EXECUTIVE SUMMARY

The Future of Plastic Recycling

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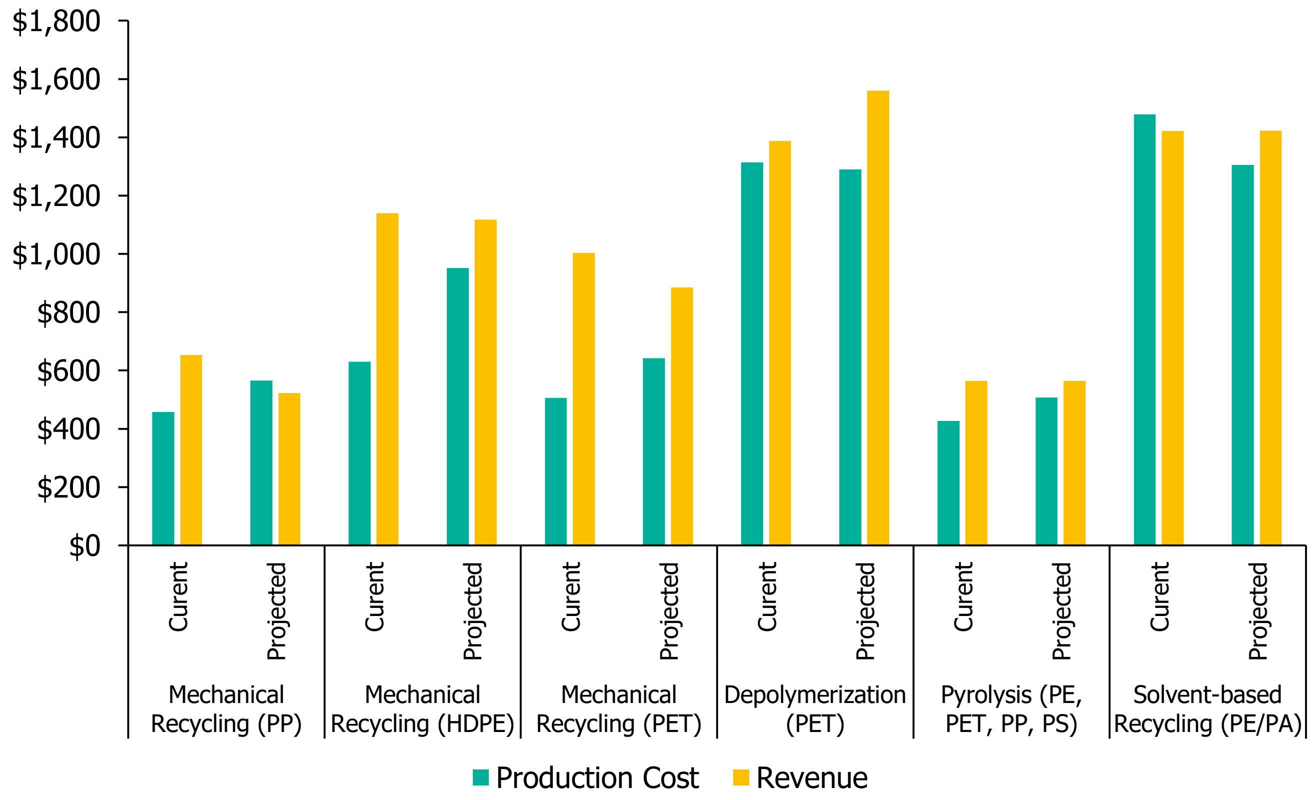
Executive Summary

The future of the plastic recycling market will mostly be a combination of mechanical recycling, depolymerization, and pyrolysis; however, waste availability will determine which becomes dominant in a specific region:

- In any region, high-quality (well-sorted and clear) plastic waste will be best addressed by the low production cost of mechanical recycling, but the mechanical recycling of “niche” plastic waste streams like polypropylene and polystyrene will remain limited, opening opportunities for solvent-based recycling and pyrolysis.
- Regions with a high throughput of cheap, untreated plastic waste will be dominated by pyrolysis.
- Regions with large quantities of low-quality PET waste will be attractive for depolymerization operations.

Future profitability of recycling technologies
2019 $/ton treated plastic



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In this report, we analyze the process economics of advanced recycling technologies being brought to scale

In this report, we modeled the process economics of the incumbent recycling process – **mechanical recycling** – as well as four advanced recycling technologies – **depolymerization**, **pyrolysis**, and **solvent-based recycling** – in order to determine the economics of these processes and understand the effects of market factors and technology development on those economics. We chose to focus on these four technologies because they have received the most funding and interest over the past two years.

The goal of this report is to help clients build a clear understanding of advanced recycling technologies and develop an outlook for the future of plastic waste. This is crucial for every stakeholder in the plastic value chain:

- **Material and chemical companies** need to understand how advanced recycling can create new market threats and opportunities.
- **Consumer-facing brands** mapping out 2025 sustainability strategies need to understand how the future development of advanced recycling will affect product design.
- **Recyclers** need to know which technologies will be economical, and the future outlook for adoption.
- **Government entities** need to decide which technologies to endorse and how the outputs of these technologies fit into regulatory frameworks.
- **Investors** need a clear picture of process economics to gauge possible returns.

Mechanical recycling is the incumbent waste valorization technology

INTRODUCTION

Mechanical recycling is currently the dominant waste valorization technology. While this well-understood and relatively simple process has low overall costs, it cannot remove additives like dyes and flame retardants or impurities like dust or organic contaminants. The recycled plastic product has altered or diminished physical properties and typically cannot be used in premium applications like food-contact packaging or performance textiles. A number of developers are improving pretreatment to improve recycled resin quality and new feed systems to enable the recycling of new form factors like monomaterial films. We used a standard mechanical recycling process for our model.

PROCESS FLOW

1. Baled plastic scraps from material recovery facilities are unbaled, manually sorted, sent through a metal detector, quality assurance (QA) checked by near-infrared sensors, ground, washed, manually QA checked, sink-float separated, auto-color sorted, washed a final time, and dried in an oven.
2. The separated and cleaned plastic scraps are extruded into pellets and sold.

1. Pretreatment

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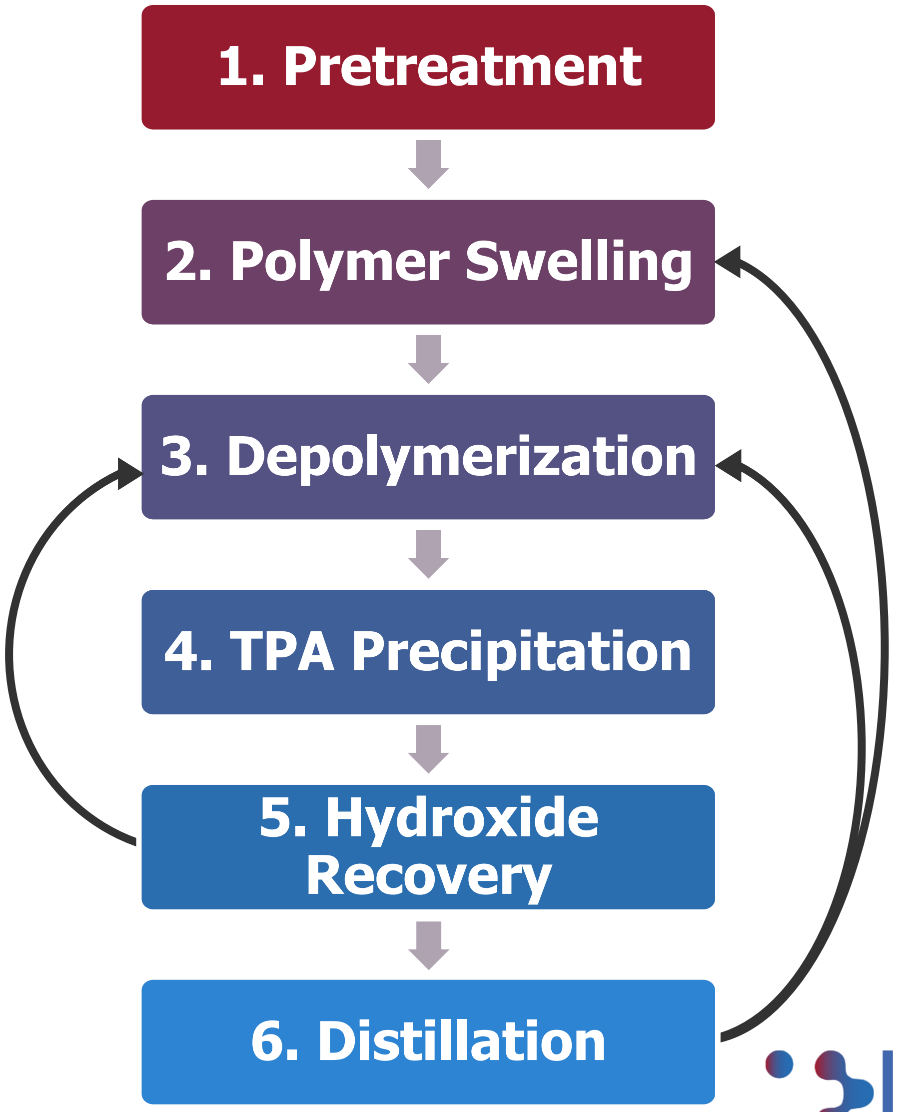
2. Extrusion

Depolymerization can recover PET from low-quality feedstocks

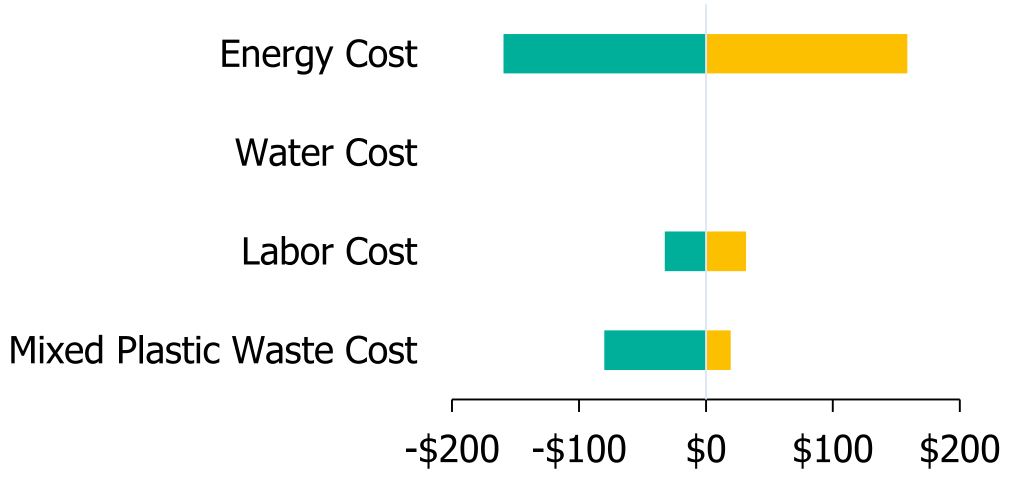
1. The feedstock is lightly washed and ground while manual sorters or automated equipment remove inhibiting containments like nylon.
2. A nonpolar solvent swells the polymer.
3. An alcohol and hydroxide solution breaks down ester functionality, depolymerizing PET polymer chains and raising pH slightly. During this step, an accelerant (catalyst, enzyme, energy) is added to speed up depolymerization.
4. A highly acidic solution is added to lower pH significantly, precipitating terephthalic acid, which is filtered, washed, dried, and sold.
5. The remaining solution is neutralized, precipitating a strong acid. Hydroxide ions are recovered in an electrolytical reaction and recycled to step 3.
6. The solution is distilled, recovering ethylene glycol for sale and solvents for recycling back into steps 2 and 3.



PYROLYSIS SENSITIVITY ANALYSIS

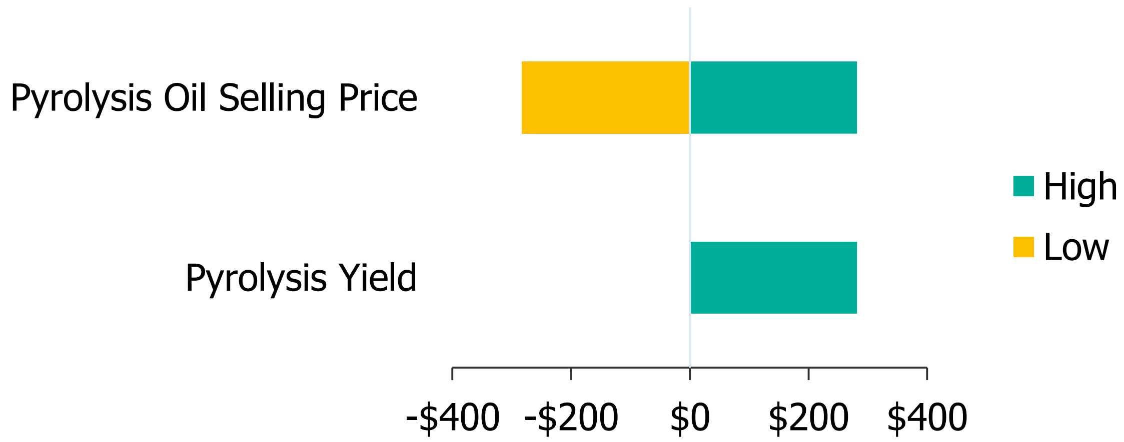
Energy costs and oil prices play a key role in determining pyrolysis' profitability

Impact of inputs on profitability
$/ton treated plastic



Parameters	Low	Baseline	High
Energy Cost	50%	100%	150%
Water Cost	50%	100%	150%
Labor Cost ($/hr)	50%	100%	150%
Unrecyclable Plastic Waste ($/ton)	-$50	-$30	$50
Pyrolysis Oil Selling Price	50%	100%	150%

Impact of price and yield on profitability
$/ton treated plastic

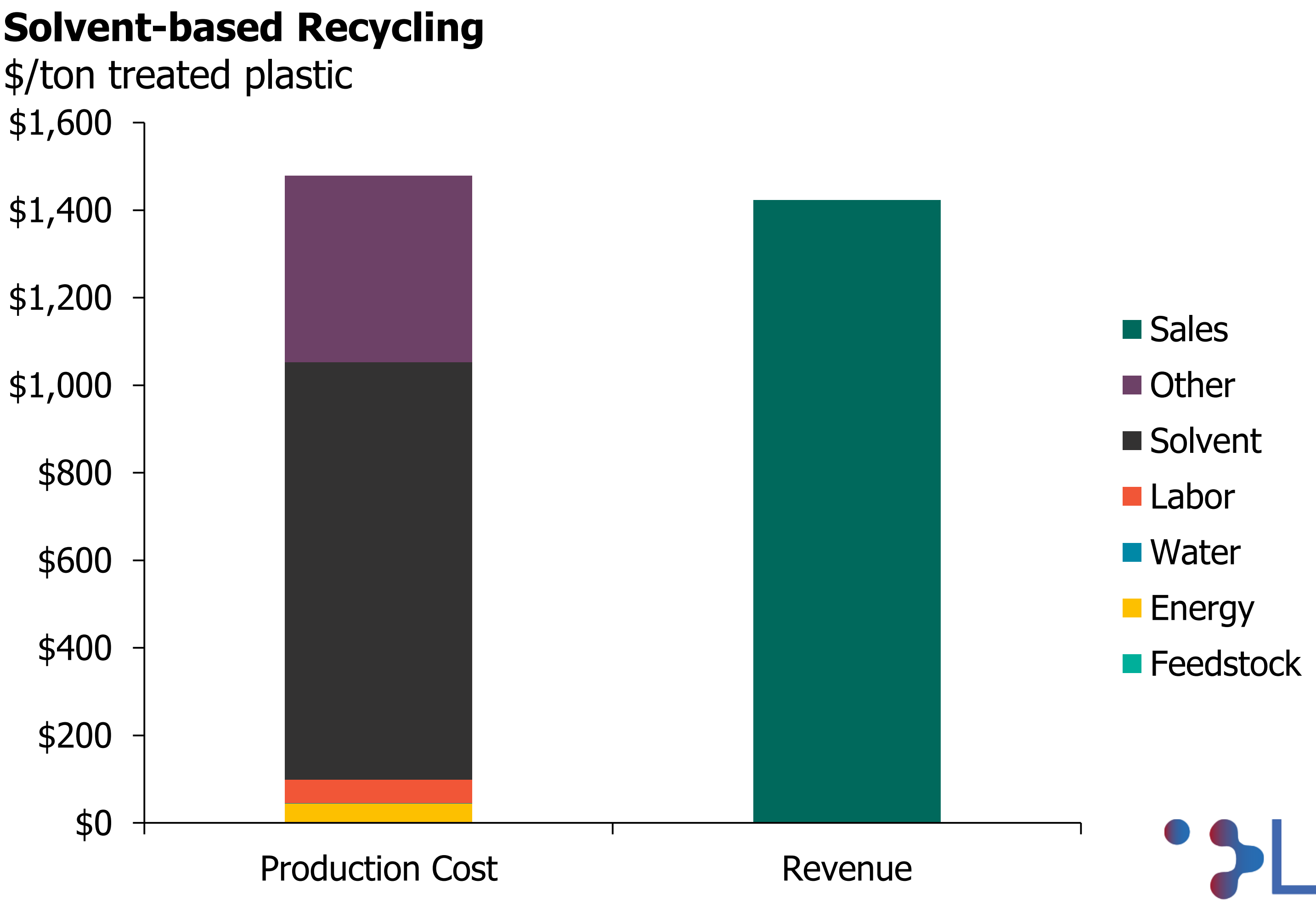


Parameters	Low	Baseline	High
Pyrolysis Oil Selling Price	50%	100%	150%
Pyrolysis Yield (barrels/ton UPW)	NA	4.2	6.3

Solvent-based recycling costs are highly dependent on solvent prices

Solvent-based Recycling Assumptions	
Treated Plastic Throughput (tpa)	100,000
Capex ($)	35 million
Film Waste Cost ($/ton)	0
PA6 Pellet Price ($/ton)	2,550
LDPE Pellet Price ($/ton)	815
Distillate Recovery Rate (%)	97

Production Cost Breakdown	
Type	$/ton treated plastic
Feedstock	0
Energy	45
Water	2
Labor	55
Solvent	955
Other	430
Total	**1,487**



We analyze three potential market scenarios and their effect on the waste valorization space

In this section of the report, we project our cost models in three potential market scenarios:

The recycling market returns to early 2017 price points

In this scenario, we set scrap plastic and recycled pellet prices back to their early 2017 levels. This scenario is a close representation of the economic conditions in the recycling market of developed regions prior to China's ban on plastic waste import.

Petroleum and energy prices rise

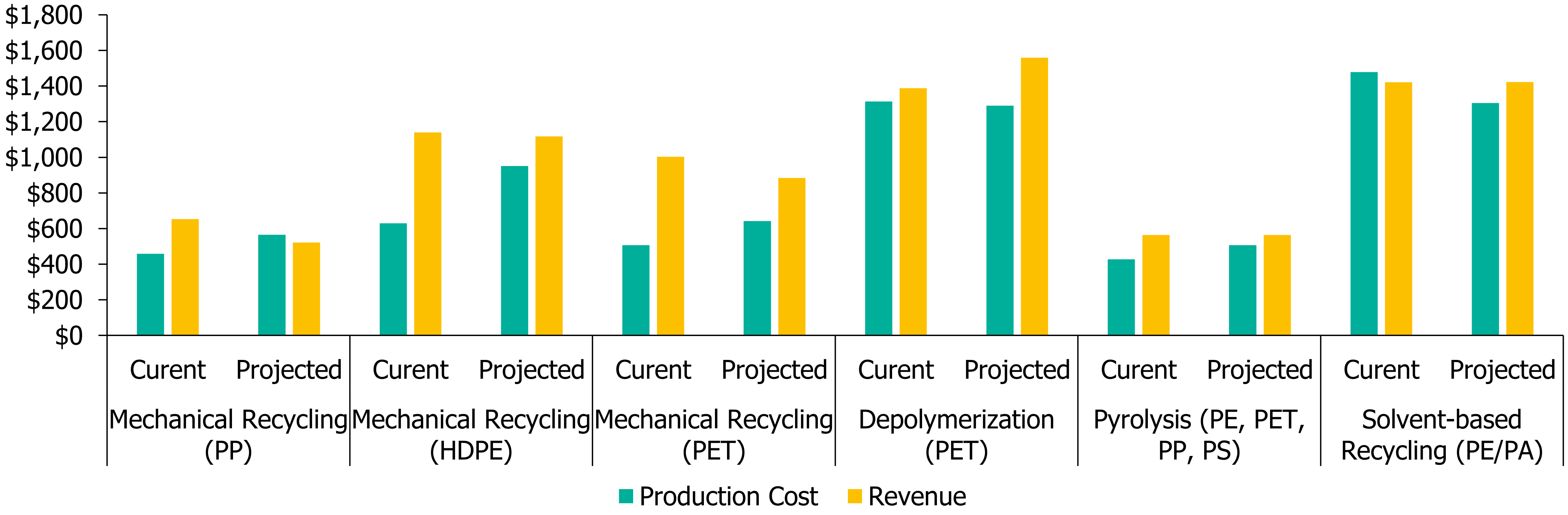
In this scenario, we increase petroleum and energy (all sources) prices by 50%. High petroleum prices increase the cost of virgin and, subsequently, recycled plastics, whose price is dependent on virgin plastic prices. This will incentivize improvements to waste collection infrastructures in developed nations, increasing both recycling yield and plastic scrap prices. Petrochemical-derived solvents also become more expensive.

Most likely case

We project future scrap prices, recycled pellet prices, process efficiencies, and other inputs to determine the most likely future scenario. We describe how we arrived at these projections within this section.

Most likely case: The future of recycling will combine incumbent and advanced recycling technologies

Future profitability of recycling technologies
2019 $/ton treated plastic



Most likely case: Mechanical recycling capacity will grow substantially but focus on "mainstream" plastics

As the demand for plastic scraps has declined sharply, domestic plastic recyclers have gained more control over the market and are demanding better-sorted plastic scraps. As recycling capacities increase, we expect plastic scrap prices to return to near early-2017 prices but not exceed them unless developers misread the market and overexpand. In the interim, municipalities and material recovery facilities (MRFs) will continue to feel the squeeze from lower demand and will need to invest in both improved collection systems and automated sorting equipment. This will have the effect of raising both the quality and the price of mainstream plastic scraps like PET and HDPE (and LDPE as feed systems are installed); however, it remains to be seen how many of the more uncommon recycling streams, such as PP, will improve. Hence, we project that PET scrap prices will rise while recycling yield remains the same, HDPE scrap prices will rise dramatically while recycling yield improves, and PP scrap prices rise while recycling yield remains the same.

While there is currently a supply-demand gap for recycled plastics, mechanically recycled pellets are fundamentally lower-quality than their virgin equivalents. Although legislation and consumer trends will continue to encourage their use, we expect future plastic pellet prices to return to virgin plastic prices.

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Regional waste availability will determine the dominant recycling technology

No one technology has a clear decisive advantage for recycling plastic waste. The future of plastic recycling will be a combination of mechanical recycling, depolymerization, and pyrolysis, with the mix varying by region. Waste availability will help determine which approach becomes dominant in a specific region.

- In any region, high-quality (well-sorted and clear) plastic waste will be best addressed by the low production cost and capex of mechanical recycling. Still, the mechanical recycling of "niche" plastic waste streams like polypropylene and polystyrene will remain limited, opening opportunities for solvent-based recycling and pyrolysis. As innovations increase the viable form factors for mechanical recycling, a wider range of plastic waste – such as films – will be considered "high-quality."
- Regions with a high throughput of cheap, untreated plastic waste will be dominated by pyrolysis. While certain locations in Southeast Asia and the U.S. are obvious and immediate opportunities, the emergence of major plastic waste accumulation centers in Europe could also facilitate massive operations.
- Regions with significant volumes of low-quality PET waste will be attractive for small-scale depolymerization deployment, located as close to PET resin producers as possible.

Companies looking to address plastic waste issues will need to use a portfolio of technologies across the materials they use or produce and regions they operate in. It will also be important to keep close tabs on market conditions in order to assess which technologies will have an edge – brands and material producers that have access to a variety of approaches will have an advantage in riding out the shifts in this market as recycling technologies grow to address plastic waste.

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