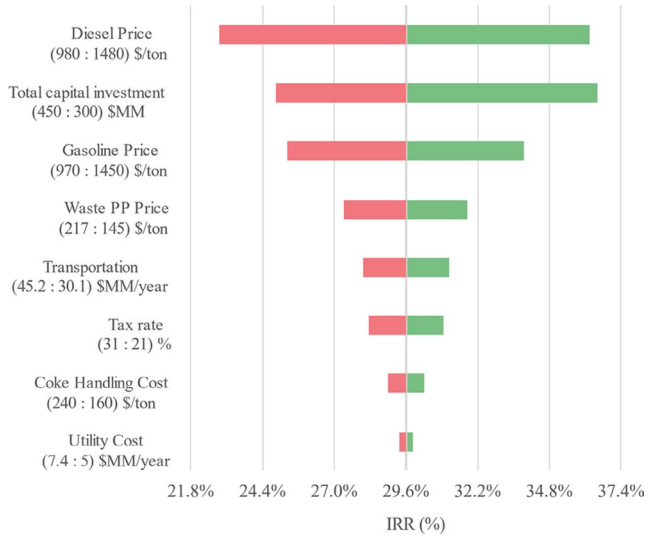


FIGURE 4 | Sensitivity analysis with ±20% change of parameters.

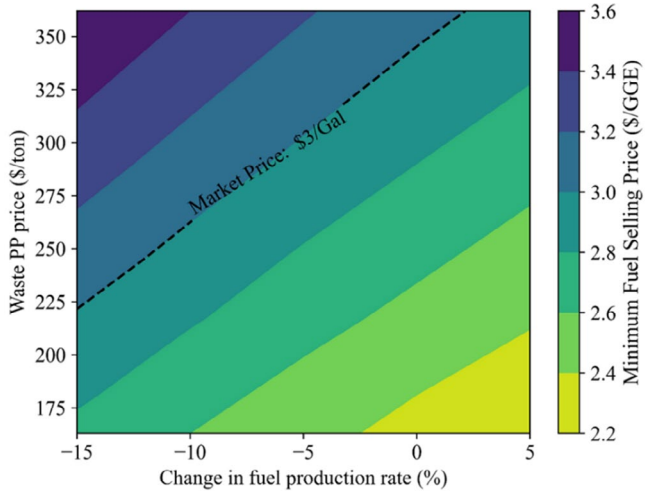


FIGURE 5 | Influence of two major process and economic factors on MFSP.

highlight the importance of stability in fuel production, which can be easily disrupted by extended maintenance times or process downtimes (e.g., excessive coke formation on heating surfaces), or by decreasing yields caused by variations in feedstock quality, contamination, and catalyst deactivation. For instance, if the plant operates at nominal capacity (with no decrease in production rate) and the purchase cost of waste PP is less than $345/ton, the MFSP would remain below $3/GGE (as the baseline). However, this threshold can decrease to approximately $250/ton with just a 10% decrease in fuel production rate. This shows that despite economic viability, the profitability of this process is highly uncertain. Additionally, although we considered a 100% increase in the average price of waste PP, in the case of increased demand, the final price of waste PP bales could match that of high-density polyethylene (HDPE), which exceeded $400/ton in 2022 [31]. In this scenario, the MSFP would exceed the market price regardless of the production rate, making the facility no longer profitable.

4.3 | Scenario Analysis

Two additional scenarios were developed with processing capacities of 240 kta and 360 kta to assess their impact on the economic feasibility of the process. For each case, separate process flowsheets with corresponding mass and energy balances were developed in Aspen Plus and equipment sizing, costing, and profitability analysis, were conducted independently for each scenario. Figure 6A demonstrates that the total capital investment ranging from $320 million to $460 million changes significantly with capacity. This is mainly due to the significant change in total installed costs of hydrogen tanks ($113MM vs. $135MM vs. $170MM). Since the major components of operational costs (including raw material, transportation, and utility costs) generally increase linearly with scale, both the annual operational cost and annual income increase linearly with increased capacity. Nevertheless, while the 360 kta plant shows highest NPV over the 30-year plant life due to highest gross earnings, it can be seen that the base case design has the highest IRR and the best return on investment (ROI) among all scenarios. This is because the higher gross earnings in 360 kta case do not fully offset the increase in total capital investment (Figure 6B). This also reflected in the minimum selling prices, with the MFSPs for three scenarios being $2.48/GGE, $2.4/GGE, and $2.42/GGE, respectively. The MFSP breakdown (Figure 6C) indicates that "Raw Material & Wastes" accounts for the largest portion of the MFSP, contributing over $0.95/GGE, regardless of capacity. "Total capital investment" and "Transportation" are the next major contributors. It is also important to note that the selling value of by-products (chemical grade ethylene and propylene) have a negligible impact on the overall profitability due to their small production rate.

5 | Conclusions & Recommendations

This TEA of the PP recycling plant via pyrolysis for the production of gasoline and diesel demonstrates promising economic viability. The process, designed to handle 300 kta of waste PP, demonstrates favorable economic profitability, with a NPV exceeding $330 million and an IRR reaching 29.6% over a 30-year lifespan. The primary products, gasoline and diesel, constitute a substantial portion of the total production, contributing to the project's financial viability. Scenario analysis on different processing capacities demonstrates that, while the 360 kta scenario yields the highest NPV, the base case design (300 kta) shows the most promising financial viability with the highest IRR and the most favorable ROI. This also emphasizes the need to consider capacity in the design and optimization of waste plastics recycling plants.

Equipment cost and CAPEX calculations show that the "Storage" area, particularly the costs associated with hydrogen storage, is a significant contributor to the total capital investment. This finding highlights the importance of on-site hydrogen production to further reduce capital investments and operational costs. The breakdown of annual operational costs highlights that raw materials and waste handling, along with transportation, collectively account for approximately

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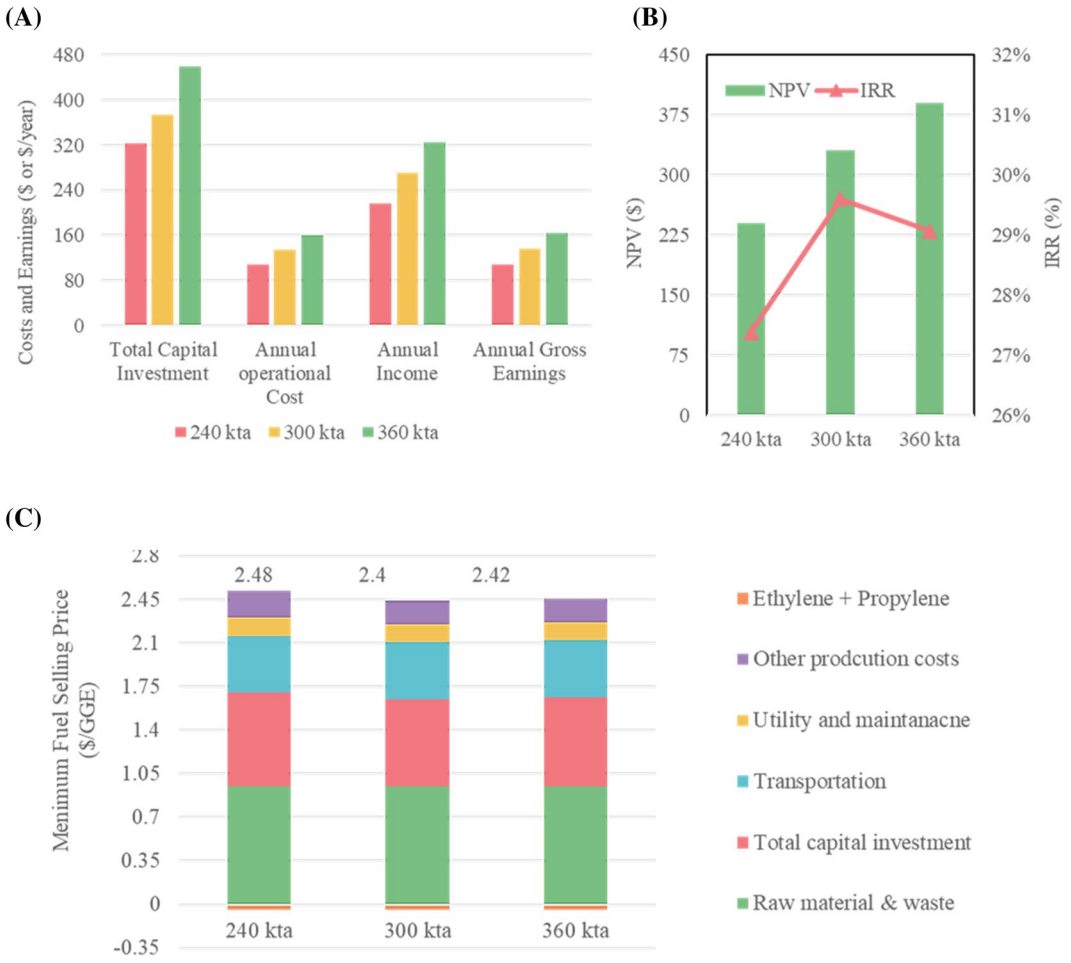


FIGURE 6 | Effect of processing capacity on: (A) costs and earnings (B) NPV and IRR (C) MFSP cost breakdown.

87% of total operational costs. Sensitivity analysis indicates that the profitability of the facility is highly sensitive to market factors such as liquid fuel prices, capital investment, and key operational costs, including the purchase of waste PP and feedstock transportation. Based on the results from this TEA study, further development efforts should focus on investigating on-site hydrogen production and exploring alternative storage technologies and configurations to optimize the proposed recycling plant and enhance overall sustainability and resource efficiency.

Author Contributions

Farhad Zaker Hosseiny: investigation, writing – review and editing, conceptualization, methodology, software, validation, writing – original draft, visualization. **Rui Shi:** funding acquisition, writing – review and editing, conceptualization, supervision, writing – original draft, project administration, visualization, methodology, investigation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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