CLOSED LOOP partners

Transitioning to a Circular System for Plastics

Assessing Molecular Recycling Technologies in the United States and Canada

The Center for the Circular Economy at Closed Loop Partners

The Center for the Circular Economy ("the Center") is the innovation arm of Closed Loop Partners, a leading circular economy-focused investment firm in the United States. The Center executes research & analysis and unites competitors to tackle complex material challenges and to implement systemic change that advances the circular economy. The Center brings together designers, manufacturers, recovery systems operators, trade organizations, municipalities, policymakers and NGOs to create, invest in, and support scalable innovations that target big system problems.

Our Advancing Circular Systems for Plastics and Packaging Initiative

At Closed Loop Partners, we envision a waste-free future for plastics. We launched our Advancing Circular Systems for Plastics and Packaging Initiative with the understanding that there is no panacea to solve complex global waste challenges. No single sector or approach can solve the systemic challenge; multiple tools need to be deployed simultaneously in order to accelerate change. This requires upstream interventions to consciously design systems and products to use fewer materials, harness innovative alternatives to plastics where appropriate, and implement circular business models like refillable and reusable products, as well as downstream interventions to recover plastics already in circulation.

Acknowledgments

This report was produced by the Center for the Circular Economy at Closed Loop Partners.

Lead Author:
Paula Luu, Project Director

Writing Team:
Kate Daly, Managing Director
Bridget Croke, Managing Director
Georgia Sherwin, Director of Communications & Strategic Initiatives
Bea Miñana, Communications Associate

Technical Partners: We are deeply appreciative of our trusted technical partners who accompanied us on an 18 month-long journey full of questions, analysis and sense-making. Anthesis Group led the financial, supply chain, and policy analysis for this study; Environmental Clarity brought their life cycle assessments (LCA) expertise to our four-part environmental impact analyses; and Ellen Martin served as a technical advisor. Resource Recycling Systems led the U.S. and Canadian plastic waste analysis and developed the Tableau-based plastic waste map. A special thanks to Scivera, for allowing us to use its impact measurement tools in our human health analyses and Wood Mackenzie for providing datasets for our supply and demand analysis.

NGO Partners: Many thanks to our Environmental Advisory Partner, World Wildlife Fund, and to the Sustainable Packaging Coalition and The Recycling Partnership for their thought partnership.

Molecular Recycling Technology Companies: A special thanks to the nine companies who provided the bulk of the data for this analysis: APK AG; PureCycle Technologies; Carbios, GreenMantra; JEPLAN; gr3n; Brightmark; Plastic Energy; and Enerkem. Additional thanks to the three companies who participated in a smaller case study on modular technologies: Recycling Technologies; Renewlogy; and Synova.

Peer Reviewers and Advisors: More than 75 companies, NGOs, brands, retailers, academic researchers, investors and policy experts contributed to our research and analysis, including the esteemed peer reviewers of this report: the Association of Plastic Recyclers; the Overbrook Foundation; National Renewable Energy Laboratory (NREL); University of Michigan School of Public Health; the Environmental Advocacy Center at Northwestern University; the Baker Institute at Rice University; As You Sow; and Safer Made. A special thanks to our LCA Third Party Review team, Dr. Chet Chaffee (Boustead Consulting) and Dr. Mahmood Sabahi (Georgia Institute of Technology), who assessed our life cycle methodology to conform to ISO 14040 standards.

Contributing Partners: Many thanks for the support of our partners: Target Corporation, Bank of America Foundation, the American Chemistry Council, Colgate-Palmolive Company, 3M, and Sealed Air Corporation.

Graphic Designers: Guyang Chen-Ware, Emily Mills, and Anthesis Group designed the graphics and report.

Disclaimer

This document has been prepared to provide investors, brands, retailers, policymakers, nonprofit groups and other stakeholders with summary results from our molecular recycling study conducted between 2020-2021. This document may not be used or reproduced, in whole or in part, for any other purpose. The information contained in this report has been prepared solely for informational purposes and does not constitute an offer to sell or a solicitation of an offer to buy any security and may not be relied upon in connection with the purchase or sale of any security. The statements in this report that contain terms such as “may,” “will,” “should,” “expect,” “anticipate,” “target,” “project,” “estimate,” “intend,” “continue” or “believe,” or the negatives thereof or other variations thereon or comparable terminology are forward-looking statements and not historical facts. Any market analysis presented in this report represents the subjective views of Closed Loop GP, LLC, and its Center for the Circular Economy (“the Center”). Actual events are difficult to predict, and are beyond the control of Closed Loop Partners and its affiliates and may differ from those assumed. There can be no assurance that estimated returns or projections will be realized, that forward-looking statements will materialize or that actual returns or results will not be materially lower than those presented. All forward-looking statements included are based on information available on the date hereof, and neither Closed Loop Partners, the Center for the Circular Economy nor its affiliates assumes any duty to update any forward-looking statement. No representation or warranty, express or implied, is made as to the accuracy or completeness of the estimates, projections and other information contained in this report, and nothing contained in this report shall be relied upon as a promise or representation whether as to the past or future performance. All performance information included herein is based on information reported by molecular recycling technology companies and other stakeholders and has not been independently verified by Closed Loop Partners or its affiliates.

Table of Contents

Executive Summary

No single sector, technology or approach can solve the plastics waste challenge. A comprehensive approach includes upstream strategies that reduce the overall use of plastic through design innovation and reuse systems, as well as downstream strategies including mechanical and molecular recycling systems that recapture existing plastics after use. In this report, Closed Loop Partners focuses on just one part of the broader circular plastics system: "molecular" recycling technologies and explores how, under the right conditions, they have the potential to support downstream material recovery and a circular and safe future for plastics.

Our Approach to Assessing Molecular Recycling Technologies in the United States and Canada

Molecular recycling, also commonly referred to as **advanced recycling** and/or **chemical recycling,** is a diverse sector that addresses plastic waste and encompasses dozens of transformational technologies that use solvents, heat, enzymes, and even sound waves to purify or break down plastic waste to create polymers, monomers, oligomers or hydrocarbon products. This report is intended to provide a summary of observations, analysis and key learnings from our 18-month evaluation across molecular recycling categories.

Across three sections - **Educate**, **Collaborate**, **Invest** - this report explores where molecular recycling fits into a circular economy. Closed Loop Partners does not disclose data or information about a specific company or technology process in this report. Instead, we speak to category averages and observed ranges across our financial, supply chain, and environmental impact analyses - and compare these technologies to the incumbent virgin plastics supply chain. This report's content is not a substitute for evaluation or diligence of any of the companies reviewed.

SECTION 1

Educate

Solving the plastics waste challenge is an urgent need and to achieve this, we need to first understand the complexities of plastic, the world's most ubiquitous and diverse material class. In this section, we dive into today's current "take-make-waste" linear system, establishing the need for upstream waste reduction strategies through design innovation and reuse systems at scale, and exploring the role of downstream strategies including molecular recycling technologies.

SECTION 2

Collaborate

Collaboration across the plastics value chain is critical in order to drive circular, safe and profitable outcomes. In this section, we examine the diverse stakeholders in the plastics value chain, including brands, recyclers, petrochemical companies, investors and policymakers, and recommend how each could play a unique role in shaping the development of the molecular recycling sector to align with sustainability goals.

SECTION 3

Invest

In this section, we dig into four critical factors — technological viability, financial viability, environmental and human health impact measurement, and integration into local markets — to help ensure that investors and other stakeholders are asking the right questions in assessments of investable opportunities around molecular recycling companies and technologies.

Supplemental Resources:

- 9 Case Studies
- Global Directory of Molecular Recycling Companies
- Online Appendix

1

To address the plastics waste crisis, industries, brands, NGOs, policymakers and consumers must look beyond single-use plastic packaging.

- The plastics waste challenge, which perpetuates the extraction of non-renewable resources, extends to the equally visible, but often overlooked, plastics used in healthcare, textiles and apparel, and electronics. These kinds of applications make up two-thirds of the plastics produced and will continue their linear path to landfill unless we build recovery pathways for all types and uses of plastics.

- We risk delaying a future free of plastic waste unless solutions that address the full range of plastics are considered. Those lost resources have serious consequences for our environment and economy.

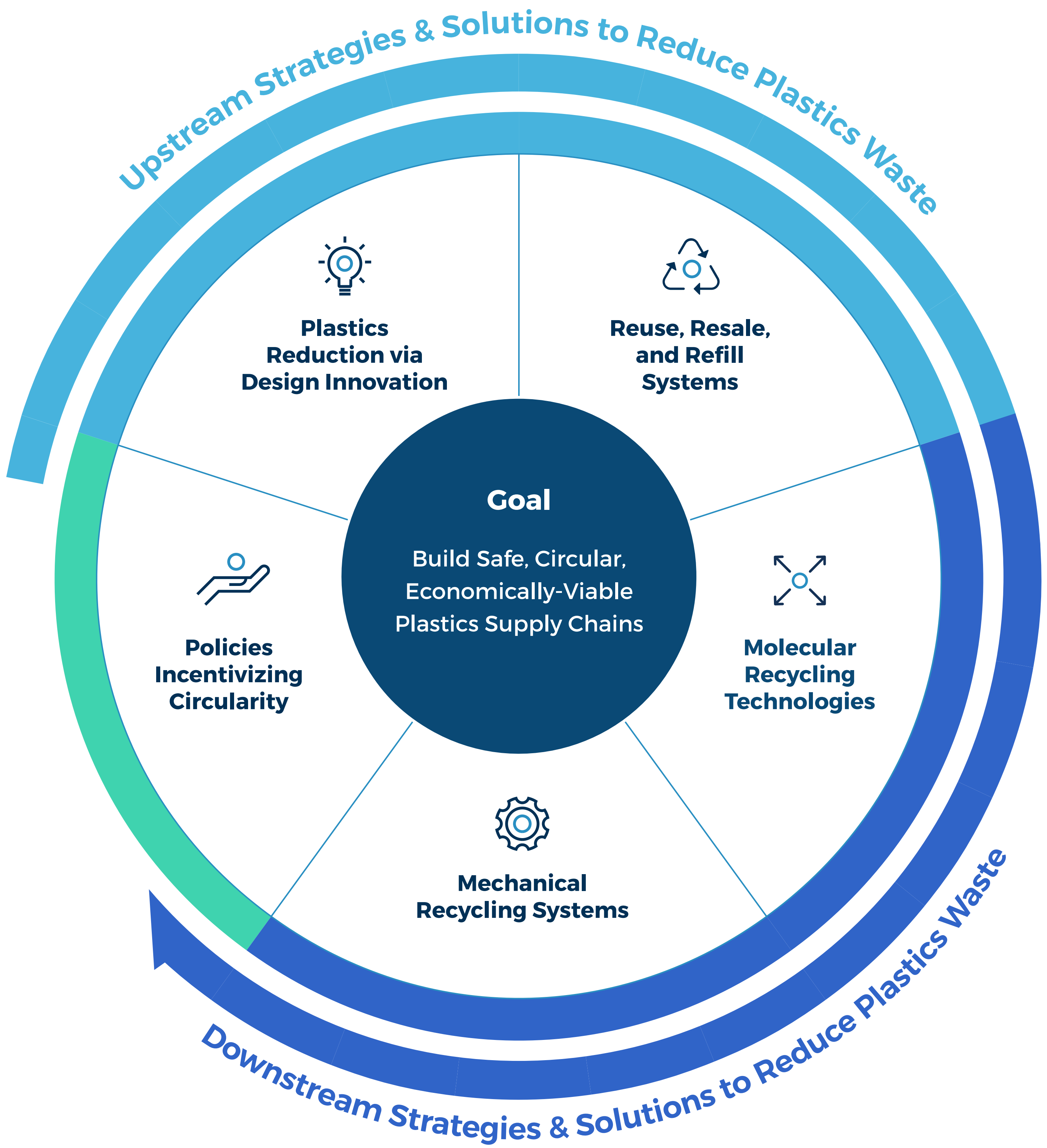
> “Plastics are ubiquitous in the fashion industry, representing over half of total fiber production. Fashion for Good is collaborating with the industry to create a range of solutions: scaling polyester chemical recycling technologies to keep these materials out of landfill and in circulation, and nurturing next generation materials, such as bio-based polyester alternatives.”
>
> **– KATRIN LEY, MANAGING DIRECTOR,**
> FASHION FOR GOOD

2 A suite of upstream and downstream solutions are needed to solve for the diversity of plastic waste.

▸ Only 9% of plastics produced have been recycled[1]. No single sector, technology or approach can solve for the diversity of plastic waste in the system. A comprehensive approach to eliminate plastic waste includes upstream strategies like plastic use reduction through design innovation and the introduction of reuse systems at scale, downstream strategies including mechanical and molecular recycling, and policy interventions to prevent waste.

▸ Because of the complexity and diversity of the plastics waste challenge, dismissing any category of solution adds risks. Reduction should be prioritized. Scaling reuse systems to curb extraction is critical, just as recycling plays an important role for plastics that are at end-of-use. In this report, we focus on one downstream solution, molecular recycling.

FIGURE A. MULTI-PRONGED APPROACH TO ADDRESS DIVERSITY OF PLASTIC WASTE



3 "Molecular" or "advanced" recycling technologies can expand the scope of materials we can recycle, help preserve the value of resources in our economy, and bridge the gap between the supply and demand for high-quality recycled plastics, like food-grade plastic.

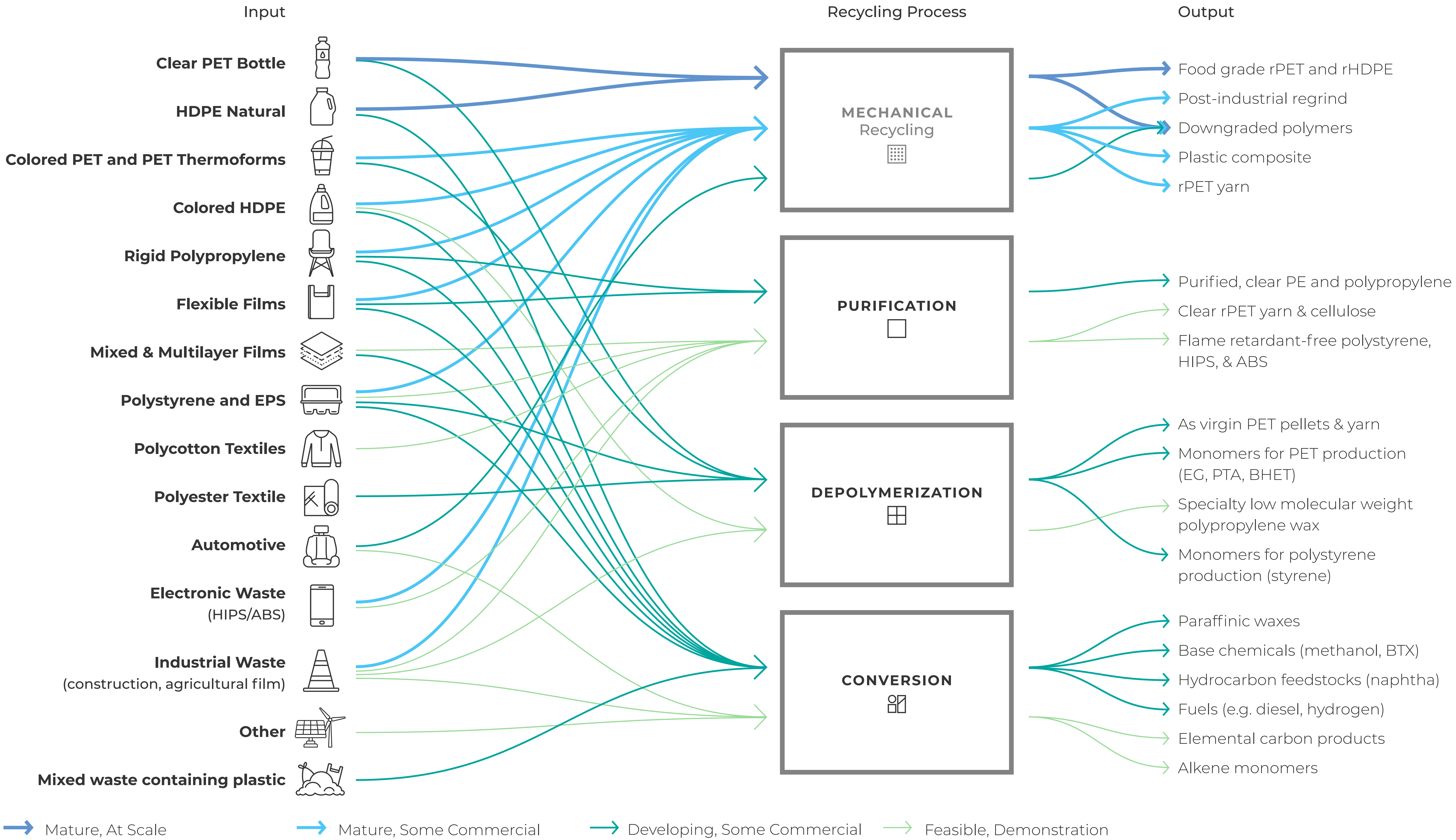
- Molecular recycling is a diverse sector that encompassess dozens of technologies that use solvents, heat, enzymes, and even sound waves to purify or break down plastic waste to create polymers, monomers, oligomers or hydrocarbon products. The sector is made up of purification, depolymerization, and conversion technologies that can process a wide range of plastic waste including packaging, textiles, healthcare plastics, and wind turbine blades, addressing overlooked plastics that today do not have end-of-use recovery solutions. Molecular recycling technologies are not just packaging recycling solutions; their full potential extends to the diverse materials they can recover.

- The term "molecular recycling" is synonymous with the term "advanced recycling" and includes more commonly known "chemical recycling" technology processes like pyrolysis. However, the term "molecular recycling" is inclusive of other types of technology processes that do not leverage chemicals and instead use enzymes, soundwaves and other technology platforms that transform plastics.

- This early-stage industry is uniquely positioned to take in a wide range of contaminated plastic waste and purify the plastics or transform them at the molecular level so that outputs can be looped back into manufacturing without being downcycled. This is especially important because there is not enough supply to meet the demand for high-quality recycled plastics (e.g. food-grade applications). Together with mechanical recycling, these two systems can symbiotically help decarbonize manufacturing and the plastics economy, and meet the demand for various grades of recycled plastic resin.

- Diverse stakeholders from petrochemical trade groups[2] to environmental advocacy groups agree that plastics-to-fuel or plastic-to-energy (PTE) should not be considered recycling.

FIGURE B. RECYCLING INPUTS AND OUTPUTS: EARLY AND DEVELOPING MATERIAL FLOWS BY TECHNOLOGY CATEGORY



4 Integrating molecular recycling technologies into plastics recycling systems in the United States and Canada could double the amount of plastic packaging recycled compared to 2019 recycling rates[3], and generate up to $970 million dollars (USD) annually.

- All nine companies in Closed Loop Partners' study required some level of feedstock preparation (i.e. pre-processing). The majority of these nine companies across all three technology categories are paying suppliers for feedstock, thus bringing value to materials that have little value in the existing plastics recycling system.

- Purification and depolymerization technologies differentiate from mechanical recycling by their ability to remove chemical additives and color from plastic waste, producing like-new plastic polymers that can go into high-value cosmetic or food-grade applications; this requires upstream suppliers to sort feedstock to a single resin. Conversion technologies can process plastic waste that is mixed or commingled with other waste materials (i.e biomass), which is more aligned to single-stream recycling and mixed waste realities.

- For this study, we modeled two scenarios to reach a packaging recycling goal of 30% across all resins and formats as an initial target; both scenarios did not divert material mechanical recycling is currently processing. Our analysis shows that a "mixed technology" approach that leverages all three kinds of molecular recycling technologies produces a better financial outcome for the existing plastics recycling system compared to a conversion-only approach which requires less sortation. Investment into our collections and sortation infrastructure is a tide that lifts both mechanical recycling and molecular recycling and will allow a wider scope of plastic waste to be recycled.

5 The average carbon emissions from producing plastic through all three molecular recycling technology categories showed an improvement compared to corresponding virgin plastics systems, with environmental impacts varying within and across the technology categories.

- In our study of nine companies, the highest-performing molecular recycling technologies demonstrate the role that technologies with a lower environmental impact than virgin production could play in decarbonizing our plastics economy by supporting the reduction of virgin plastic production, and helping make more recycled material available to manufacturing industries. Our study also found examples of technology processes that performed worse than virgin across greenhouse gas emissions and bluewater [a]. Scaling molecular recycling technologies, particularly those intending to link up to plastics supply chains, will require comprehensive diligence by investors and supply chain partners to ensure that circular plastics supply chains are also meaningfully decarbonizing plastic supply chains.

- Molecular recycling can help mitigate climate change when it displaces the use of virgin plastics. The transition towards a circular future will rely upon the petrochemical industry shifting a significant proportion of their investment to solutions that address plastic waste, like molecular recycling, and shifting away from oil exploration and new extraction infrastructure.

- Environmental impact reductions (i.e. carbon emissions, energy, and bluewater) demonstrated today by molecular recycling technologies can be magnified with renewable energy since the majority of energy usage from molecular recycling is indirect energy use [b]. Thus, renewable energy has the potential to further decrease the environmental impact of molecular recycling technologies and should be a critical component of any

a. Bluewater is the total of all water evaporated during production or physically incorporated into the product. Thus, blue water does not include non-contaminated water returned to the environment (i.e. from steam heating or cooling water systems) or contaminated water that is returned to the environment via a wastewater treatment process (i.e. from a manufacturing plant or municipal wastewater treatment plant).

commercialization strategy for technology companies intending to participate in the circular plastics economy.

- In addition to key environmental metrics like energy use, greenhouse gas emissions, and water use, investors need to consider factors like the quality of outputs from specific processes and total material yields.

b. Indirect energy use is the energy produced outside a company or facility's boundaries by the electricity suppliers, and consumed on the company or facility site. Indirect energy depends on the local electricity grids where the company or facility operates. It is measured in gigajoules or megawatt hours.

6

Molecular recycling technologies can reduce human health risks associated with virgin plastic production by avoiding the need for additional virgin chemicals to build back the plastic polymer.

- In general, the less a polymer is broken down, the fewer steps are needed to build back the plastic polymer, reducing human health risks associated with the virgin chemicals used to build back the plastic polymer.
- By reducing virgin chemical use, molecular recycling can reduce the human health impacts associated with the virgin production of plastics. Those savings differ across technology types and the types of plastic feedstock they take in as well as the outputs they produce.
- The nuances among different molecular recycling technologies — and the varying feedstock different companies process — points to a need for nuance in regulation and permitting. Molecular recycling technologies are manufacturing facilities when they are not processing untreated waste and when they produce outputs that do not link to fuel or energy supply chains.

7 The trade-offs between purification, depolymerization, and conversion technologies relate to their commercial availability, feedstock requirements, material processing efficiency, and environmental and financial performance.

- All three types of molecular recycling technologies have a role to play in a future circular economy because of their performance and the different types of hard-to-recycle plastics they can process. The appropriate solution(s) depend on the material make-up of the plastic wasteshed [c], the degree of contamination and commingling in the wastestream, the capacity of the regional collection and sortation infrastructure to pre-process plastic waste, and local policy—all of which impact the technical and financial viability of any process.

- Conversion technologies can process the largest proportion of plastic packaging waste in the system and are the most commercially available for scaling. Today, conversion is the only viable downstream solution for some types of plastic waste (e.g. bulky rigids, some multilayer films, and wind turbines).

- Purification and depolymerization technologies are less commercially available than conversion technologies and their commercial success will rely on the ability to access or produce feedstock that is cleaner and more pre-processed. Our study suggests that purification and depolymerization technologies have the highest potential for favorable environmental and human health outcomes across all types of molecular recycling technologies evaluated.

- On average, the less a polymer is broken down in the recycling process the fewer mass losses occur along the journey to making plastic resin for packaging and products. Purification and depolymerization demonstrated the highest plastic mass yields, compared to conversion technologies. This directly correlates to the type of feedstock each technology group is processing: the cleaner and purer the feedstock, the greater plastic mass yield.

c. A wasteshed is a geographic area that serves as supply of post-consumer and post-industrial feedstock for recycling technologies.

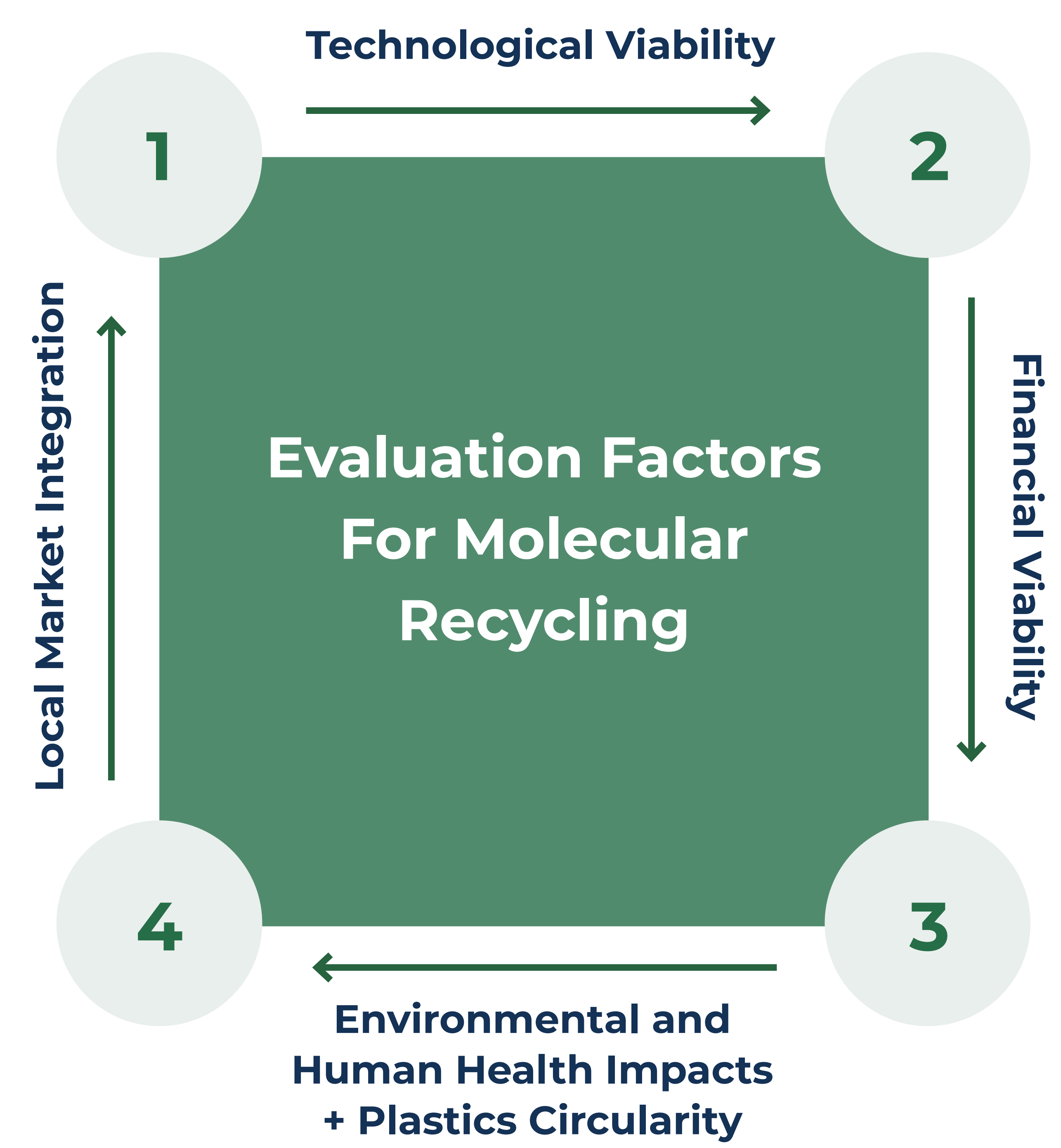
8 Closed Loop Partners' evaluation checklist can help investors and corporate partners execute the comprehensive diligence an early-stage sector this complex requires.

- Investors and industry partners should be prepared to jump into the technical nuances of this early-stage sector so that they support and scale best performing technologies that maximize value creation, sustainability, and circularity at the local level. Closed Loop Partners has developed an evaluation checklist with over 100 questions to support investors' diligence process.

- To realize the potential of this sector and mitigate financial, environmental, and human health risks, policymakers, investors, and corporate actors need to support and incentivize the development and commercialization of molecular recycling technology in a way that ensures the industry is scaled in ways that are circular, safe, and sustainable.

- Closed Loop Partners has introduced a framework for investors which evaluates technologies according to four key factors shown in Figure C.

FIGURE C. FOUR FACTORS FOR EVALUATING MOLECULAR RECYCLING TECHNOLOGIES



9

Brands can support the sustainable growth of the plastics recycling sector by stabilizing the demand for recycled plastics and investing across the entire recycling value chain.

- Entering into long-term supplier contracts is a key step companies can take to act on their public commitments to using recycled plastic content

- Technology is not a silver bullet. Scaling molecular recycling technologies that are safe, circular, and economically viable will require supporting investment into the existing collection and sortation infrastructure in the U.S. and Canada, as well as upstream solutions.

- Brands have an opportunity to collaborate across sectors and with peers to address multiple types of plastic waste (i.e. colored PET and polyester) to create new product standards that align and expedite the scale of recycled content end markets.

10 Policymakers can help expand the volume and types of plastics that are recycled and support a circular future for plastics by including molecular recycling in legislation that pertains to downstream material management and by setting regulatory guardrails that guide the sector's development toward circular outcomes that decarbonize plastics production .

- The molecular recycling sector has historically been shaped by cultural and economic forces that drive toward linear outcomes like waste-to-fuel, but a collective desire for a waste-free future is now pushing the industry towards circularity.

- Policies that support circular, safe, and sustainable downstream material management:
  1. help stabilize the demand for recycled plastic (PCR) through recycled content mandates for products and packaging;
  2. incorporate molecular recycling into extended producer responsibility legislation;
  3. support decarbonization and circular outcomes and protect human health and communities;
  4. provide financial incentives like tax credits that encourage upstream collaboration, investment into feedstock pre-processing, and investments in best performing molecular recycling operations.

Introduction

Over the last seven years, Closed Loop Partners has researched, tested and invested in multiple solutions to tackle the urgent plastic waste challenge. We launched the *Advancing Circular Systems for Plastics & Packaging Initiative* to chart a more sustainable pathway forward. The initiative prioritizes scaling reuse and refill models and reducing material usage in product design, while also bolstering the material recovery infrastructure to address existing plastic waste. Focusing on both upstream and downstream strategies is critical to address the diversity and volume of plastics in our economy.

Our work includes partnering with retailers to eliminate the single-use plastic bag, piloting reusable packaging models across the United States, investing more than $50 million in recycling infrastructure[4], launching global innovation challenges to identify alternatives to single-use plastics, and financing novel molecular recycling technologies that can advance circularity for plastics.

In this report, Closed Loop Partners focuses on just one part of the circular plastics system: molecular plastics recycling technologies and how they can support downstream material recovery and a circular future for plastics. We define molecular recycling as those technology processes that purify or break the plastic polymer apart to produce commodities like finished plastics, monomers, and hydrocarbon products that can be used to make new products. In recent years, there has been a surge of innovations, investments and partnerships forming across this diverse and nascent recycling sector, sometimes also referred to as “advanced recycling” or “chemical recycling.” At the same time, some environmental nonprofit organizations have expressed concerns about specific technologies and a need for increased transparency around their environmental and human health impacts[5, 6, 7].

To date, there is a scarcity of comparative analysis among different molecular recycling technologies and a lack of systems-level analysis of their potential opportunities and risks; this is why Closed Loop Partners continues to conduct research on this early-stage sector. We are committed to supporting data-backed decision-making to demystify novel solutions, go deeper into unanswered questions and conduct the appropriate due diligence required to avoid unintended consequences.

Our vision for the future prioritizes the technologies that can keep resources cycling in the economy, leading to plastics-to-plastics and plastic-to-product outcomes that are sustainable, circular, safe and economically-viable. Although there is no single solution to address the plastics waste crisis, this report seeks to equip stakeholders across the value chain with key data and insights to inform ongoing efforts to build circular plastics supply chains in the U.S. and Canada.

About this Report

As follow up to our 2019 report, *Accelerating Circular Supply Chains for Plastics: A Landscape of Transformational Technologies That Stop Plastic Waste, Keep Materials in Play and Grow Markets*, this report explores molecular recycling's role in a circular and safe plastics economy. The report summarizes findings from our research and shares our recommendations to align these technologies with sustainable and circular outcomes in the U.S. and Canada.

About the companies and data: Between March 2020 and October 2021 (Figure 1), Closed Loop Partners and its Center for the Circular Economy collaborated with nine diverse molecular recycling companies to develop this seminal report for investors, brands, retailers, policymakers and nonprofit organizations seeking education and actionable information on the potential, risks and benefits of this early-stage industry. Anthesis Group was our technical lead, supporting the data collection, data analysis, and interpretation of results in our study. This report reflects our insights from the evaluation of those nine datasets, while individual company case studies can be found on the Closed Loop Partners website. Separately, Closed Loop Partners collected financial data from three molecular recycling

FIGURE 1. STUDY TIMELINE AND KEY MILESTONES

March to July 2020

Data Collection
Data collected from nine technology companies. Data was self-reported and included detailed process technology information, as well as real and projected data on capital costs, development costs and all operational expenses.

July to November 2020

Data Quality Assurance
Technical and financial teams vetted self-reported data via:
1. Mass Balance
2. Energy Balance
3. Comparing and benchmarking the data against industry and market information
4. Return on Investment (IRR and NPV) calculations under different cost and revenue assumptions. All companies are modeled under the same set of assumptions.

December 2020 to March 2021

Data Analysis
1. Technical-Economic Analysis + Modularity Case Study
2. & 3. Environmental and Human Health Impact Analysis
4. Supply Chain Integration
5. U.S. and Canada Policy Analysis

February to October 2021

Writing and Peer Review
Over 30 peer reviewers with expertise in life cycle assessment, U.S. policy, public health, plastics recycling, investing, technology development, petrochemical industry and molecular recycling provided comments and feedback on draft versions of this report.

November 2021

Report Release
Summary of findings released in main report, along with nine case studies, and 100+ questions to support diligence of molecular recycling technology companies.

companies to produce our case study on the role of small-scale, modular technology systems.

Financial and technology process data were self-reported by each technology company. Our teams ran a quality assessment on all data collected because all nine molecular recycling companies operate in different parts of the world and are at different maturity levels (e.g. pilot, early commercial, growth). All technology process data went through a mass and energy balance to ensure all processes meet thermodynamic realities. Financial data collected included development costs, capital expenses, and operational expenses. All technology companies were modeled under the same set of assumptions. Our baseline scenario uses average U.S. 2021 and 2019 commodity prices for all inputs and outputs to project the return on investment for molecular recycling projects in the United States and Canada; we performed sensitivity analyses across all financial data, which are illustrated across this report.

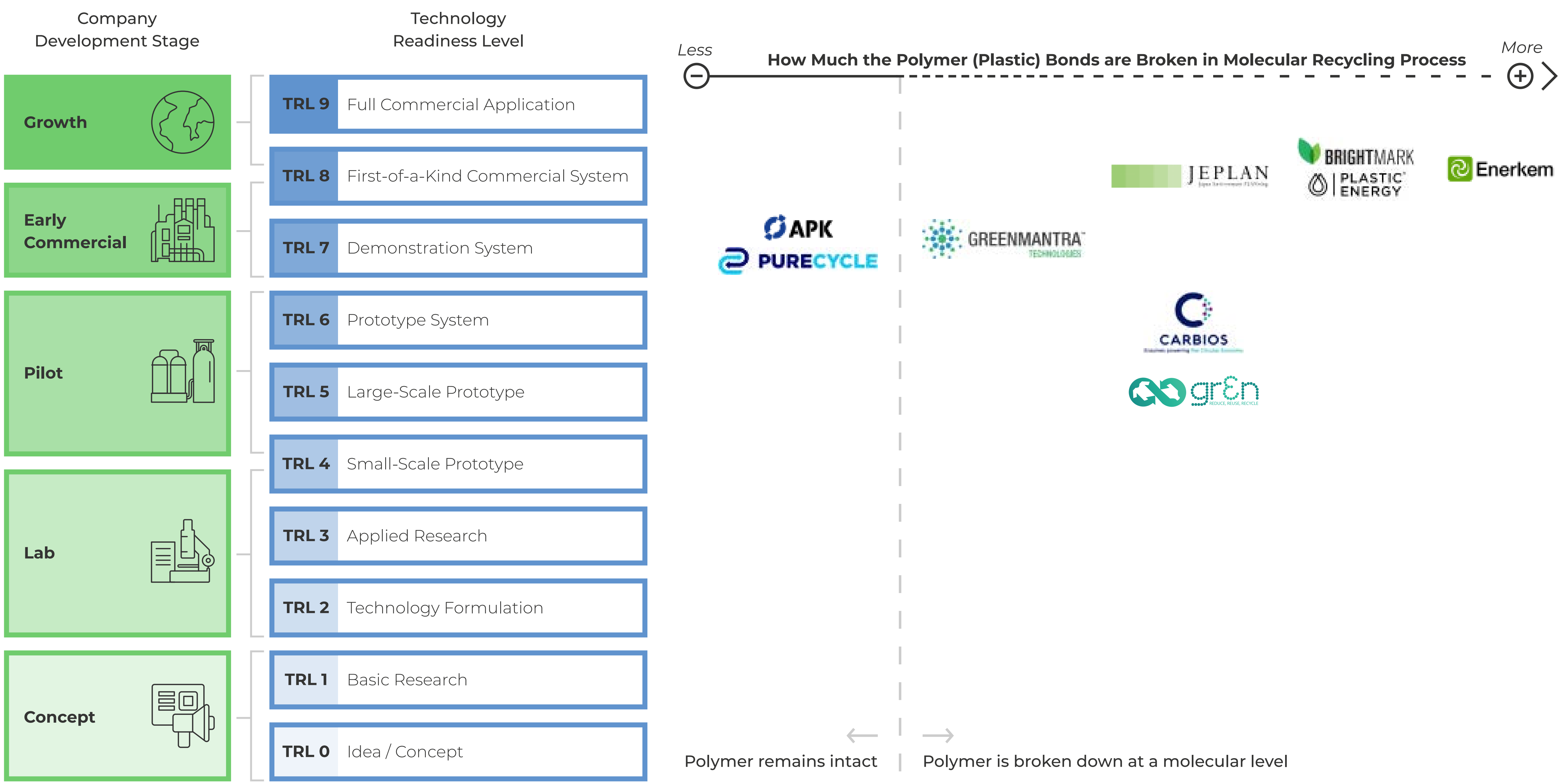
Throughout the report we offer readers the opportunity to dig into the details of our analysis, assumptions, and research. Click on the "Read More" buttons located throughout the report to be taken to the report's [web-based appendix](#) on Closed Loop Partners' website.

Appendix 1.0 outlines how these nine companies were selected for this project

> "Closed Loop Partners evaluated and tested the financial viability, environmental impacts, and human health risks of diverse advanced recycling processes using data provided by nine participating technology companies. The scarcity of comparative analysis among different molecular recycling technologies and the lack of systems-level analysis of their potential opportunities and risks is why Closed Loop Partners continues to conduct research on this early-stage sector."

– KATE DALY, MANAGING DIRECTOR, CENTER FOR THE CIRCULAR ECONOMY,
CLOSED LOOP PARTNERS

FIGURE 2. TECHNOLOGY READINESS LEVELS[1] (TRL) OF THE COMPANIES EVALUATED IN THIS REPORT AND WHERE THEY FALL ON THE PLASTICS RECYCLING SPECTRUM



Notes:
1. Technology readiness levels were initially developed by NASA as a method of measuring the maturity of space exploration technology, but have since been adopted by a range of industries to provide a consistent approach to assessing technology readiness. Figure 2 represents an adaptation to molecular recycling technologies paired to common commercial terms that refer to the stage of maturity of a company (i.e. pilot, growth)

The **Global Directory of Molecular Recycling Technologies** features profiles on these nine companies and 70+ others.

Educate

Solving the plastics waste challenge is an urgent need, and to achieve this, we need to first understand the complexities of plastic, the world's most ubiquitous and diverse material class. In this chapter, we dive into today's current "take-make-waste" linear system, establishing the need for upstream waste reduction strategies through design innovation and reuse systems at scale, and exploring the role of downstream strategies including molecular recycling technologies.

Educate

The Challenge: Plastics Waste Today

Plastics play a critical role in many industries, including fashion, healthcare, automotive and food & beverage, but less than 9% of plastics are recycled.

Plastic is one of the world's most ubiquitous and diverse material classes. It is lightweight to transport, relatively inexpensive to produce, and efficient in preserving goods. Over the last 70 years, the "take-make-waste" linear economy has been optimized for efficiency and profitability: raw materials are extracted at the lowest cost and products and packaging are designed to be thrown away, ending up in landfills, or worse, the environment. With plastics production set to triple by 2050[8], policymakers and industries working across borders are prioritizing closing the loop on plastics as an urgent challenge to address. A great deal of attention has been paid to the impact of single-use packaging on global plastic pollution but at Closed Loop Partners, we recognize that to create fully circular systems for plastics, we must deploy multiple strategies and harness diverse innovations to build a system that can recycle and recover *all kinds of plastics.*

> Plastics are ubiquitous in the fashion industry, representing over half of total fiber production. Fashion for Good is collaborating with the industry to create a range of solutions: scaling polyester chemical recycling technologies to keep these materials out of landfill and in circulation, and nurturing next generation materials, such as bio-based polyester alternatives.

– **KATRIN LEY, MANAGING DIRECTOR,**
FASHION FOR GOOD

1 Industries, brands, NGOs, policymakers and consumers must broaden their focus beyond single-use plastic packaging, and instead support recovery pathways for all types of plastics. Otherwise, we risk delaying a future free of plastic waste.

The “plastics waste crisis” has been defined in the public and policy discourse as created by single-use plastics. Yet, two-thirds of plastics put into use in the U.S. today are used for purposes other than single-use packaging[9]. These types of plastics are equally visible and challenging to recover and reuse: they make up half the volume of every car[10]; they comprise a significant portion of the electronic waste going to landfill every year[11]; and they comprise the majority of all apparel, in the form of polyester fibers[12] (Figure 3). While there are recycling systems for some plastic packaging, we have failed to act holistically to address all the types of plastic waste.

FIGURE 3. COMMON PLASTICS WITHOUT COMMERCIAL RECOVERY SOLUTIONS, TYPICALLY SENT TO LANDFILLS EVERY YEAR

Notes:

1. Source: *Primary Microplastics in the Oceans: a Global Evaluation of Sources*. 2017.
2. Source: *United Nations’ Global E-waste Monitor 2020,*
3. Source: *Circularity for Healthcare Plastics: The Challenges and Opportunities. 2020.*
4 Souce: *Plastics in the US: toward a material flow characterization of production, markets and end of life. 2020*

2 Our current recycling systems have not been optimized to process the diversity and volume of plastic waste.

Mechanical recycling is the dominant recycling system today, producing nearly 100% of recycled plastic content in the U.S. and Canada[13]. Most recovered plastics are processed through mechanical means without substantially altering the chemical structure of the plastic. Historically, the demand for recycled plastics has only created economic incentives for the recycling industry to target a small fraction of the plastics being put into the market that have existing collection and reverse supply chains —namely, clear polyethylene terephthalate (PET) and natural high-density polyethylene (HDPE) bottles (e.g. soda bottles, milk jugs), and in some markets, rigid polypropylene (PP). Other types of plastic packaging, like low-density polyethylene (LDPE), PET thermosets, and black and colored plastic, are recycled in lower quantities because there is less consistent demand for these recycled plastics so most end up in landfill[14]. The technical and financial barriers to mechanically recycling more plastics are some of the many reasons why plastic recycling rates remain so low in the U.S. and Canada, where only 18% of plastic packaging[15] is recycled, and only approximately 9% of plastics are recycled globally[16].

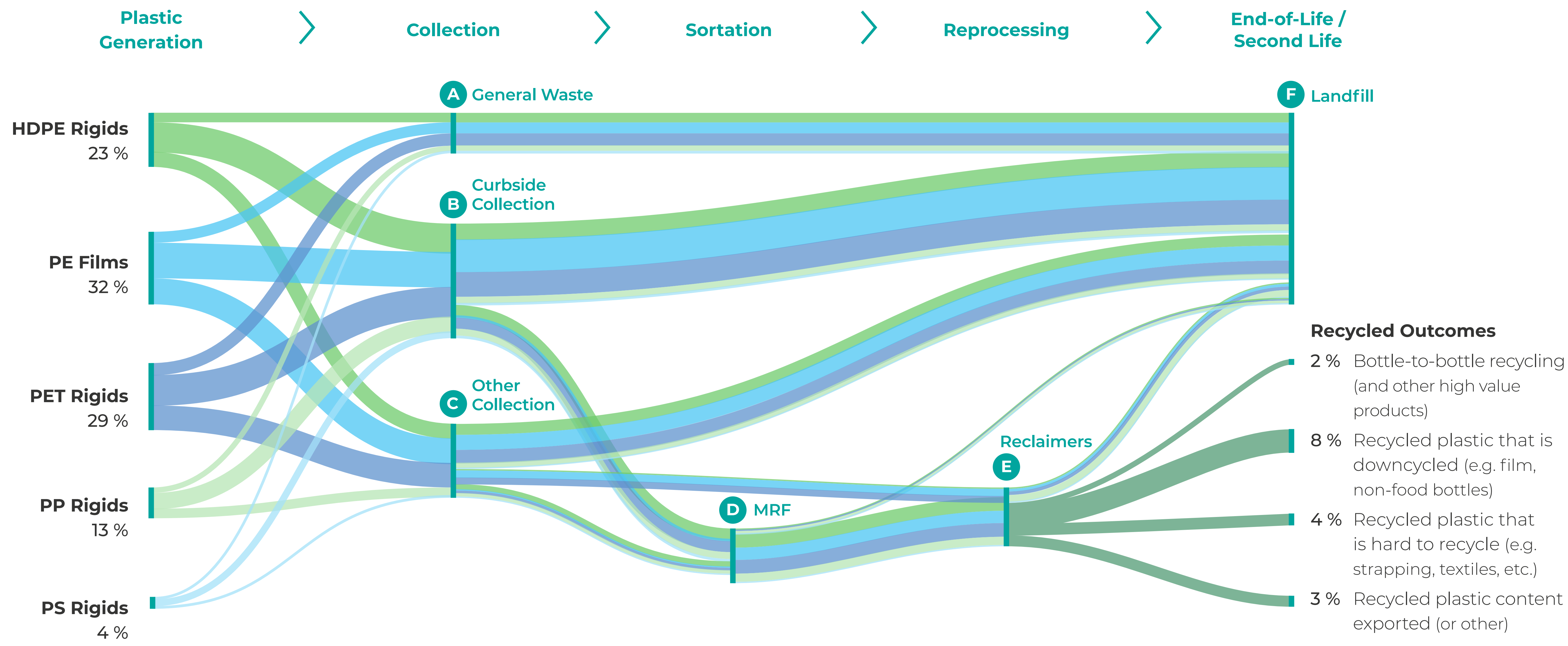
> Current approaches in the plastics recycling system are on track to leave the industry woefully undersupplied with high quality recycled feedstocks. Advanced recycling will need to play a key complementary role in the waste recovery ecosystem if this gap is to be closed.
>
> – **GUY BAILEY, HEAD OF INTERMEDIATES AND APPLICATIONS,** WOOD MACKENZIE CHEMICALS

3 The inconsistent supply of high-quality recycled plastic for industries like food and automotive, as well as the lower cost of virgin plastic, drives industries to use virgin plastic in products and packaging rather than recycled plastic content.

Approximately 170,000 metric tons of PET and HDPE bottles are recycled into new bottles[17] using existing mechanical recycling processes, which keeps these materials in play at their highest value. However, most of the post-consumer recycled content (PCR) used in manufacturing is downcycled[18] where the resulting recycled material is of lower quality and functionality than the original material. The persistence of chemical additives in PCR that is put through a mechanical recycling process makes the recycled content ineligible for food-grade or medical grade-applications, and less in demand for other applications[19]. PCR is used to produce goods like composite decking, agricultural film and pipes, despite competitive demand for high-quality PCR, such as recycled PET (rPET). However, over 50%[20] of all rPET in the United States and Canada is downcycled into recycled content fibers for apparel—but those textiles do not currently have end-of-life solutions[21].

The inconsistent supply of high-quality PCR is compounded by virgin plastic currently being cheaper and more readily available than recycled plastic[22]. Historically, market incentives and policies in the United States and Canada have not focused on developing circular, plastic-to-plastic supply chains. In these markets, manufacturers are not rewarded for using recycled plastic content, nor are they penalized for using virgin resin. As a result, manufacturers have favored the lowest priced commodity on the market, which is often virgin polymers instead of mechanically recycled polymers.

FIGURE 4. PLASTIC PACKAGING FLOWS ACROSS THE VALUE CHAIN: MAJORITY OF PLASTIC PACKAGING IS DOWNCYCLED IN THE U.S. AND CANADA[22]



A

Waste With No Available Recycling Collection

B

Curbside Recycling Collections
Around 50% of plastics are captured in curbside waste collections. However, over two-thirds of this material is discarded in non-recycling bins and doesn't enter the recycling.

C

Other Recycling Collections
Roughly 30% of plastics are collected by non-curbside routes. Most of this material goes through a sorting facility, with some collected material being sent directly to reclaimers or secondary processors.

D

Materials Recovery Facility (MRF)
Sorting facilities separate plastics by resin and produce commodity waste plastic bales which can be sold to reclaimers and secondary processors.

E

Reclaimers & Secondary Processors
Reclaimers and other secondary processors typically shred and wash waste plastic to produce feedstocks for manufacturing.

F

Landfill
Nearly 85 % of plastic waste will end up not being recycled, either being discarded with general waste, or rejected by the plastics recycling supply chain.

Click here to see this data on an interactive dashboard on the Closed Loop Partners' website.

Educate

How do we effectively address mounting plastic waste in the U.S. and Canada?

1 No single sector, technology or approach can solve the plastics waste challenge.

A circular system for plastics requires consciously designing systems and products to use fewer materials from the outset, while keeping existing materials in circulation at their highest value for as many generations as possible, if not infinitely.

This transition from linear to circular will require the full arsenal of strategies, including reduction, reuse and refill systems, mechanical recycling, molecular recycling, and policies to take into consideration economic incentives, environmental benefit and healthy communities (Figure 5). It is critical to invest across all five strategies to create a circular system for plastics and stop plastic waste.

Without this holistic approach, the majority of plastics produced today across every sector will continue to slip through the cracks of the system, steadily mounting in landfills or our environment, with limited end-of-life solutions.

Plastics serve a critical role in many industries, such as healthcare and packaging, and for certain use cases plastics will remain the highest-performing and best materials of choice. Even upstream

FIGURE 5. MULTI-PRONGED APPROACH TO ADDRESS DIVERSITY OF PLASTIC WASTE

plastic waste solutions, like deploying reuse and refill systems, are not necessarily plastic-free. As such, downstream solutions are needed to provide the reverse logistics mechanism to recapture the value in plastics already in circulation. Downstream solutions, including mechanical recycling and molecular recycling, enable circularity when they are transparent, efficient, and supported by investment and policy.

> For a problem as massive and systemic as plastic waste, it is essential to consider all possible solutions and to rely on data to inform decision-making. This report provides a sober analysis of some of the best data so far available for a range of advanced recycling technology processes and what role they may be able to play in addressing plastic waste at scale.
>
> – **ELLIE MOSS, PLASTICS SOLUTIONS CONSULTANT,** OVERBROOK FOUNDATION

How Closed Loop Partners Takes a Multi-Pronged Approach to Address Plastic Waste	Closed Loop Partners' Educational Resources
Plastics Reduction via Design Innovation Through the NextGen Consortium, Consortium to Reinvent the Retail Bag and Compostable Packaging Consortium, managed by our Center for the Circular Economy, we advance innovative design solutions that keep end-of-life in mind: reducing material use; incorporating alternative, renewable raw materials; enabling modularity.	A New Way Home: Assessing the design opportunities to replace today's single-use plastic retail bag ↗ Navigating Plastic Alternatives In a Circular Economy ↗
Reuse, Resale, and Refill Systems Through our Ventures Group, as well as the NextGen Consortium and Consortium to Reinvent the Retail Bag, we scale reuse models that extend the useful life of products and packaging, and reduce our reliance on single-use materials.	NextGen Cup: Reuse Pilots ↗ Algramo Introduces State-of-the-Art Refill Model to Deliver Affordable Cleaning Product Without Waste in New York City ↗ The Rise of Resale: Digitizing Vintage ↗ Bringing Reusable Packaging Systems to Life: Lessons Learned from Scaling Reusable Cups ↗
Molecular Recycling Technologies Through research conducted by our Center for the Circular Economy, and investments through our Infrastructure Group, we explore the potential of molecular recycling technologies to address the most difficult-to-recycle plastics, and meet the growing demand for high-quality food and medical grade recycled plastics.	Accelerating Circular Supply Chains for Plastics ↗ Closed Loop Infrastructure Group ↗ GreenMantra Technologies: From Yogurt Cups to Asphalt Roads ↗
Mechanical Recycling Systems Through our Infrastructure Group and Private Equity Group, we invest in materials recovery infrastructure, technologies and companies that recapture and recycle materials after use, therefore reducing the need to extract virgin resources.	Closed Loop Infrastructure Group ↗ Eureka Recycling: Eureka! The Twin Cities Are Raising the Recycling Game ↗ Lakeshore Recycling: From 20 Tons Per Day to 20 Tons Per Hour ↗ AeroAggregates: Turning Glass Waste into Construction Materials ↗ Adding Value to MRF Outputs by Enhancing Polypropylene Recovery ↗
Policies Incentivizing Circularity Through our vast network of partners, we support policies and market incentives that advance profitable circular systems and solutions, and enable a strong, stable market for recycled and renewable materials.	Circular Economy Infrastructure Will Build Value for All Americans ↗ Closed Loop Partners at the United States Senate Environment and Public Works Committee on Recycling ↗

Educate

What is molecular recycling and how can it contribute to the circular economy?

1 Molecular recycling is a diverse sector, encompassing dozens of different technology processes that are characterized by the types of outputs they produce.

Like plastics, molecular recycling is not a monolith. The diverse sector is rapidly evolving, and is in its early stages of development and commercialization. The term "molecular recycling" refers to the dozens of types of technology processes that purify or break down plastic to create polymers, monomers, oligomers or hydrocarbon products[24]. It includes more commonly known "chemical recycling"[25] technology processes like pyrolysis, as well as other types of technology processes that leverage enzymes, soundwaves and other technology platforms to transform plastics. At the broadest level, these processes can be divided into three technology categories: purification; depolymerization; and conversion[26]. The three technology categories are defined by the outputs that they produce, outlined in Figure 6.

Purification processes are distinguished from other molecular recycling categories by not breaking the bonds of the plastic polymer[27]; purification is a physical process. Purification processes use solvents to extract color and additives from single-polymer feedstock or mixed plastics to produce virgin-like polymers. These processes guarantee a plastic-to-plastic outcome.

There are two types of **depolymerization** processes that both take single-resin feedstock and break down the polymer chains and limit side reactions to produce a specific set of products[28] monomers or oligomers. Monomers are precursors to polymers and can be synthesized, or "repolymerized" to produce a plastic resin; for example, the monomers TPA and MEG can be repolymerized into PET polymer to make PET bottles or polyester fabric[29]. Oligomers are longer chained monomers and include products like polypropylene wax[30].

Partial depolymerization breaks only some of the bonds in the polymer chain to produce low molecular weight polymer chains, which can be sold as a standalone product, or in some cases repolymerized after the removal of colorants and additives. Full depolymerization completely breaks down the polymer chain into monomers (or sometimes oligomers), which can be polymerized back to plastic or moved to other supply chains in an open loop system. Both types of depolymerization require cleaner, plastic-only feedstock as inputs.

Like depolymerization, **conversion** technologies break bonds in the polymer chain and can be divided into "partial" and "full" sub-categories. Conversion targets polyolefin plastics like polypropylene and polyethylene, as well as polystyrene (PS). **Partial conversion**, such as pyrolysis, breaks the polymer chains and can involve side reactions to produce diverse hydrocarbon products with a relatively large range of molecular weights

FIGURE 6. BREAKDOWN OF TECHNOLOGY CATEGORIES AND TYPES IN MOLECULAR RECYCLING SECTOR

	PURIFICATION	DEPOLYMERIZATION		CONVERSION	
		Partial	Full	Partial	Full
Main Polymer Inputs	• Polypropylene (PP) • Polyethylene (PE) • Polystyrene (PS) • ABS Molecular homogeneity in input is preferred to ensure high output quality[1]	• Polyethylene terephthalate (PET) • PP • PE	• PET • Polyamide (PA) • PS • Polylactic acid (PLA) • Poly(methyl methacrylate) (PMMA) • Polyurethane (PU)	• Mixed (PE, PP, and PS preferred)	• Mixed
Features of Reaction	• Polymer bonds are not broken	• Limited chain scission • Limited side reactions	• Full chain scission • Usually chain-end scission reactions (where monomers are removed one-by-one)[2]	• Random chain scission • Side reactions such as cyclisation	• All bonds broken including C-C and C-H • Initial products of process are not hydrocarbons (e.g. syngas from gasification or carbon from flash-joule heating)
Typical Technology Outputs	• Colourless polymer flakes or pellets	• Oligomers • Polypropylene wax • Polyethylene wax	• Monomers, e.g. monoethylene glycol (MEG) & purified terephthalic acid (PTA) • Solvents • Polyethylene waxstyrenic polymers	• Crude oil • Naphtha • Paraffinic waxes • Alkenes (ethylene & propylene) • BTX • Diesel and other fuels	• Syngas (carbon monoxide and hydrogen mixture) • Methanol • Elemental carbon
Features of Products	• Molecular structure of polymers are unchanged from the input material	• Specific molecular products (oligomers, narrow distribution waxes)	• Specific molecular products (monomers)	• Products consist of mixtures of molecular species, often separated into fractions • Relatively wide distribution of product molecular weight	• Specific molecular products which are often fed directly into another reactor to produce other chemical products such as methanol or hydrocarbons
Technology Process Types	Solvent Extraction, De-inking	Enzymatic Degradation, Microorganism Degradation, Solvolysis (e.g. Hydrolysis, Glycolysis, Methanolysis, Ammonolysis), Pyrolysis, Hydrothermal, Microwave, Ultrasonic			Gasification, Flash Joule Heating, Plasma-arc Gasification

Notes:
1. E.g. for polypropylene, a single stream of homopolymer PP would be preferred, while a mixture of homopolymer and copolymer PP may be harder to process
2. Mechanisms for some polymers (such as PS and PMMA) can be complex

like naphtha, paraffin waxes, other petrochemical products, and fuels[31]. **Full conversion**, which includes gasification and flash joule heating, completely breaks down the polymer to form syngas or elemental carbon products like methanol and hydrogen[32]. Full conversion technologies are distinguished by being able to process mixed waste with plastics commingled in it.

Several conversion outputs can be used in plastic-to-plastic supply chains[33]. The most common outputs used in conversion-based circular supply chains is naphtha. Plastic can also be produced via methanol-to-olefin (MTO), as well as diesel, if the customer has a specific steam cracker kit. There is yield loss and extra energy required with each additional unit operation.

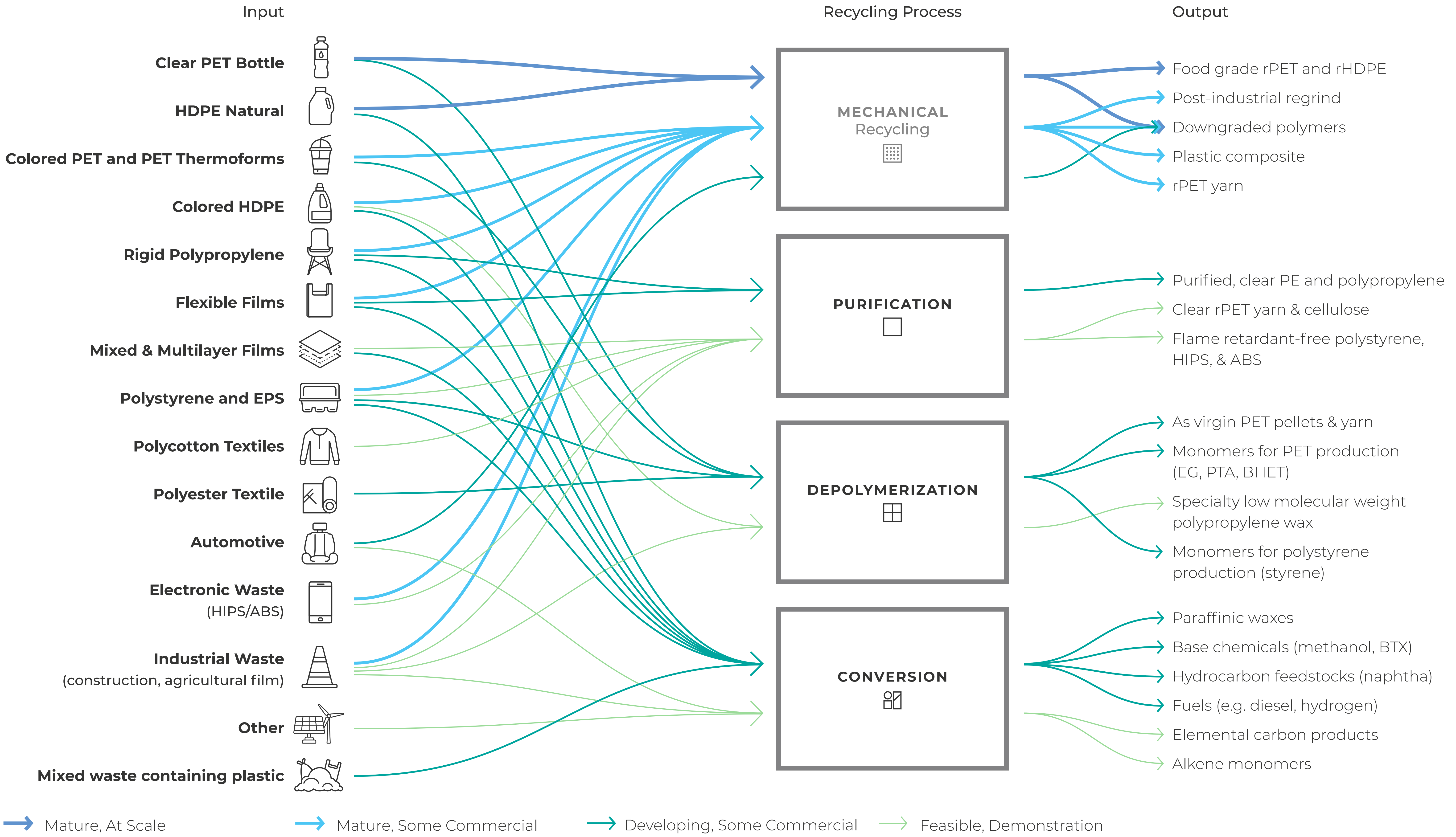
The risks, impacts and benefits of a particular molecular recycling technology are specific to that technology and its chosen inputs and outputs, which vary depending on availability and market demand. Treating this diverse sector as uniform, whether from a regulatory or investment perspective, risks overlooking or underestimating the potential benefits and impacts of distinct technology solutions.

2 Molecular recycling technologies can take in a wide range of plastic feedstocks —including textiles, electronics, construction materials and healthcare products— and thus, expand the scope and volume of plastic materials that can be recycled back into manufacturing.

While most molecular recycling technology companies today target post-consumer and post-industrial plastic packaging as feedstock, a growing number target other types of hard-to-recycle plastic waste—including the 41 million metric tons of textiles[34] and approximately 8,000 wind turbine blades expected to go to landfill in the U.S.[35] over the next four years. The diversity of plastic waste being processed by the early-stage sector demonstrates both the flexibility of some solutions and the direction that the sector can head, if we can create a strong remanufacturing base and commercialize safe and circular technologies. Figure 7 illustrates the most and least common flows of materials through the mechanical, purification, depolymerization and conversion technologies, from input to output.

Molecular recycling can process plastic waste that would otherwise be landfilled and not targeted by mechanical recycling, and convert it into high-quality plastics or products, such as food- and cosmetic-grade plastics, monomers that can go into textile softeners, and petrochemical products that can go into paint. But, molecular recycling has

FIGURE 7. RECYCLING INPUTS AND OUTPUTS: EARLY AND DEVELOPING MATERIAL FLOWS BY TECHNOLOGY CATEGORY



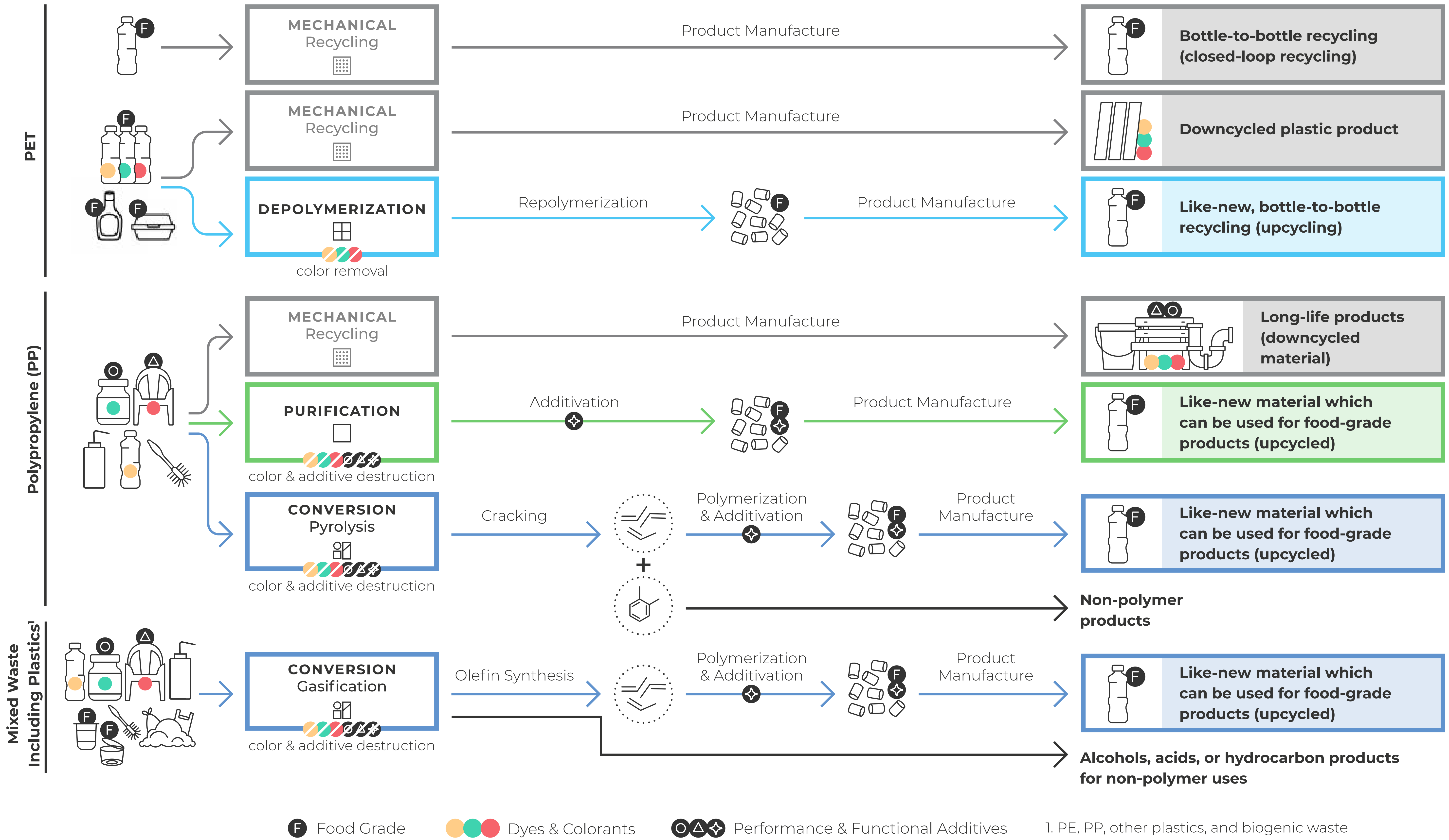
applications beyond just the hardest-to-recycle parts of the plastics wastestream, including some of the most common types which are not treated by mechanical recycling. We must look at the full range of applications in order to fully understand molecular recycling's role in a circular economy.

3 Molecular recycling is uniquely positioned to upcycle lower-quality plastics to high-quality outputs that maintain high economic value because the technologies purify the polymer or change the plastic waste at a molecular level. The industry can reduce the need for fossil fuel extraction for virgin plastics by bridging the gap between the demand for and supply of high-quality recycled plastic.

Today, most of the recycled plastics that enter the market are downcycled, meaning that the recycled output is downgraded in use and value compared to its original format. The main technical barrier that inhibits the widespread application of mechanically recycled plastics in the production of high-quality recycled content is the challenge of removing performance additives such as stabilizers and biological preservatives from plastic packaging and products[36]. The mechanical recycling system requires food-grade plastic feedstock to produce food-grade recycled plastics. That is challenging when so many of the plastics in the market contain high proportions of additives such as fillers or flame retardants, depending on their application and needed functionality. For example, polypropylene can be compounded with high ratios of calcium carbonate (e.g. 20-50% of total weight) to improve mechanical properties, impact resistance, and thermoforming[37]. PET bottles typically contain additives such as oxygen scavengers and barrier layers (e.g. polyamide), making up between 5-8% of a bottle's total weight[38]. Producing food-grade plastic through mechanical recycling requires feedstock made up of more than 90% food-grade plastics. Securing this feedstock is a challenge since most plastics collection in the U.S. and Canada is single-stream, which would not typically have such a high share of food-grade material.

Molecular recycling works differently by thermodynamically "resetting" the polymer material and removing contaminants, such as color and performance additives, from the recycled plastic to create a virgin-like polymer or petrochemical product[39]. Purification, depolymerization and conversion technology processes each do this distinctly from one another, and they do not need high-quality plastic feedstock (i.e. food-grade) to produce high-quality outputs (Figure 8)[40]. The trade-off is that resetting a polymer through molecular recycling requires more energy than mechanically recycling plastic, an issue discussed later in this report.

FIGURE 8. THE SCIENCE BEHIND PLASTICS RECYCLING: DIFFERENCE IN OUTPUT QUALITY BETWEEN RECYCLING PET AND POLYPROPYLENE THROUGH MECHANICAL AND MOLECULAR RECYCLING PROCESS



1. PE, PP, other plastics, and biogenic waste

4 Purification, depolymerization, and conversion technologies can all fit into a circular economy. The collaborative efforts of policymakers, industry, community and environmental groups, and investors will determine how circular, safe, and sustainable these technologies will be.

The potential applications of molecular recycling outputs have uses outside of plastic supply chains; for example, outputs from depolymerization and conversion processes can be used in the hundreds of manufacturing sectors that utilize monomers and petrochemical products. Molecular recycling operators will sell their outputs into the markets which offer the strongest economic opportunities. But, the variety of outputs from molecular recycling technologies represent varying degrees of circularity. It's critical that the industry develops specifically in alignment with circular outcomes. For example, in the European Union, where recycled plastic content has been mandated for products and packaging since 2020[41], there are over 50 pilot project announcements made that represent plastic-to-plastic outcomes and investment commitments of €7.2 billion Euros[42] by various petrochemical companies.

Closed Loop Partners' vision for a circular future prioritizes the growth of technology solutions that lead to plastics-to-plastics and plastics-to-product outcomes. We do not consider plastics-to-fuel to be recycling or circular[d], a perspective that is held across a range of stakeholder groups including the petrochemical industry, mechanical recyclers, and environmental NGO groups.

d. Closed Loop Partners does not consider plastics-to-fuel recycling circular because the carbon resources transferred to fuel products do not stay in the economy for multiple generations and because a circular economy is underpinned by a transition to renewable energy. Our goal is to maximize the economic opportunity, create more circular supply chains, and mitigate climate change and human health risks.

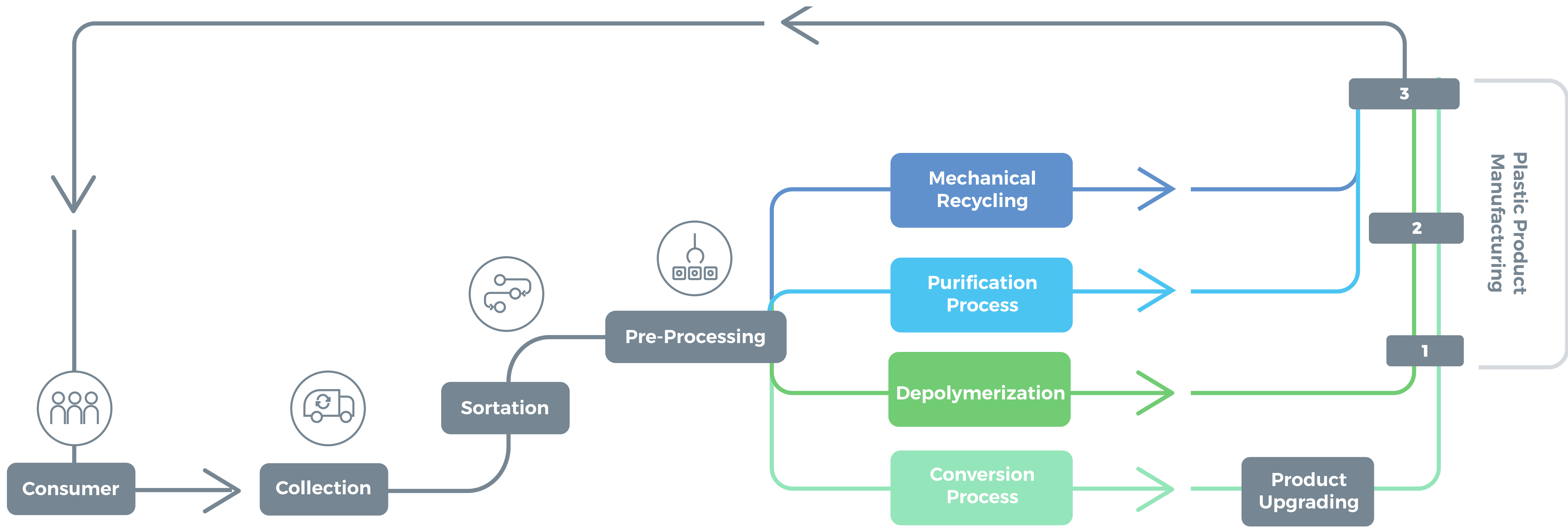
5

Mechanical recycling and molecular recycling can be complementary and symbiotic sectors which together process the diversity of plastics waste and produce distinct outputs that can be applied to different end markets.

Use of molecular recycling outputs will not make economic sense for many sectors. For example, plastic bucket and park bench manufacturers do not need to use virgin-quality recycled polypropylene (rPP) from a purification technology company, when lower-grade plastics suffice. The diversity of end markets for recycled plastics—and their associated quality specifications—highlight that mechanical and molecular recycling are complementary. Working in tandem, these two systems can recover a wider range of plastic waste in our system and produce an expanded range of plastics and products that can be appropriately directed to the market that makes most sense.

The potential for a symbiotic relationship between mechanical and molecular recycling is already illustrated in the existing collections and the mechanical recycling system. Today, material recovery facilities are an important source for plastic feedstock for many molecular recycling technology companies in the United States and Canada. Collaboration between mechanical recyclers and molecular recycling operators can create new pathways to increase plastics recycling and develop more circular and collaborative plastic supply chains involving plastics recyclers, the chemical & petrochemical industry, plastic packaging producers, industrial users, and most importantly, the retail and consumer goods sectors who are the key users of plastic material and packaging (Figure 9). There are economic reasons for collaboration between these sectors too, which the next section dives into.

FIGURE 9. A VISION FOR THE FUTURE: MECHANICAL AND MOLECULAR RECYCLING SUPPORT CIRCULAR PLASTICS SUPPLY CHAINS



Mechanical

A physical process of grinding, washing, separating, drying, re-granulating and compounding post-use plastics to produce recycled plastic content.

Purification

Because purification technologies do not break the bonds of the plastic polymer, their route back to plastic is the shortest of all advanced recycling technologies.

Depolymerization

Depolymerization technologies that feed back into the plastics supply chain go through at least one polymerization process to combine monomers back into plastics. Partial depolymerization creates polymers (i.e .waxes) that can be used as additives within the processing of virgin or

Conversion

Since conversion processes bring plastic back to the molecule or hydrocarbon state, these technologies require multiple steps to be transformed back to plastics. Most often that includes distillation of target molecules, steam cracking, and repolymerization.

Product Upgrading

Steps that molecules and hydrocarbons from conversion or depolymerization technologies must undergo to meet a market product standard or serve as an input that replaces virgin products in the plastics supply chain.

Plastic Product Manufacturing

The multiple steps in the value chain that converts petrochemicals into plastics used in products and packaging. The more steps back to a finished plastic, the further a recycling process has broken down the plastic polymer.

DEEP DIVE

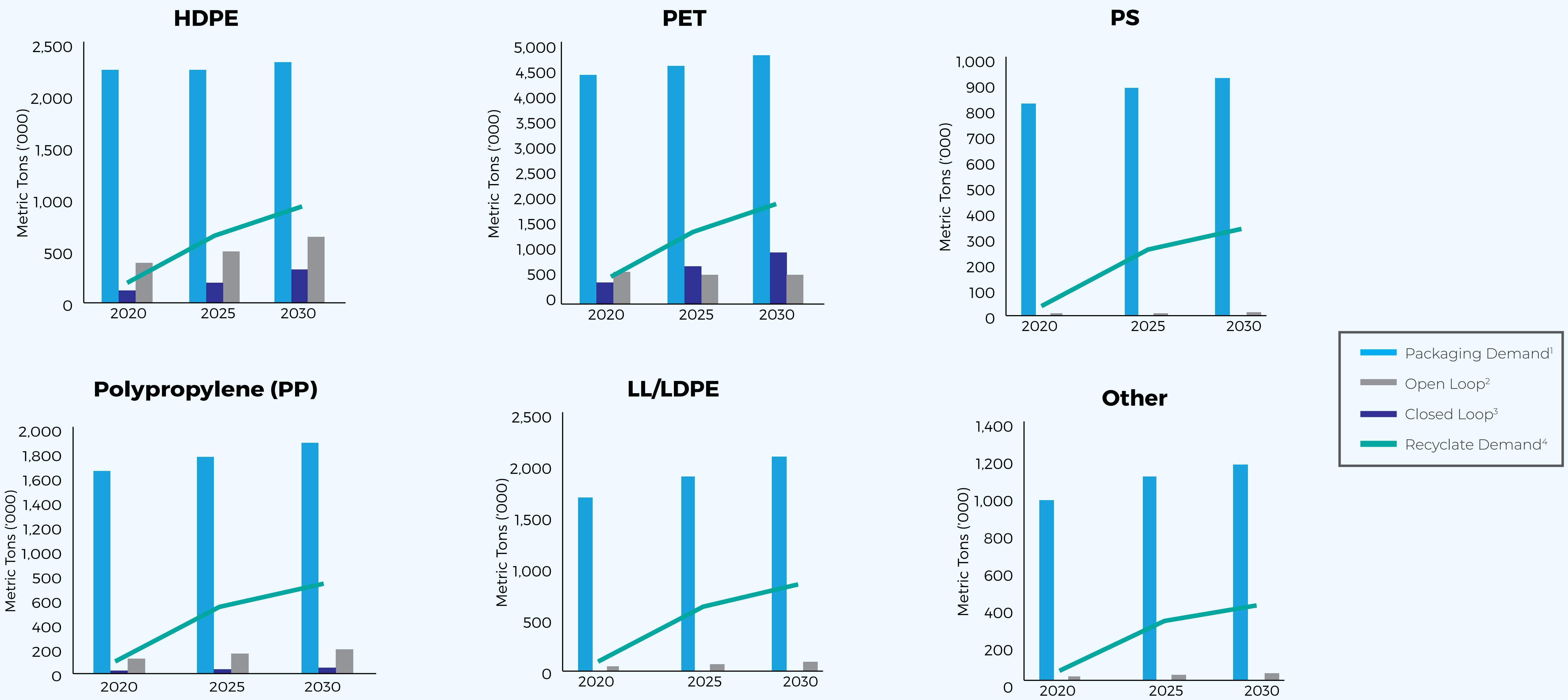
Why upcycling plastic waste matters in a circular economy

In the U.S. and Canada, the supply of recycled plastics meets just 6% of demand for the most common plastics.[43] Even when the aspiration to achieve circularity exists, there is not enough supply of high-quality recycled plastic content to meet the projected industry demand by 2030. Using data from Wood Mackenzie's Material and Application Platform, we found that only 6% of the total demand for food-grade resin was met in 2020; that number is exected to grow to 12% by 2030 in a busines-as-usual scenario.[44] Figure 10 breaks down the supply and demand for food-grade plastics in the United States and Canada between 2020 and 2030. The graph visualizes the volumes required to meet a 30% recycling goal across resins. Between 2020 and 2025, the demand for recycled plastic content increases 255%; by 2030 the demand for recycled content is four times the demand volumes in 2020. Reaching a goal of a 30% packaging recycling rate during this decade (i.e. teal line in Figure 10), will require investment design innovation to align with downstream systems and increased investment into the collection and soration system and downstream solutions. Without scaled recycling solutions to help maintain the quality of recycled plastic for broad application across consumer goods and food and beverage industries, the deficit illustrated between recyclate supply and packaging demand will continue to be filled by the virgin plastics industry.

In the U.S., more than 80 corporate retailers, brands and packaging producers have made aggressive public commitments under the U.S. Plastics Pact. With these commitments, they have pledged to make all plastic packaging 100% reusable, recyclable or compostable; to recycle or compost 50% of plastic packaging; and to use an average of 30% recycled content in all packaging by 2025.[46] Petrochemical trade associations like the American Chemistry Council have committed to recycle or recover all plastic packaging used by 2040.[47] Though voluntary, these commitments to use PCR content for products and packaging signal and accelerate market opportunities for the molecular recycling industry to help supply high-quality recycled content.

One clear path to mitigating climate change and waste in the economy is circularity, which research has shown can reduce 45%[48] of global emissions associated with making products. By creating like-new plastics or feedstock to make new plastics or other products, molecular recycling can help play a role in replacing the need for fossil fuel extraction for virgin plastics.

FIGURE 10. SUPPLY AND DEMAND FOR FOOD-GRADE PLASTICS IN THE U.S. AND CANADA 2015-2030



Source: Wood Mackenzie's Materials and Applications Platform, Q2 2021

Notes:

1. Packaging demand - the amount of demand forecasted for that polymer in packaging applications in the given year
2. Open Loop - the amount forecasted that will go into open loop mechanical routes, after process losses (estimated at ~25%)
3. Closed Loop - the amount forecasted that will stay within the packaging sector via mechanical routes, after process losses
4. Recyclate Demand - the amount of material that would be needed to reach a 30% recycling rate across all applications using that polymer in that given year

Educate

What are the risks of molecular recycling? What do we stand to gain?

1

Molecular recycling is like any early-stage sector: there are some strong, economically-viable investment opportunities across all three technology categories, as well as variability in the financial performance and environmental impact within and across the categories. The due diligence process will be critical to ensure that only the strong-performing, safe and circular technology companies are scaled.

A principal concern from investors and NGOs looking to understand the viability of this sector is whether companies can meet investor expectations for profitability. In our analyses, seven of the nine technology companies evaluated had a positive internal rate of return (IRR) ranging from 6 to 62% in the 2021 base case (see Methodology for explanation and Figure 11 for summary). It is significant that two-thirds of the technology companies in our study had positive IRRs since our base case holds these technologies to the expectation of selling their outputs at market commodity prices without a premium. Our analysis over 18 months highlights the fast changing forecast for this sector; the last two years has created a significantly more positive outlook for technologies in this space. Figure 11 summarizes the expected rate of return across three scenarios: 2021 market pricing; 2019 market pricing; and the expected output pricing cited by the technology companies themselves.

Methodology: Internal Rate of Return (IRR)

2021 Base-Case Scenario assumes:

- Technology companies in our study would pay for plastic waste feedstock in the U.S. and Canada—or for the conversion technologies that can process mixed waste, they receive a modest tipping fee for avoided landfill costs (i.e. CLP study average: $50 USD/metric ton).

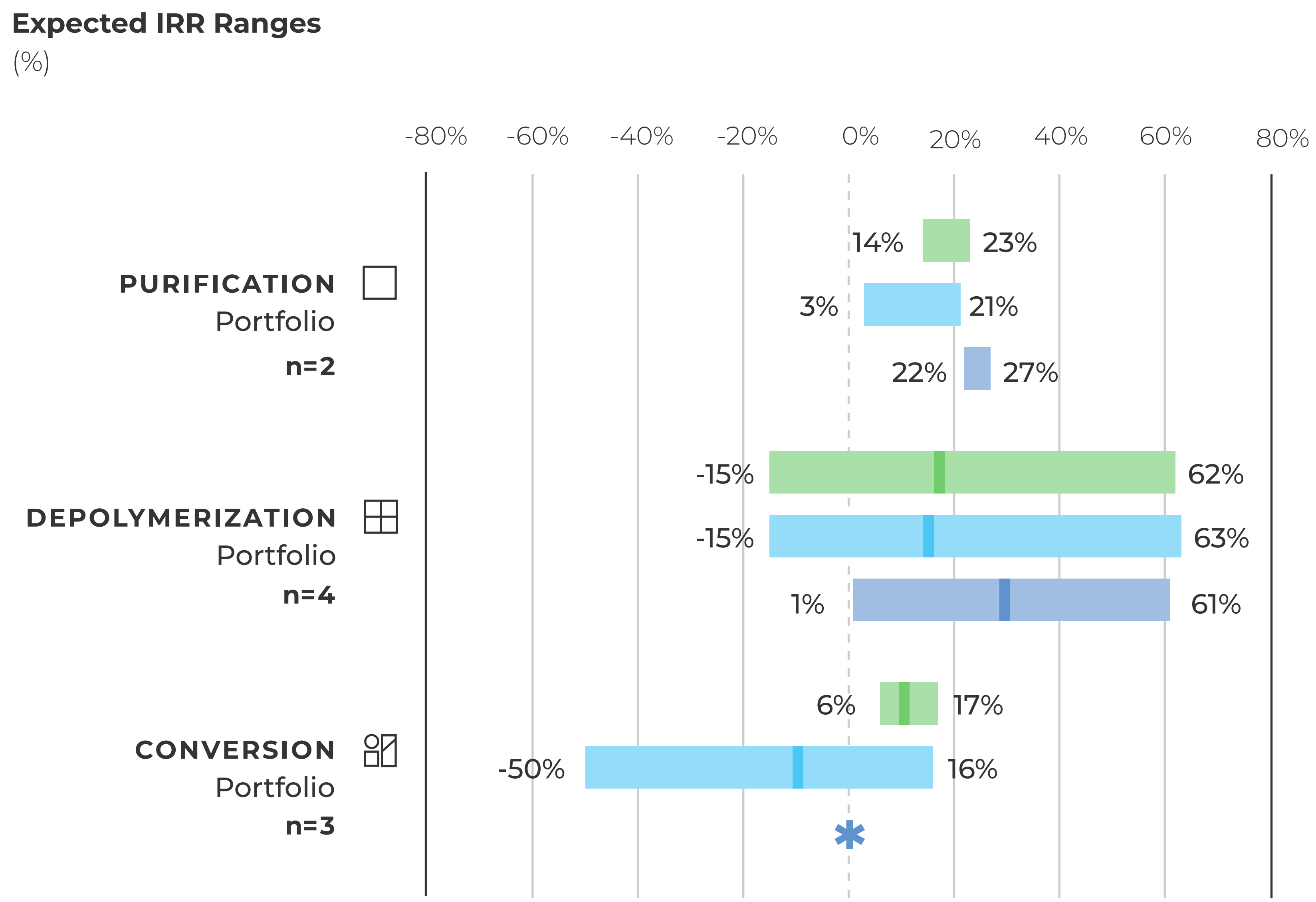
- Companies sell outputs at 2021 commodity prices (sometimes virgin, sometimes recycled commodity price)

2019 Base-Case Scenario assumes:

- Technology companies in our study would pay for waste plastics feedstock in the United States or Canada - or for the conversion technologies that can process mixed waste, they receive a modest tipping fee for avoided landfill costs (i.e. CLP study average: $50 USD/metric ton).

- Companies sell outputs at 2019 virgin commodity prices

FIGURE 11. EXPECTED INTERNAL RATE OF RETURN OF MOLECULAR RECYCLING ACROSS THREE MARKET SCENARIOS



Notes:
* Output prices not given by conversion suppliers

IRR averages provided for portfolio groups with 3+ data points

Current Market Pricing: IRR results when primary product output prices are set to 2021 market prices. Appendix 2.1 details these market prices.

2019 Market Pricing: IRR results when primary product output prices are set to 2019 market pricing.

Company's Assumed Pricing: IRR results when prices for primary product outputs set to technology company's expectations.

- Current Market Pricing (2021)
- 2019 Market Pricing
- Company's Assumed Pricing

Learn more about our financial analysis methodology and data assumptions in **Appendix 2.0** and **Appendix 2.1**

A few findings emerge when we compare the rates of return across molecular recycling companies in 2019 and 2021. First, profitability is at risk if the molecular recycling output is expected to directly compete with virgin market pricing. In the 2019 base-case (see Methodology), only three companies had IRRs above 10%, but in 2021 that number jumped to 6 companies because the virgin prices in the market had changed. Next, because some molecular recycling companies are uniquely positioned to create like-new outputs and commodities with environmental benefits, the companies in the sector are creating new commodity prices where companies do not necessarily have to sell at or compete with prices for virgin materials. This has a positive impact on their financial viability, sustainability and outlook. Of the three technology categories, conversion has most benefited from the changes in commodity prices of the three technology categories.

Purification and depolymerization technologies, on average, appear to be more profitable and create better returns than the conversion technologies studied, despite having higher capital expenditures (CapEx) and operating expenses (OpEx) per metric ton. Four out of the six purification and depolymerization technology companies achieved returns of 15% or higher in the 2021 base case. The financial results of these companies are supported by current market conditions in which recycled plastics are commanding higher prices than virgin plastics.

The required price premiums for outputs from molecular recycling technologies are aligned with current market pricing and customers willingness to pay.

Closed Loop Partners wanted to understand what it would take to make the molecular recycling projects that were not viable in the 2021 base case scenario viable. To do so, we looked at what "threshold pricing[e] " was necessary to lift the rate of return of these projects to 10% and 20%. We were surprised to find that the premiums needed were not multiples above 2021 market prices, and never reached above a 55% premium. For the molecular recycling projects that could not meet 10% IRR in the 2021 base case scenario, a premium between 10-15% would be required to reach a 10% IRR. To reach a 20% IRR hurdle, these same projects would need output price premiums between 15-55%.

In our study, the highest margins correlated to processes that produced finished polymers (i.e. plastic resin) or specialty chemicals, and were therefore able to access consumer-facing end markets such as the plastics processing sectors that make packaging, automotive parts, and other products. With these business models, companies are capable of creating alternative circular supply chains to the existing virgin plastics value chain and producing substitutes to virgin-polymers that attract a ~30%

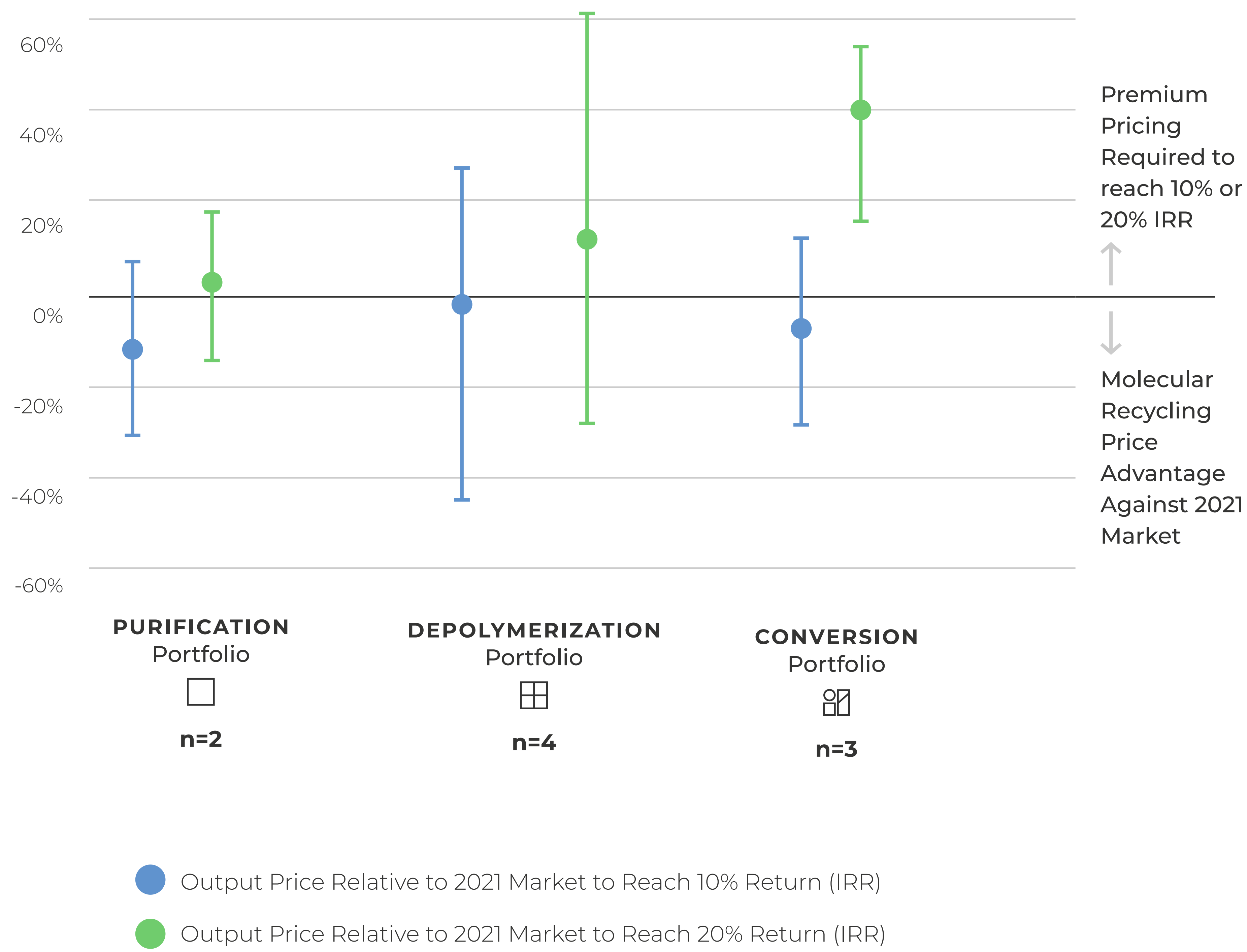
e. Threshold pricing is defined as the output price needed to achieve breakeven net present value (NPV).

premium compared to virgin, on average, and are less influenced by the fluctuating prices of oil.

In some cases, the price point to reach returns of 10% and 20% fell below 2021 average commodity prices. Figure 12 summarizes the average price premium required across all three technology categories.

Learn more about our methodology and data assumptions in **Appendix 2.2**

FIGURE 12: MOLECULAR RECYCLING OUTPUT PRICING REQUIRED TO REACH 10% OR 20% IRR COMPARED TO 2021 MARKET PRICES



Note: Premium price requirements are based on the average basket of outputs for each technology individually and ranges are presented by category group. As such each category group includes multiple commodity prices.

DEEP DIVE

How molecular recycling technology providers can accelerate the pathway to premium prices

Levers That Can Help Molecular Recycling Technology Providers Accelerate the Pathway to Premium Prices:

The business case for molecular recycling is driven by target output revenues, which accounted for 80-100% of the total revenue streams across the technology companies we evaluated. The technology providers that can command these premium prices are able to do so when:

- **Quality is on par with virgin products:** The outputs match the quality of virgin comparables and can directly replace virgin product in applications, such as food grade packaging, cosmetic and healthcare products.
- **Outputs add value to downstream customers**: Some molecular recycling outputs (i.e., polypropylene wax) can support cost cutting measures in the plastic formulation stage or allow compounders to use higher volumes of recycled content. These value drivers will need to be confirmed when individual projects undergo due diligence.
- **Demand outpaces supply:** The demand for high-quality recycled content far outstrips the supply of recycled content, where the price is set by technology providers based on the availability of recycled plastics.
- **Policy encourages molecular recycling:** Opportunity costs arise from avoiding extended producer responsibility fees, which are penalties for not meeting recycled content targets in products, or taxation on the use of virgin products. Such taxation is a key driver of the development of circular supply chains in Europe, while the North American market does not currently have regulatory support for separation, sorting and recycling infrastructure.

2

Molecular recycling complements existing plastics recycling infrastructure and waste management by processing plastics that material recovery facilities (MRFs) and municipalities currently pay to send to a landfill or incinerators. Purification and decomposition technologies demonstrate the greatest potential to generate shared value to the system, while conversion technologies deliver a net benefit compared to landfilling and are most aligned to the current realities of plastic waste today.

The Potential Economic Advantages of Processing "Non-Target" Plastics with Molecular Recycling

Our study of two **purification technologies** found that these technologies **can generate between $600 and 700 USD per metric ton of material processed.** This is because purification uses low-value plastic waste feedstocks to produce high-value recycled plastics including food-grade applications and for health

Methodology: Added Value Analysis

To calculate the **potential value added** by each molecular recycling technology, we used a value-chain view to understand the costs embedded in the supply chain, from waste generation through sorting to output generations. We consider collection costs, sorting costs, and treatment costs as embedded value in recycling activities, and compare this to the value generated by returning products to market in the form of monomers, polymers, fuels or other products. Thus, value added is estimated as the value placed on the output product by end markets minus any costs embedded in the processes to produce those products.

Net benefit utilizes the same approach but compares the value added of advanced treatment technologies to that of the alternative: landfill. In this case landfill represents value loss as costs are embedded in collection and treatment with no value returned to the economy. As a result, net benefit calculations reflect the value added from molecular recycling plus the avoided costs that would have otherwise been incurred had the waste been landfilled.

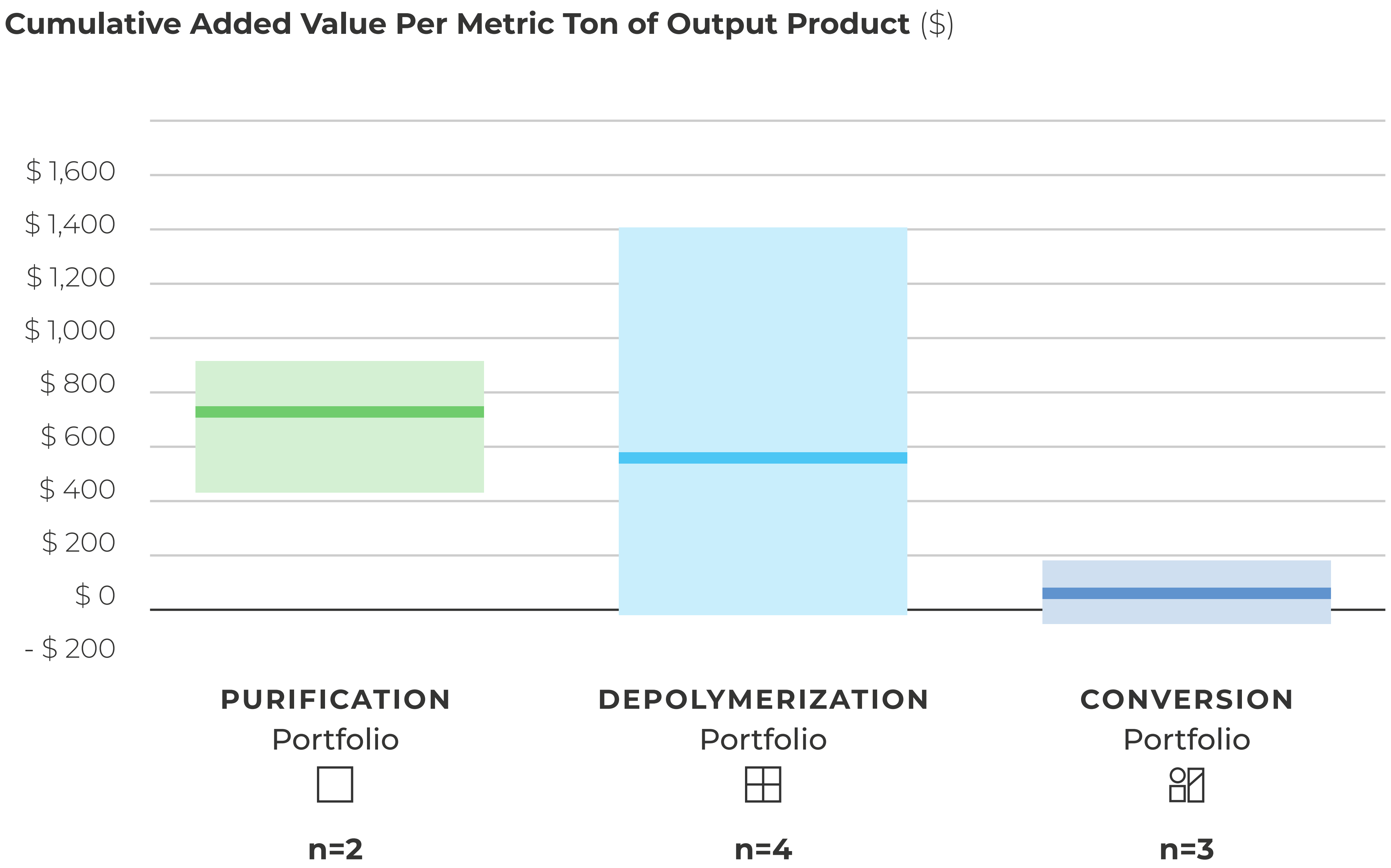
Plastics sent to a landfill or incinerator are referred to as **"non-target" plastics**, meaning that the mechanical recycling sector does not prioritize or process these resins or formats at scale. Scaling molecular recycling technologies would bring value to currently landfilled plastics, as well as residues from mechanical recycling.

and beauty sector uses. These companies can tap into a market in which certain recycled plastics (i.e., rPET, rPP, rPE) command a higher price than virgin plastics. When evaluated against an alternative of landfilling the material, the net benefit of purification technologies is even higher, at $800-$1,000 USD per metric ton of material managed.

Our study of four **depolymerization technologies** found that these technologies **can generate between $50 and 1,000 USD per metric ton of material processed.** This technology category had the highest variability in value created, which reflects both the different stages of development within this cohort and the variability in operational costs observed across this technology group in our study. As that technology group matures, we anticipate the range of value creation for commercial scale decomposition will be comparable to that of purification (i.e. $600 - $1,000 per metric ton of material managed); with companies who produce smaller-scale, high-value specialty products which can be sold directly to plastics manufacturers at the high end of the range.

Our study of three **conversion technologies** found that these technologies **can generate between $-10 and 133 USD per metric ton of materials processed**. While this figure appears the lowest of the three technology categories, conversion technologies have the benefit of diverting mixed waste that could otherwise incur the costs of sorting and separating feedstock to a single resin or format (i.e PET, films); purification and depolymerization technologies do not have this capacity. At the low end of this conversion range, the value of final products produced is not high enough to offset the costs of collection and waste processing. In these cases, the net benefit is a better marker of value creation for these technologies which provide waste management services and process mixed waste with plastics. Using net benefit calculations, conversion adds a meaningful net benefit of between $240 and 400 USD per metric ton of waste managed and diverted, because the avoided costs of landfilling mixed waste are incorporated.

FIGURE 13. RANGE AND AVERAGE OF NET VALUE CREATION ACROSS THE THREE MOLECULAR RECYCLING TECHNOLOGY CATEGORIES



Notes:
Supply chain modeling has applied variable discount rates depending on level of technology development to account for the different levels of commercial risk:
Pilot: 15 %
Early commercial: 12 %
Growth: 10 %

The purification portfolio consists of early commerical technologies; the depolymerization portfolio consists of a mix of pilot, early commercial, and growth technologies; the conversion portfolio consists of growth technologies.

Learn more about our methodology and data assumptions in **Appendix 2.3**

DEEP DIVE

How could the current recycling system benefit if molecular recycling were integrated to reach a 30% plastic packaging recycling rate?

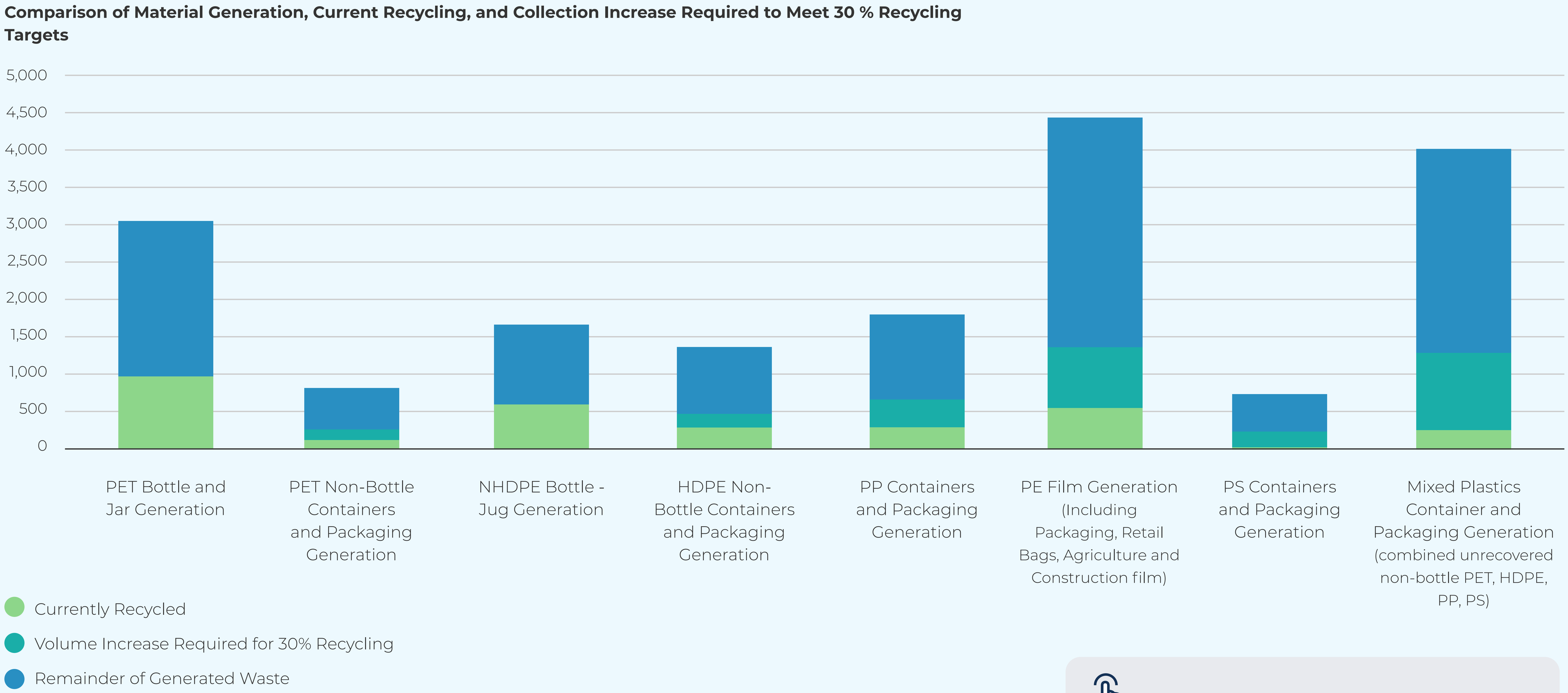
Integrating new technologies into the downstream plastics recycling systems in the U.S. and Canada could double the amount of plastic packaging that was recycled in 2019 and generate up to $970 million dollars (USD) annually.

Plastics-related goals, such as the U.S. Plastics Pact's target of a 50% recycling rate for all plastic packaging by 2025[49], represent ambitious corporate efforts that will require the scaling of circular supply chains for plastics. Considerable investment is needed to meet these goals and improve the current recycling systems performance in the U.S. and Canada, as well as the continued advancement of reduction, reuse and refill strategies to decrease overall plastic use. Based on Pew Charitable Trust and SYSTEMIQ's analysis, which models reuse systems addressing up to 30% of plastic waste by 2040[50], we have built out a scenario that assumes that reuse will play an integral role to curb plastic industry growth by 2030, and assumes that at least as much plastic packaging as was produced in 2019 will continue to be produced in 2030.

Infrastructure investments take time to scale and reach impact, so **we chose to model an initial target of reaching a 30% recycling rate across all plastic packaging by 2030**. This scenario represents a realistic infrastructure and investment trajectory based on our assessment of an expanded packaging recovery rate for all plastic resins and formats. Looking towards the future, it is critical that industry strive to recycle beyond 30%. For plastic packaging alone, an additional 2.5 million metric tons of plastic waste per year will need to be recycled in the U.S. and

DEEP DIVE

FIGURE 14. 2019 GENERATION AND RECYCLING QUANTITIES ACROSS PACKAGING RESINS AND ADDITIONAL MASS RECOVERY REQUIRED TO ACHIEVE 30% TARGET



Learn more about this analysis in **Appendix 3.0**

Canada to reach the 30% recycling rate by the 2030 goal. This is twice as much as the plastic packaging recycled through mechanical processing in 2019 (Figure 14).

Our model included two scenarios and metrics:

Scenario 1: Only conversion technologies that took mixed plastic waste through pyrolysis and gasification technologies were added to the existing mechanical recycling system to reach a plastics packaging recycling target of 30% across PET, PS, PP, HDPE, and LDPE packaging formats.

Scenario 2: A mixed-technology approach that integrates all three types of molecular recycling and mechanical recycling was used to reach a plastics packaging recycling target of 30% across PET, PS, PP, HDPE, and LDPE packaging formats.

Added Value: Represents the economic value generated from producing a product

Added Value = Market Value of Product Output – Costs Embedded in its Generation

Net Benefit: Represents the additional opportunity cost or benefit of diverting material from landfill.

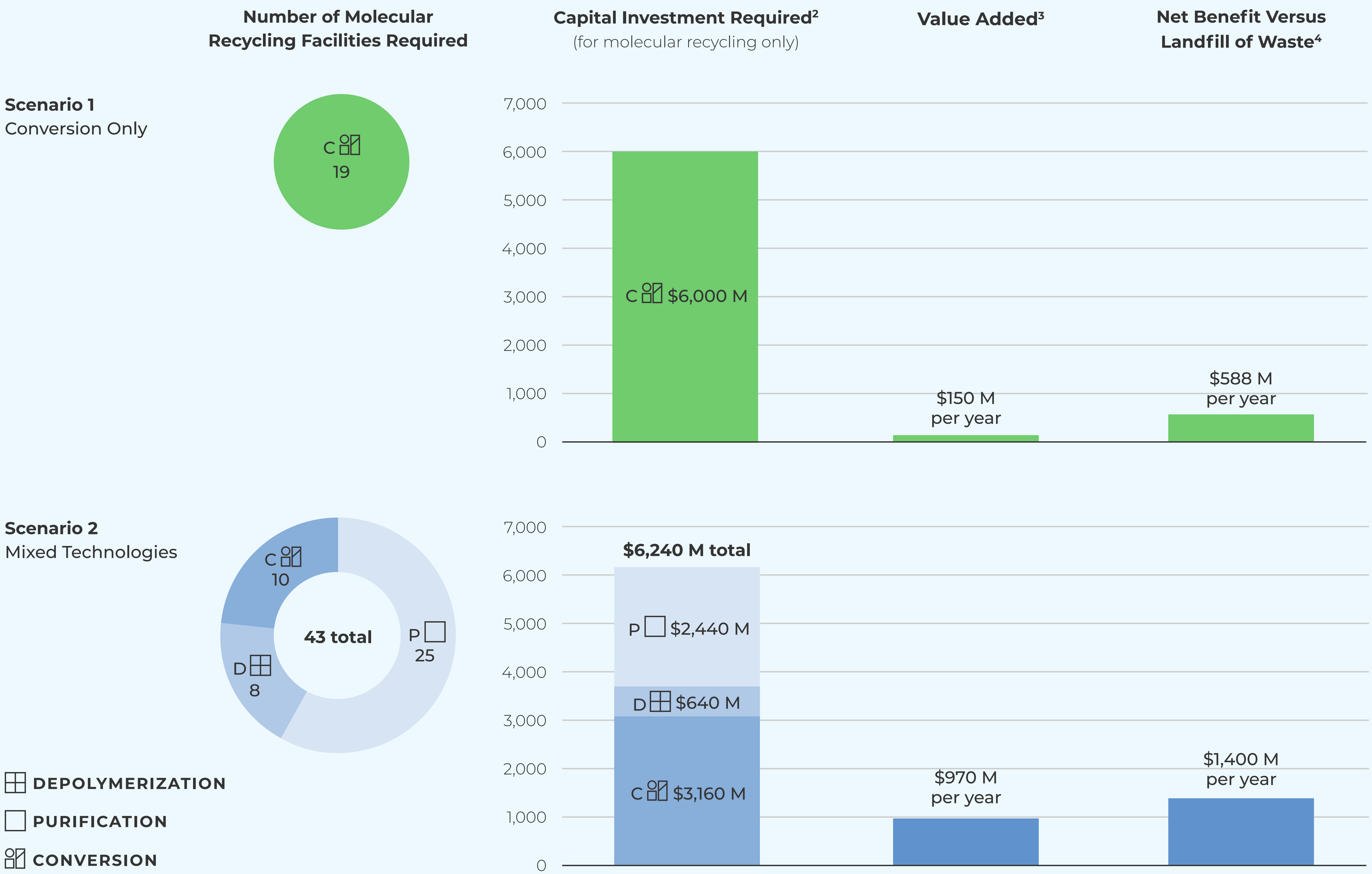
Net Benefit = Added Value of Molecular Recycling - Added Value of Avoiding Landfill (i.e. cost)

Creating Value for the System: Conversion-Only Approach vs Mixed-Technology Approach

At a systems-level, investing in conversion technologies alone (Scenario 1) creates an average net benefit of $230 per metric ton of mixed plastic processed. In this scenario, achieving the 30% plastic packaging recycling rate would generate a net benefit of $588 million annually compared to sending the material to landfill. Investing in all three molecular recycling categories yields an average net benefit of $540 per metric ton of plastic processed. In Scenario 2, reaching the 30% plastic packaging recycling rate goal would generate a net benefit of $1.4 billion per year compared to landfilling — or an estimated annual value of $968 million.

Our supply chain analysis indicates that a conversion-only approach would offer the economic benefits of diverting plastic waste away from landfills, even to lower value outputs circulated back into the petrochemicals sector. However, a mixed-technology approach that includes purification, depolymerization, and conversion technologies is able to address the volume and diversity of plastics in ways that match the condition of plastic waste (i.e. mixed or sorted) *and* generate positive economic value and returns for investors, municipalities, and the existing recycling system (Figure 15). This future requires a robust collection and sorting system that allows both mechanical and molecular recycling to access the plastic packaging currently sent to landfill.

FIGURE 15. TWO SCENARIOS TO REACH A 30% PLASTICS PACKAGING RECYCLING RATE[1]



Notes:
1. Our model takes into account the operational costs at each stage of the recycling supply chain: in this instance, from the point of collection onwards, including collection and sorting costs (although these are consistent across like technologies) as well as costs associated with treatment processes and costs for feedstocks. Revenue drivers and value added is based on output markets and market value of products produced from molecular recycling technologies, relative to costs of disposing to landfill.
2. All figures are USD
3. Value Added = market value of product output – costs embedded in its generation
4. Net Benefit = Added Value of Molecular Recycling - Added Value of Alternative End-of-life Fate (i.e. landfill)

Appendix 2.4 details our methodology and data assumptions.

Integrating Molecular Recycling into the Existing System

When taking the whole supply chain view, an additional $5 to 6 billion dollars (USD) is needed across the system, from collection to processing, to manage the additional 2.5 million metric tons of plastic packaging material diverted from the mixed solid waste streams. When reviewed against the potential value added opportunities, this investment in infrastructure could be repaid within 5 to 6 years, generating a net additional value added of $4 to 5 Billion (USD) over a 10-year investment cycle. Figure 16 summarizes the additional throughput in the system, the investment needs across the value chain, and capital costs (CapEx) of these investments.

This analysis is based on a materials recovery facility's (MRF) ability to process 50,000 tons of recyclables annually, which is typical of the current sortation infrastructure in the US and Canada. Thus, there is a need for an additional 230-370 sortation facilities, and an associated $280 to 440 million (USD) capital investment. With plastics representing 10 to 15% of the input stream, larger MRFs will be more viable and able to provide more sophisticated sortation equipment to extract more plastics waste for recycling and help build a viable supply chain for mechanical and molecular technologies. Future MRF infrastructure could take a "hub & spoke" approach, with smaller, local sortation plants feeding into larger regional MRFs producing high-quality plastics waste streams to meet specifications of molecular recycling technologies or other end markets.

> "This study highlights how advanced recycling technologies can be incorporated to address lower-value materials and provide recovery pathways for materials from durables, carpet, and fiber to re-enter the packaging system. Developing optimized material streams for each recycling system, alongside continued value chain collaboration and innovation in design and reuse, will all play a role in the packaging industry's future."
>
> – **Nina Goodrich,** Director, Sustainable Packaging Coalition, Executive Director, GreenBlue.

FIGURE 16. ADDITIONAL PLASTIC PACKAGING AMOUNT, CAPACITY AND CAPITAL NEEDED TO REACH A 30% RECYCLING TARGET BY 2030

	Collection	Sortation	Secondary Processors & Reclaimers	Molecular Recycling
Estimated Volumes	**3.0 Million** metric tons per year	**1.4 – 2.2 Million** metric tons per year	**1.0 – 1.3 Million** metric tons per year	**1.8 – 2.0 Million** metric tons per year
Capacity	**1.0M – 1.8M metric tons per year** require alternative curbside collection (mixed or separate material stream) **3.0M metric tons per year** diverted by additional collections fleet	**230 – 370 new material recovery facilities (MRFs)** with average sorting capacity of 50,000 metric tons per year [2]	**10 – 15 new reclaimer facilities** with average processing capacity of 90,000 metric tons per annum[2] to mechanically recycle suitable plastics	**40 – 50 new molecular recycling facilities** to process plastic streams such as films, mixed plastics, and non-bottle rigids
Capital[1]	**$350M – $500M USD** investment in collections infrastructure	**$280M – $330M USD** investment in additional plastics sortation capacity [3]	**$700M – $1B USD** investment in additional mechanical recycling reclamation infrastructure[3]	**$4.2B – $5B USD** investment in infrastructure to target non-mechanically recycled plastic[3]

Notes:
1. Capital investment ranges not all cumulative due to scenario based analysis
2. Actual MRF / reclaimer facility size will depend on composition of plastics in waste stream and collection system
3. Not accounting for total size of MRFs managing mixed materials

Learn more about our methodology and data assumptions in **Appendix 2.5**

Systems-Level Life Cycle Assessment Methodology: Macro Impact Analysis to Finished Plastic

Portfolio Analysis Approach

The environmental results of this study are aggregated using a portfolio approach in order to appropriately aggregate and anonymize individual company datasets and account for the differences in target feedstock and outputs produced by the nine companies in our study. To enable comparison between technology categories and the virgin system, each portfolio is set to produce 1,000 kg of finished plastic pellets and non-pellet products (i.e. paraffin wax), with each technology contributing an equal share of products (i.e. for a portfolio of two technology companies, each technology contributes 500 kg of plastic; for 3 technologies, each technology contributes 333.3 kg; etc.). The environmental impact for each of these companies are summed to produce the aggregate portfolio impact. Throughout the report, we note information about each portfolio (i.e. product outputs produced by portfolio, number of companies in portfolio).

Life Cycle Boundaries and Functional Units of Recycling System

The boundaries of the recycling system are material recovery facility (MRF) inputs to polymer products. For each of the three technology portfolios this begins at the source of waste plastic feedstock: the MRF and in some cases, additional industrial feedstock sources. Transport from the MRF to the molecular recycling facility is included and assumed to be similar when industrial sources are used. The end point in the recycling system is finished plastic resin (top half of Figure 17). The functional unit of our life cycle assessment is one metric ton of finished product (i.e. polymer pellet plus non-pellet products, if applicable)

Comparison to Virgin: We compare the environmental impact of each molecular recycling technology portfolio to the avoided virgin system. The boundary for the avoided virgin system is cradle-to-gate, which includes extraction to pellet production. Figure 17 summarizes boundaries for the recycling system and the avoided virgin system.

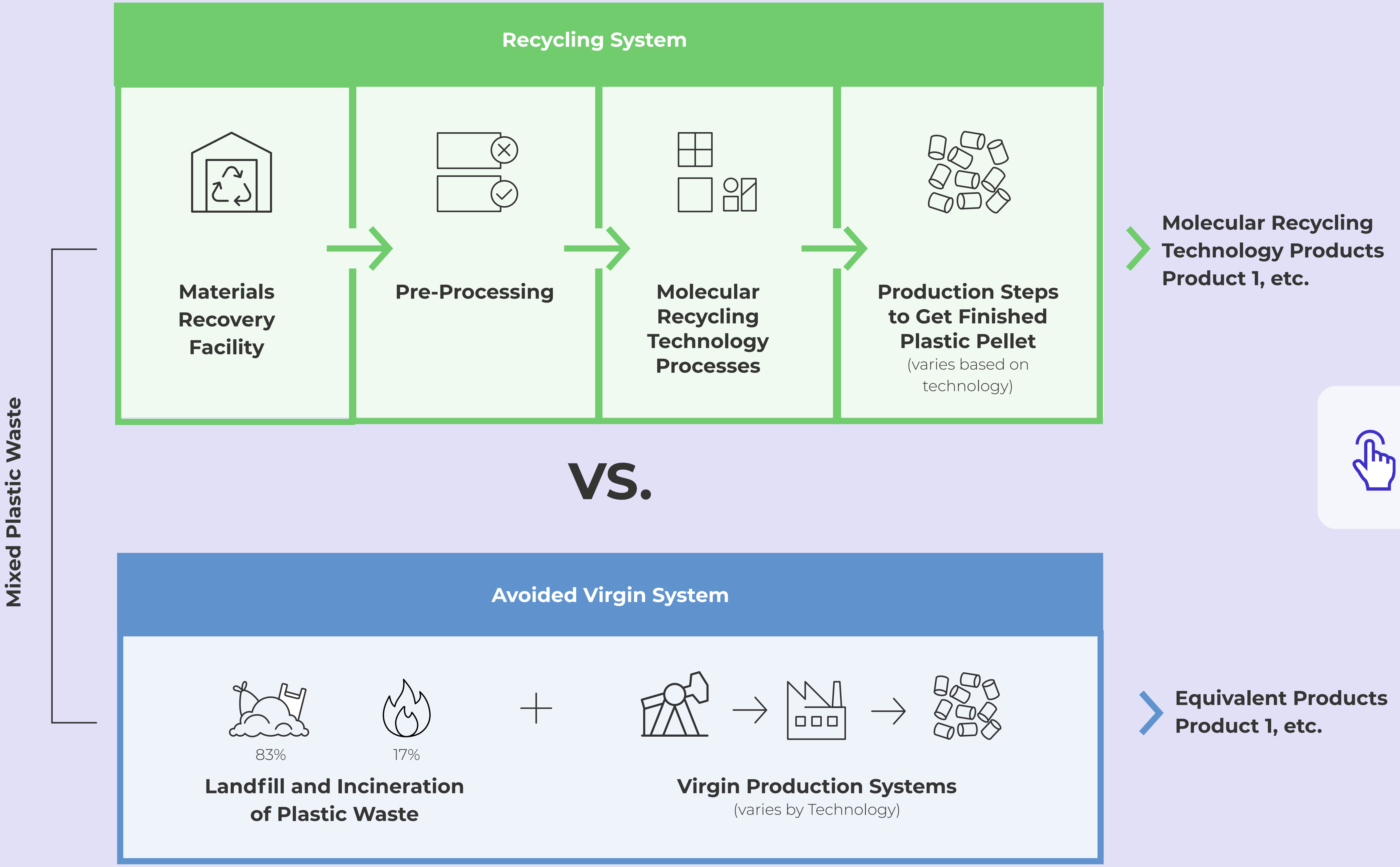
The recycling system portfolio receives an “environmental credit” for the avoided virgin system[f]; in this case it is the impact of avoiding landfill, incineration, and virgin-plastics production. On average, plastic is landfilled 83% and incinerated only 17% of the time based on the Environmental Protection Agency. We use the same end-of-life assumptions across all companies to determine the “avoided virgin system” credit given to each technology portfolio.

Impact Metrics: Several Traci 2.1[g] key performance indicators (KPIs) are evaluated in our study, including human health impact factors and Global Warming Potential (GWP) which is labeled “Climate Impact Potential” across our figures. Other key metrics our study focuses on include: Natural Resource Energy, total (NREt) and Bluewater[h].

---

f. Avoided Virgin System refers to the impact of virgin material production that is avoided by the use of recycled material.
g. Traci 2.1 is an environmental impact assessment tool created by the EPA that provides characterization factors for Life Cycle Impact Assessment (LCIA), industrial ecology, and sustainability metrics. Characterization factors quantify the potential impacts that inputs and releases have on specific impact categories in common equivalence units.
h. Bluewater: The total of all water evaporated during production or physically incorporated into the product.

FIGURE 17. SYSTEM-LEVEL LIFE CYCLE ASSESSMENT BOUNDARIES AND COMPARISONS IN CLOSED LOOP PARTNERS STUDY



Learn more about our life cycle assessment scope and methodology in **Appendix 4.0** and **Appendix 4.1**

3 Not all molecular recycling processes offer an environmental improvement compared to virgin plastic production, but the best-performing molecular recycling technology processes can mitigate the negative climate change impacts of the extractive and virgin plastics industries.

Closed Loop Partners analyzed the energy, greenhouse gases and water impacts of individual technology processes, and the systems-level impact of producing different polymers via purification, depolymerization and conversion technologies. We expected larger reductions in energy, water and greenhouse gas emissions from the technologies that require a shorter "route" back to polymer compared to those that had more process steps, but our hypothesis was incorrect. Instead, within and across each technology category, there was a wide range of environmental performance.

Using the virgin petrochemical and plastic supply chain system, one of the most mass and energy efficient sectors, as a point of comparison sets a high bar for the molecular recycling industry, which is nascent by comparison and faces the challenges of establishing itself in a challenging operating environment while also producing consistent products. Despite this, our study found that purification, depolymerization and conversion technologies, on average, require less energy and emit less greenhouse gases, compared to equivalent virgin plastics supply chains. The best performing processes in each molecular recycling technology portfolio showed significant reductions in energy and water use and greenhouse gas emissions compared to their corresponding virgin systems. On average, purification was the best performing category across all environmental measures.

Still, there is nuance and variation across and within technology portfolios, which is summarized in Table 1. Purification, depolymerization and conversion each had processes that performed better than the virgin system, just as each technology category had processes that performed worse than virgin. This reinforces that meticulous due diligence is important for the success of this early-stage and nuanced sector.

TABLE 1. SUMMARY OF ENVIRONMENTAL IMPACT RESULTS: MOLECULAR RECYCLING SYSTEMS COMPARED TO THE AVOIDED VIRGIN SYSTEM[1], ANALYSIS TO PLASTIC PELLET

		Total Natural Resource Energy [2] (NREt)		Climate Impact Potential (CO_2e)		Bluewater[3]	
		MJ / kg Plastic Pellet	% Change vs Virgin System	$kgCO_2e$ / kg Plastic Pellet	% Change vs Virgin System	$kgCO_2e$ / kg Plastic Pellet	% Change vs Virgin System
PURIFICATION							
	Portfolio average	28.8	↓ 59 %	1.6	↓ 20 %	2.8	↓ 43 %
	Range	22.0 – 35.6	↓ 47 % to ↓ 70 %	1.2 – 2.0	↑ 7 % to ↓ 45 %	2.0 – 3.6	↓ 19 % to ↓ 65 %
DEPOLYMERIZATION							
	Portfolio average	46.7	↓ 38 %	2.5	↓ 12 %	5.9	↓ 17 %
	Range	18.0 – 68.1	↓ 17 % to ↓ 72 %	1.1 – 3.5	0 % to ↓ 36 %	2.8 – 8.9	↑ 4 % to ↓ 34 %
CONVERSION							
	Portfolio average	35.8	↓ 47 %	2.8	↓ 7 %	5.0	↑ 1 %
	Range	12.6 – 59.1	↓ 14 % to ↓ 80 %	1.2 – 4.4	↑ 22 % to ↓ 26 %	2.1 – 7.0	↑ 23 % to ↓ 38 %

Notes:

1. These two systems are multi component and are compared and referred to as recycled system and avoided virgin system. The recycling system boundary includes the MRF, the cradle to gate of all other inputs including energy, and the recycling facility itself. The avoided virgin system is the cradle-to-gate of the polymer pellet plus additional equivalent products plus the avoided U.S. waste management system (i.e. landfill or incineration).
2. Total Natural Resource Energy (NREt) - The sum of Natural Resource Energy Combusted (NREc) and Natural Resource Energy for Materials (NREm). It is the total energy value of fossil fuels extracted from the ground. This is similar to the non-renewable fossil component of the Cumulative Energy Demand (CED) metric that is widely used in life cycle assessment.
3. Blue water - The total of all water evaporated during production or physically incorporated into the product. Thus, blue water does not include non-contaminated water returned to the environment (i.e. from steam heating or cooling water systems) or contaminated water that is returned to the environment via a wastewater treatment process (i.e. from a manufacturing plant or municipal wastewater treatment plant).

A circular plastics economy requires quantitative environmental goals to achieve zero-waste and low-carbon outcomes.

To increase the supply of high-quality recycled content in the market and meaningfully decarbonize the plastics economy, molecular recycling technologies need to perform at high levels across all three categories. This is especially critical for depolymerization and conversion technologies which, on average, yield less than 20% greenhouse gas savings compared to the equivalent virgin system. Policymakers, academia, environmental NGOs, and industry all have a role in defining the minimum environmental expectations for this early-stage sector. How much of a reduction in greenhouse gases, energy, or water should the circular plastics economy yield? Should the sector align with the goal of limiting global temperature rise to 1.5°C[51]?

The energy, water and carbon emissions savings demonstrated by molecular recycling today can be magnified if renewable energy is integrated, making green energy sources a critical strategy for molecular recycling operators.

The results of the environmental impact analysis model all technology processes on the same set of assumptions, one of which includes the average 2019 U.S. grid. Closed Loop Partners wanted to understand the impact of renewable energy on the environmental impact results of different molecular recycling technologies and used the projected future uses of the various electricity generation technologies from 2019 to 2050 (U.S. Department of Energy).

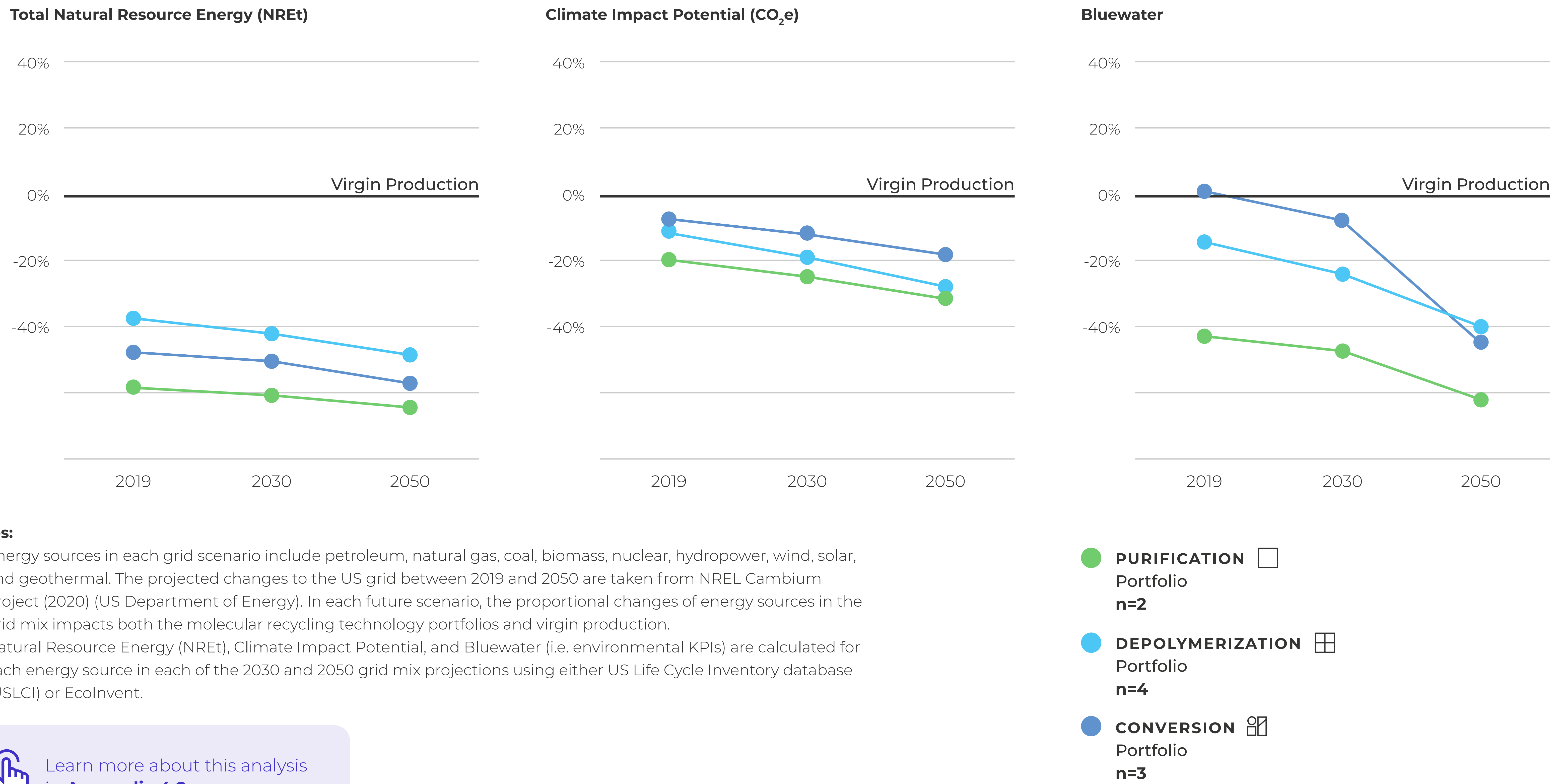
Our analysis found two things. First, renewable energy has a positive impact on grid electricity. Therefore, processes which rely more heavily on electricity than natural gas will see greater improvements in environmental footprint as renewable energy takes up a greater share of the grid mix. Similarly, a molecular recycling technology that utilizes non-grid renewable energy sources (e.g. on-site solar panels) for part or all of its electricity use will have a lower environmental footprint compared to the same process that does not. Our model shows that between 2019 and 2050, pyrolysis technologies net the lowest improvements in kilograms of CO_2e per metric ton of plastic pellet produced, compared to purification or depolymerization technology processes and even gasification technologies, which can use a higher proportion of electricity than natural gas.

Second, one of the fastest ways to ensure that molecular recycling facilities linking to the plastics supply chain reduce greenhouse gas emissions, water and energy use in manufacturing is to site these facilities in areas that already use a clean energy grid mix, or utilize clean energy to power these processes wherever possible. Figure 18 shows how energy and water usage and greenhouse gas emissions decrease over time as the U.S. grid is expected to use more renewable energy.

Renewable energy can reduce the environmental footprint of a facility significantly as compared to use of traditional grid power. Technology providers and investors must consider the local energy source and grid and project siting in their evaluation of the environmental impact of their investments and operations.

> The [life cycle] methodology used in the Closed Loop Partners study is thorough, transparent, and verifiable for assessing the environmental impacts of molecular recycling technologies. The concept of grouping technology types into portfolios is especially valuable.
>
> – **DR. MAHMOOD SABAHI, LIFE CYCLE INVENTORY,** GEORGIA INSTITUTE OF TECHNOLOGY

FIGURE 18. ANTICIPATED CHANGES TO ENERGY, GREENHOUSE GASES, AND BLUEWATER AS GRID GREENS BETWEEN 2019 AND 2050[1,2]



Notes:

1. Energy sources in each grid scenario include petroleum, natural gas, coal, biomass, nuclear, hydropower, wind, solar, and geothermal. The projected changes to the US grid between 2019 and 2050 are taken from NREL Cambium Project (2020) (US Department of Energy). In each future scenario, the proportional changes of energy sources in the grid mix impacts both the molecular recycling technology portfolios and virgin production.
2. Natural Resource Energy (NREt), Climate Impact Potential, and Bluewater (i.e. environmental KPIs) are calculated for each energy source in each of the 2030 and 2050 grid mix projections using either US Life Cycle Inventory database (USLCI) or EcoInvent.

Learn more about this analysis in **Appendix 4.2**

DEEP DIVE

Lessons From Using Life Cycle Assessments to Evaluate Molecular Recycling Technologies

A life cycle assessment (LCA) is a systematic analysis of the environmental impact of existing and planned products, services and manufacturing processes. Life cycle assessments are conducted based on detailed boundaries established within a system. Within LCA, it is standard practice to credit a process with the avoided outcome(s) (e.g. avoided incineration).

Our findings on the energy demand of molecular recycling processes are very similar to those of other life cycle experts who have assessed the same or similar molecular recycling technology processes. Our LCA results represent molecular recycling technology processes modeled under the average U.S. energy grid mix (2019), which may be different from what is reported in other geographies. Our analysis concludes that the most significant drivers that influence molecular recycling LCA results are (1) the energy grid that these technologies are modeled on; and (2) the differences in how the technology processes are "credited" based on local end-of-life scenarios of plastic waste.

For example, two LCAs of the same technology process could yield different results if one LCA was modeled in Germany where all plastics are incinerated and the second LCA is modeled in the United States where landfilling plastic is the predominant end-of-life scenario. The credits given to the molecular recycling process for landfilling are drastically smaller than carbon credits given from incineration. That is because LCA treats landfilling as a carbon sequestration activity, since plastics do not generate methane emissions in the landfill.

DEEP DIVE

Investors, policymakers, and potential partners to molecular recycling technology companies should understand the utility and limitations of LCAs for evaluating the value of plastics circularity. Other metrics to consider include ones we have highlighted in this report: economic value created to the system compared to landfilling; quality of outputs produced; application of outputs; and alignment to circular outcomes. Closed Loop Partners has developed a basic set of questions to consider when reviewing a life cycle assessment to support the technical and environmental evaluation of molecular recycling technologies (Figure 19).

Download a copy of the life cycle impact assessment methodology used in this study in **Appendix 4.1**

DEEP DIVE

FIGURE 19. WHAT TO ASK AND CONSIDER WHEN LEVERAGING LCA FOR MOLECULAR RECYCLING TECHNOLOGIES

CREDIBILITY

LCA Team: Are they qualified and independent? Are they using industry standard tools (i.e. Traci 2.1)?

Certification: Is the LCA ISO or ISCC+ certified?

BOUNDARIES & ASSUMPTIONS

Process or System LCA: What are the boundaries of the impact analysis?

Assumptions: What is the process or system displacing (i.e. environmental credit given)?

LOCAL INPUTS

Energy: What are the assumptions for the source of electricity?

Pre/Post-Processing: What's required upstream and downstream to the process? What's the impact of that?

CLAIMS AND COMPARISONS

Data Use: What claims will be made based on the LCA or impact assessment? How do these results compare to similar systems?

LIMITATIONS OF DATA

Other Factors: What other metrics are critical to understand the successful integration of this technology into an existing supply chain (i.e. output quality, feedstock contamination tolerance, etc.)

4 Molecular recycling may reduce human health risk compared to virgin plastics production, since it reduces the total virgin chemicals used.

While upstream solutions like reuse and material-switching may scale enough to slow the need for extraction to make virgin plastics, downstream technologies will still be critical to produce the recycled plastic content for manufacturing, so even less extraction occurs. At the same time, it is critical to understand the human health impacts of molecular recycling operations because plastics circularity and recycling cannot come at the cost of worker or community health.

Today, toxicology's ability to measure the chemical footprint of a recycling process, much less an entire plastic system, is nascent. Attempts to understand, characterize and accurately measure the contribution of environmental toxicity to human life is still "pre-emergent",[52] and life cycle impact assessments are not comprehensive enough in scope or depth to adequately capture all of the elements of a complex and dynamic system, much less quantify their impacts. Still, our teams wanted to provide a perspective that would lay groundwork for others to build upon and later quantify the chemical footprint of: 1) virgin polymer production; and 2) the reduction of human health risks by avoiding the production and use of toxic chemicals through recycling activities.

Our teams conducted a qualitative analysis of the potential human health risks avoided by putting different plastics through a recycling process using two life cycle and hazard assessment tools, the **Environmental Genome Initaitive** and **SciveraLens Rapid Screen**. With these tools, we visualize the hazard category risks of different polymers and attempt to characterize the benefits of different molecular recycling processes that are not adequately addressed in LCA analyses, including avoided chemical use and resulting emissions or by-products, which have the potential to reduce the negative health impacts of virgin plastic manufacturing.

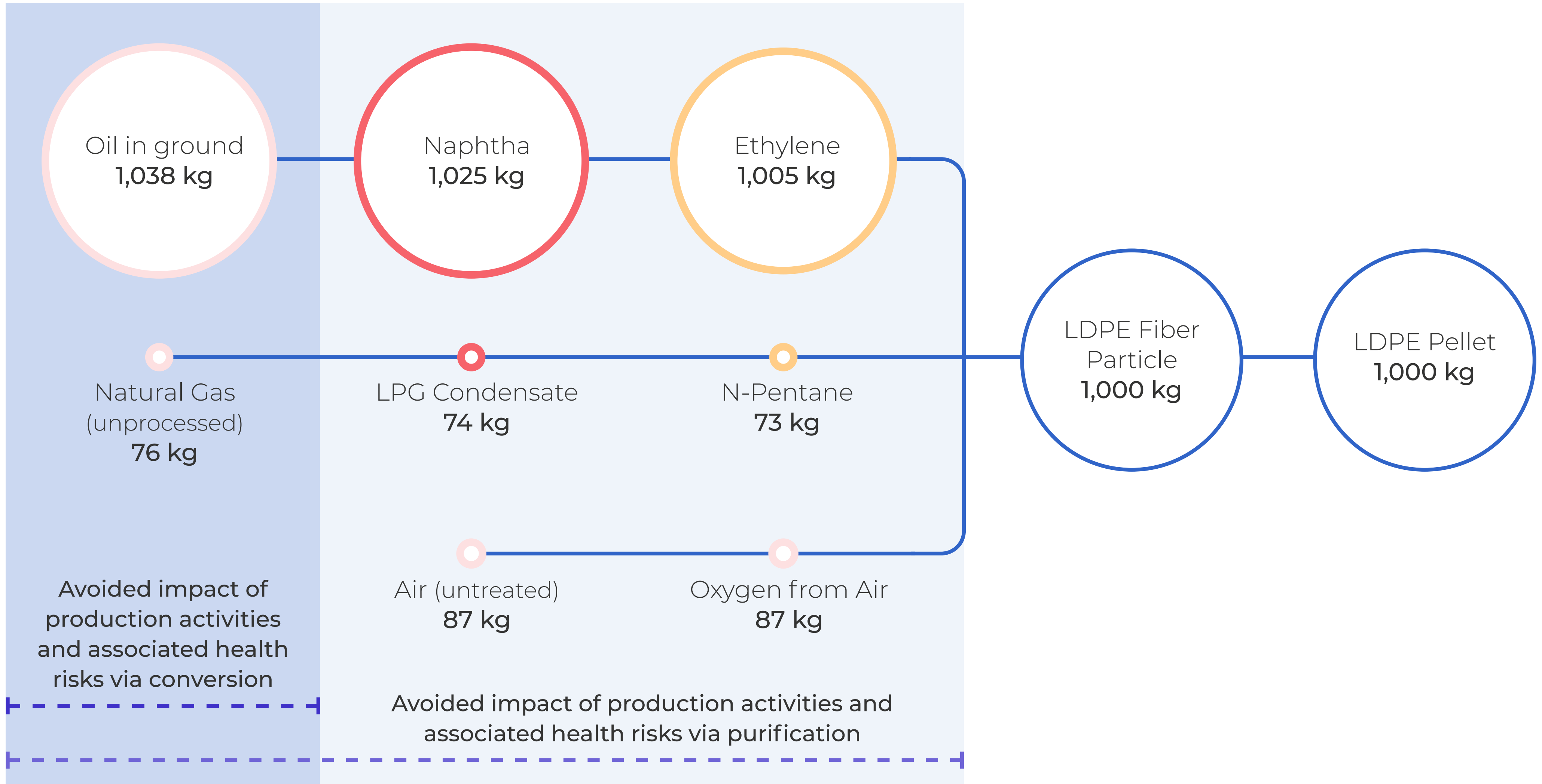
Read the full scope of our human health impact analysis in **Appendix 5.0**

The chemical footprint for each type of plastic is not the same.

There are two aspects of a chemical footprint for virgin polymers: the number of different chemicals that must be used in order to make a certain amount of plastic, and the hazard potential of each chemical used. More chemicals are deployed to produce one kilogram of PET compared to other resins like polypropylene, polyethylene or polystyrene. As can be seen by comparing Figures 20 and 21, more chemicals are used to produce one kilogram of PET than to produce other resins, including LDPE. Then, because molecular recycling processes differ in the degree to which the plastic polymer is broken down, the amount of virgin chemicals displaced from processing plastic waste through molecular recycling differs by technology type. Appendix 5.1 shows the chemical tree structure and chemicals used in five common plastics and what molecular recycling processes are able to avoid. More research is needed to refine the concept of calculating chemical footprints for polymers that would include total chemical usage for virgin production (e.g., including those used in natural gas fracking) to fully quantify the avoided impacts of virgin production of chemicals by using molecular recycling processes.

> Climate, plastic pollution, and chemical toxicity, which at first might each seem like distinct problems, are actually interrelated and require a systems approach to solve. Chemicals are the building blocks of all products. It is not enough to focus on carbon emissions. A circular economy only works if it is built with chemicals and materials that promote human health and the resilience of the natural world.
>
> – **MARTIN MULVIHILL, MANAGING PARTNER AND CO-FOUNDER,** SAFER MADE

FIGURE 20. CHEMICAL TREE OF LDPE AND MATERIALS AVOIDED THROUGH DIFFERENT MOLECULAR RECYCLING TECHNOLOGIES

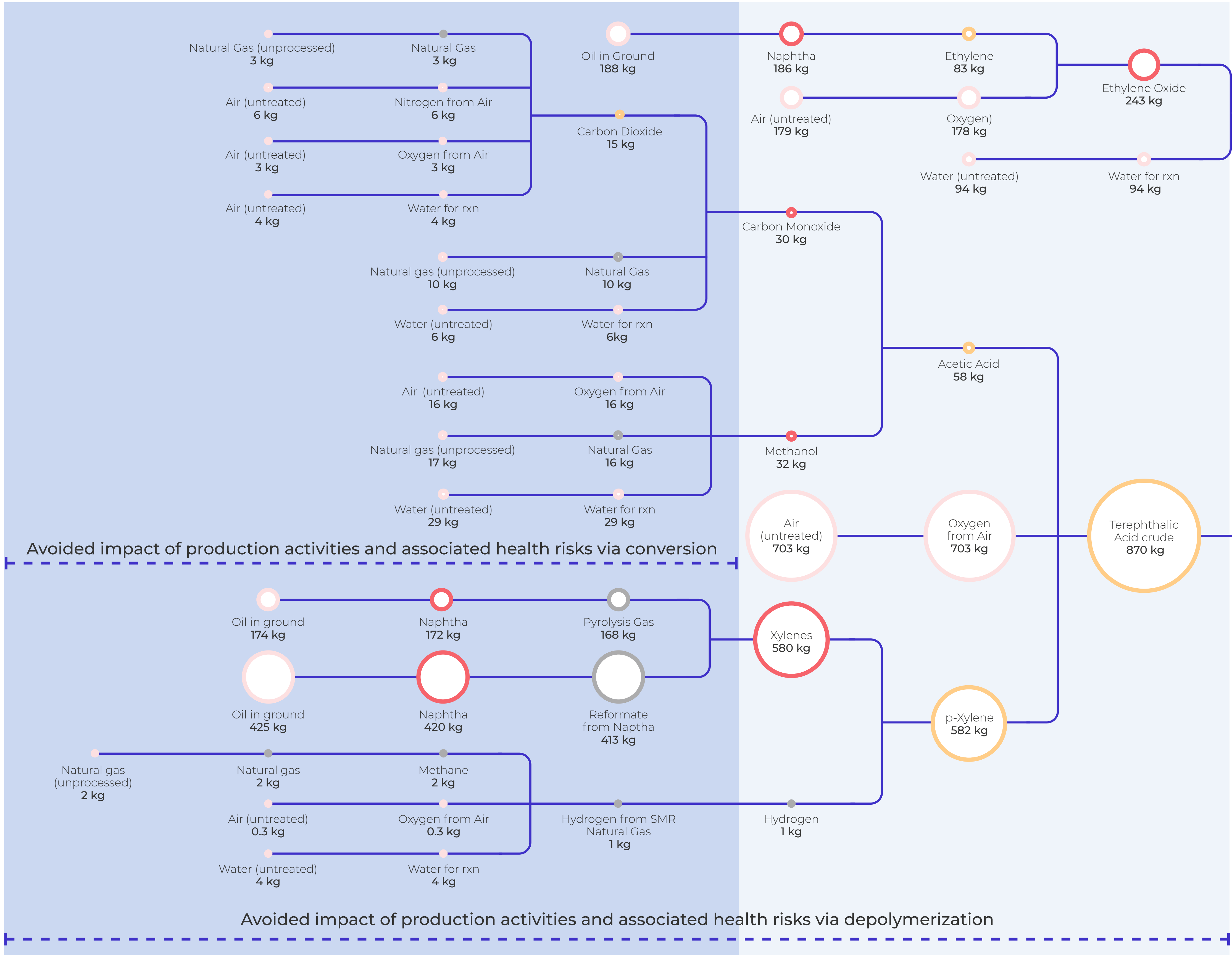


Sources:
Environmental Genome Initiative and SciveraLENS® Rapid Screen

Scivera Hazard Category Score

- High Hazard
- Moderate to Low Hazard
- Acceptable
- Natural Resource
- Incomplete Data or Mixture of Substances

FIGURE 21. CHEMICAL TREE OF PET AND MATERIALS AVOIDED THROUGH DIFFERENT MOLECULAR RECYCLING TECHNOLOGIES



Sources:
Environmental Genome Initiative and SciveraLENS® Rapid Screen

Scivera Hazard Category Score

- High Hazard
- Moderate To Low Hazard
- Acceptable
- Incomplete Data or Mixture of Substances
- Natural Resource

The total chemical savings of a recycling process is determined by how much or little it breaks the polymer bond.

Our findings strongly suggest that the less a polymer is broken down through a molecular recycling process, the lower the human health risk because fewer chemicals and processing are required to build back the polymer. This implies that purification technologies have an advantage over depolymerization and conversion technologies because purification displaces more of the virgin supply chain to create an equivalent amount of plastic. Our chemical footprint analysis examined only the chemicals that are used in the manufacturing of each polymer of this study. It does not include, for example, chemicals that are used in fracking operations and their impacts to water or air or fugitive methane emissions from fracking wells.

Figure 20 uses LDPE as a model while Figure 21 uses PET as a model of how different molecular recycling technologies are mitigating health risks by reducing the need for virgin chemical deployment to make plastics.

Walk through additional polymer examples and learn how to calculate a chemical footprint in **Appendix 5.1 and 5.2**

Human Health Impact Methodology

Using TRACI 2.1, our teams estimated the impacts from indirect emissions from the energy used by the molecular recycling processes, but could not obtain detailed data sets for other direct emissions of chemicals or compounds to air, water or solid waste (i.e., identifying specific chemicals, their amounts,and end-of-life handling). It was out of the project scope to collect data on the emissions of facilities or test the quality and contents of the outputs and residuals of the technology processes evaluated; this is needed as part of a detailed project diligence exercise.

In addition to the analysis using TRACI 2.1, the research teams conducted a supplemental review of the potential human health impacts of direct emissions from molecular recycling technologies. This review included a selective literature review and a qualitative assessment of the hazards associated with virgin production of polymers (see Appendix 5.2). Our research did not find any chemicals or reaction by-products that are novel to the manufacturing of polymers via molecular recycling technologies, or any other evidence that raised obvious human health concerns from any of the nine molecular recycling companies evaluated.

Educate

What are the trade-offs between plastics recycling solutions? When should molecular recycling be deployed?

1

Purification, depolymerization, and conversion technologies each have a role to play in a future circular economy. Trade-offs between the technologies relate to their commercial availability, feedstock requirements, local infrastructure and policy, and environmental and financial performance.

Conversion processes are more "feedstock flexible" and provide additional value by processing material that would otherwise end up in landfill or incineration.

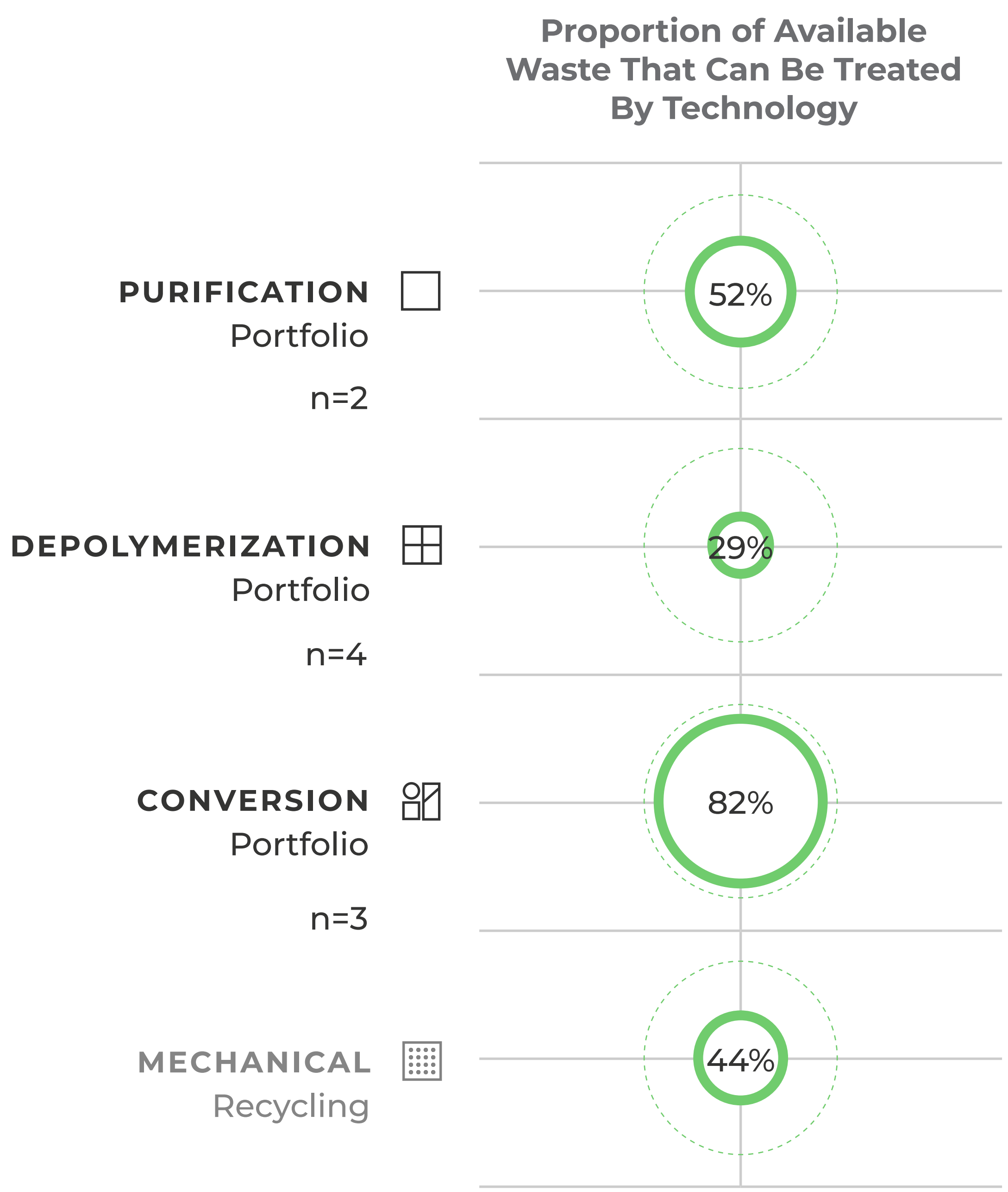
Our study and analysis suggest that the greatest advantages that conversion technologies have over other molecular recycling technologies are their ability to process mixed waste and their commercial maturity.

Conversion can be a comprehensive solution to plastic waste in areas where collections and sortation infrastructure are limited, or when plastic waste will not be separated from municipal solid waste (MSW). When evaluating the total packaging volumes across the United States and Canada, we found that the conversion technologies in our study could address 82% of all plastic packaging waste in the system, which is more than mechanical, purification, or depolymerization technologies could address alone, based on the technologies we reviewed (Figure 22). For some conversion technologies, like gasification, biocomponents like tissue paper, diapers and food waste commingled with plastics can improve process yields, whereas they would be considered contamination to traditional mechanical plastic recyclers and other molecular recycling technology processes. Therefore, conversion technologies play an important role in avoiding costs and destruction of resource value — and why some conversion technology companies are getting paid to take feedstock rather than paying for feedstock.

Conversion is more commercially available than other molecular recycling technologies and can address a wider range of plastic waste.

The molecular recycling sector is in its early stages of maturity and commercialization, although there are many examples of companies in operation for several decades[53, 54]. Of the three categories, conversion technologies are both the most commercially available, and the most quickly evolving, receiving considerable support by the petrochemical industry as these technologies align to their supply chain, whereas purification and depolymerization do not. There are many examples of mature conversion technologies retooling their processes to align with changing market dynamics. For example, some gasification

FIGURE 22. PROPORTION OF AVAILABLE PACKAGING WASTE THAT CAN BE PROCESSED BY DIFFERENT RECYCLING TECHNOLOGIES IN OUR STUDY



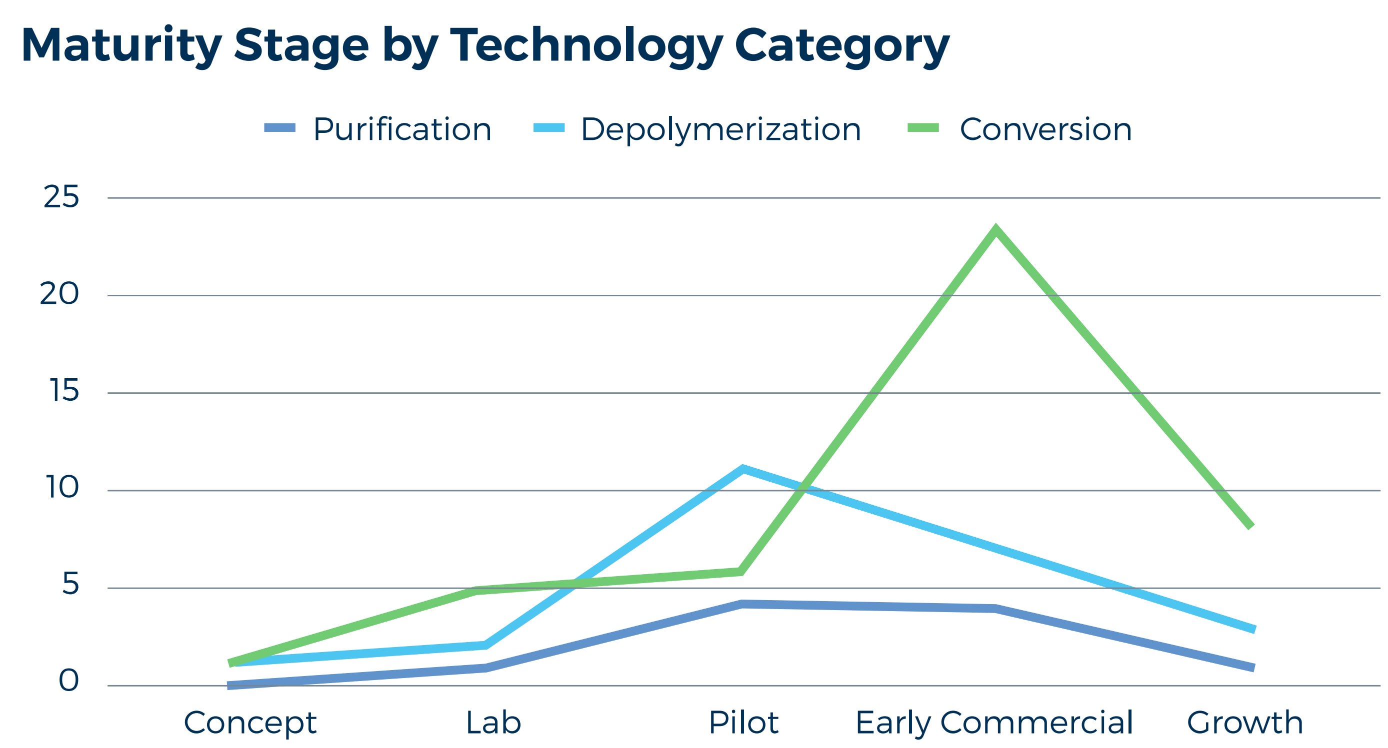
Note: Proportion of available packaging waste treated by different technologies based on assessment of waste plastics packaging data. Current U.S. and Canada plastic packaging recycling rate of 18% aligned with available plastics for conversion. Mechanical recycling proportion based on PET and PP and PE packaging in either bottle or container form.

technology companies are moving away from biofuel production and instead are producing recycled plastics with a petrochemical partner.

Closed Loop Partners took inventory of molecular recycling technology companies around the world to understand the state of development of the sector and published the *Molecular Recycling Global Directory*. We found that 52% of conversion technologies in the market were at a commercial growth stage; far more than purification and depolymerization, proportionally. Figure 23 illustrates where on the development curve each technology category is: purification and depolymerization have fewer commercial facilities globally and are less developed, as a whole. Depolymerization technologies are the least developed, with the majority of technologies in the pilot stage.

A technology's commercial availability is an important consideration in the context of circularity, climate mitigation, and pledges and commitments to both. Hundreds of brands and retailers around the world have made public commitments to both increase the recyclability of their products and packaging and increase the volume of recycled plastic content in their products and packaging in the next five or ten years. This time pressure is one reason that industry continues to focus on conversion technologies, as well as the quality of the outputs for conversion, which is less sensitive to waste input quality for most processes in this category. Lastly, for many formats of plastic waste like wind turbine blades, complex multilayer films, and other bulky rigids like plastic car parts, conversion technologies appear to be uniquely positioned to process these kinds of feedstock because they are able to process a wide range of polyolefin plastics, can tolerate contamination with other waste materials and typically operate large facilities that are able to take large commercial volumes of plastic waste.

FIGURE 23. COMMERCIAL DEVELOPMENT OF MOLECULAR RECYCLING TECHNOLOGIES, BY TECHNOLOGY CATEGORY

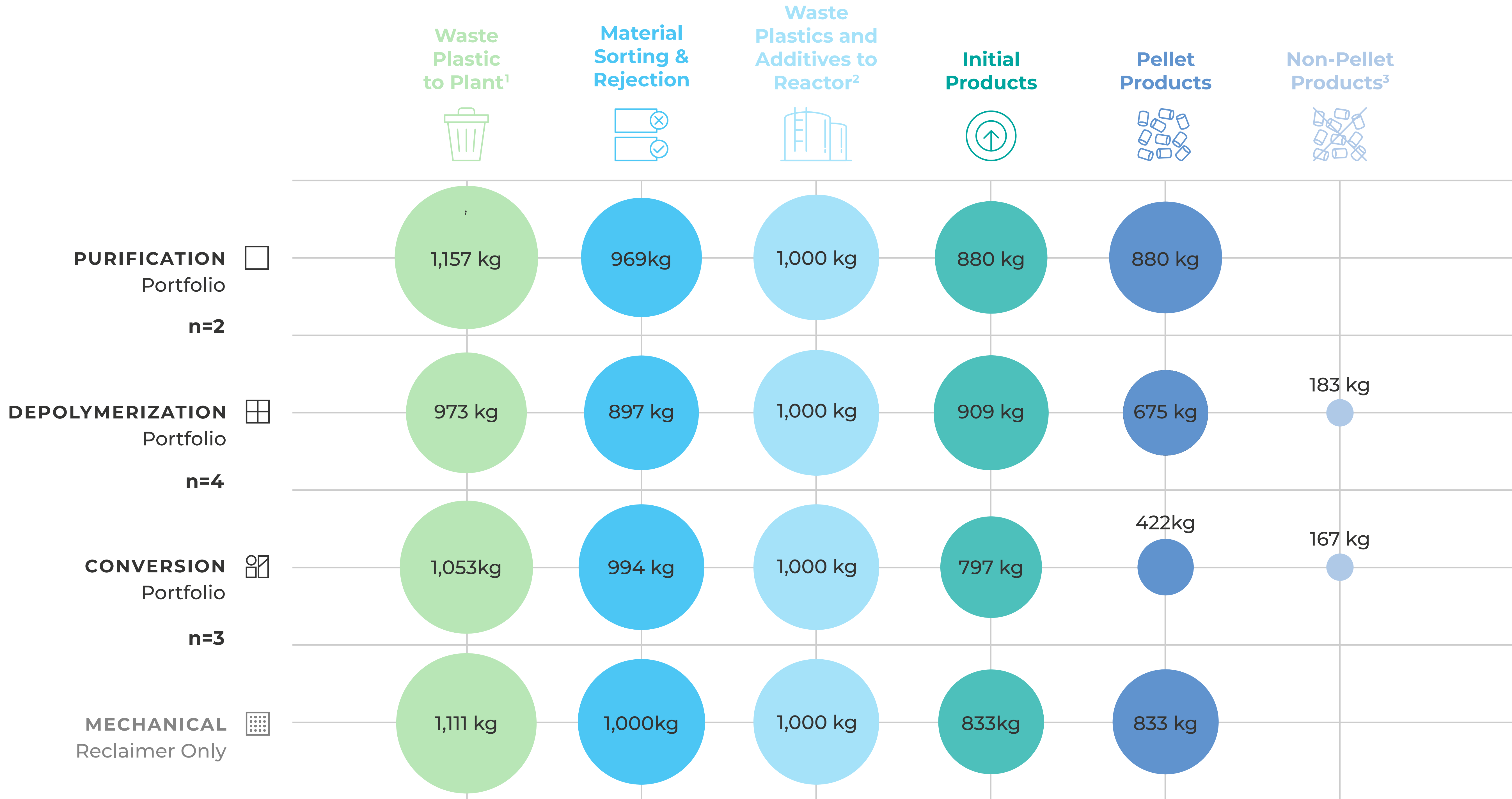


Purification and depolymerization technologies would yield higher volumes of recycled plastics, with the most favorable environmental results, of the molecular recycling technology categories evaluated in this report.

Our analysis suggests that the more process steps between an output and a finished polymer, the more mass losses occur in the value chain. Thus, it holds that from a product yield perspective, purification and depolymerization technology processes have the least mass loss and the highest product yields when polymer pellets are produced.

While conversion technologies can take mixed plastics and even prepared municipal solid waste with plastics (i.e. with some pre-processing needed), the conversion-based plastic supply chain yields 20-30% less finished plastic compared to purification and depolymerization-based plastic supply chains. We calculated how much plastic resin would be produced by each technology category if we were to put 1,000 kilograms of plastic feedstock into the technology reactor. Each technology category's feedstock corresponds to their specifications and is therefore different from one another. Purification yielded the highest amount at 88% material processing efficiency. Depolymerization and mechanical recycling had 67% yields, and the conversion technology had a plastic yield of 44% including non-pellet products (Figure 24).

FIGURE 24. AVERAGE MASS YIELD WHEN 1,000 KG OF PLASTIC WASTE IS PUT INTO EACH TECHNOLOGY PROCESS



Learn more about our methodology and assumptions of our mass yield analysis in **Appendix 4.5**

Notes:
1. Mass balance starts at delivery of feedstock to the recycling facility, after material has been processed at a MRF or equivalent facility.
2. Initial products include polymer pellets, monomers, methanol, pyrolysis oil and other hydrocarbon products.
3. Non-pellet products include waxes, fuels, and other hydrocarbon products which are not converted to polymer products.

Purification and depolymerization technologies commercial success will rely on upstream collections and sortation.

Material processing efficiency is one of several markers of success in a circular plastics economy. Thus, it is important to maximize material yields from molecular recycling technologies. For purification and depolymerization, process yields are correlated to the feedstock quality. Five of the six purification and depolymerization companies that we evaluated in this study require single-resin, homogenous feedstock. However, that feedstock could be more contaminated than a mechanical recycling process would require. Some purification and depolymerization technologies can process multiple plastic resins. However, they are only able to do so one at a time, in batches or on separate plant lines. This is because specific solvents, or the process itself, needs to be adjusted to specific polymers.

These technologies today demonstrate material yields of 75% to 90% but rely on the existing plastics recycling system meeting their feedstock specifications. Alternatively, a molecular recycling company can make capital investments to develop its own pre-processing system to take more contaminated or mixed waste. In the absence of this additional investment, at least in the short-term, purification and depolymerization companies may often compete with mechanical recyclers for pre-processed feedstock unless additional supply is created. This also represents a massive financial opportunity for the existing collections, sortation, and mechanical recycling system to support the development of companies whose business models can support paying $600 to $1,000 USD per metric ton of feedstock. Another feedstock strategy that can support these technologies as they scale would be blending post-industrial feedstock, which tends to be less contaminated, with post-consumer feedstock.

Summarizing the Trade-offs

The molecular recycling sector is incredibly nuanced and diverse. Not all technology groups are at the same level of development. Their tolerance for mixed plastics or other contamination varies company to company, just like their performance across environmental impact metrics like energy, bluewater, and greenhouse gas emissions. Due diligence prior to investing in strong performing technologies is critical. To support this decision-making, we've summarized the results when observing the category averages between purification, depolymerization, and conversion in Table 2. This summary is based on our review of nine technology companies and should only serve as a point of data, not a definitive source on the state of the sector at large.

TABLE 2. SUMMARY OF TRADE-OFFS OF DIFFERENT MOLECULAR RECYCLING TECHNOLOGIES BASED ON TECHNOLOGY CATEGORY AVERAGES IN CLOSED LOOP PARTNERS STUDY

Ranking	Commercial Maturity and Availability [1]	Feedstock Flexibility	Value-add to Existing Collections & Sortation System[2]	Climate Impact Potential[3] (CO2e)	Material Processing Efficiency to Produce Plastic[4]
1	Conversion	Conversion	Purification	Purification	Purification
2	Purification	Purification	Depolymerization	Depolymerization	Depolymerization
3	Depolymerization	Depolymerization	Conversion	Conversion	Conversion

Notes:
1. Based on Closed Loop Partners Global Directory of Molecular Recycling Technolgoies
2. Based on Closed Loop Partners supply chain analysis and study of nine molecular recycling technologies
3. Climate Impact Potential at the systems level assumed (i.e. total plastic recycling and manufacturing supply chain to produce plastic resin)
4. Material Processing Efficiency: Total amount of plastic feedstock that is converted into plastic resin pellets, expressed as a percent. This is a more direct measure of the efficiency of each supply chain to convert plastic waste back into recycled plastics.

2 Each type of plastic requires a different strategy to maximize profit, circularity, climate change mitigation, and contribution to healthier and safer communities.

Closed Loop Partners sought to understand how specific recycling solutions align best with diverse input materials. The results of our financial, environmental and human health impact analysis point to an expanded plastic waste strategy that recognizes the role of molecular recycling technologies to address a broader scope of materials and our hardest-to-recycle plastics. That role complements, not competes with, mechanical recycling. Mechanical recycling should continue to process clear and rigid PET bottles, natural HDPE, select polyethylene films, and fractions of the polypropylene MRF streams for which there are end markets because it is able to do so with a smaller environmental footprint. There will come a point where some plastics that have been mechanically recycled for multiple cycles will be too degraded to be relooped through the mechanical recycling process. At that point, molecular recycling becomes a suitable complement and solution to “reset” the previously mechanically recycled plastic.

Molecular recycling emerges as a more sustainable and circular solution for hard-to-recycle plastics that cannot be processed by mechanical recycling and where reuse is not viable at scale. In some cases, the choice for recycling technology is clear because there is only one type of molecular recycling technology that can process a particular resin or plastic waste format (i.e. composite plastics and conversion; electronic waste and purification). However, there are multiple recycling options available for most plastics waste. For example, some PE and PP films can be processed by mechanical or several different molecular recycling technologies.

Conversion technologies are often the first consideration for recycling hard-to-recycle polyolefins but our study found that when purification can process these materials, they yield an average of 25% more finished plastic per ton of plastic waste managed and can have up to 45% fewer CO2e emissions per kilogram of plastic resin produced (i.e., 1.6 kg/CO_2e per kg of plastic pellet with purification vs 2.8 kg/CO_2e per kg of plastic pellet with conversion). These figures only represent the differences in category averages we observed in our study of two purification and three conversion technologies; the variance observed within these technology categories would change these percentages.

The critical trade-off is that conversion can take these films in a more contaminated state— even commingled in trash—while purification requires, in general, more pre-processing to manage that plastic waste. Therefore, the viable solution is dependent on factors beyond the technology. **In practice, the appropriate technology or system will depend on the volume of material that needs to be processed, the makeup and consistency of that waste, local collections and sortation capacity, and local policies that can influence a project's economics and viability.**

To develop circular systems for plastics, there must be a shared understanding around the optimal routes for material processing. Figure 25 summarizes the optimal routes for recycling based on our financial, environmental and human health impact analysis. This illustration does not take into account local infrastructure or policy landscape which affect project feasibility, but it does illustrate what is possible given the realities of downstream plastic recycling systems today.

> "As potential solutions to the plastic pollution crisis take shape, it's critical that we ensure they do not trade one harm for another, while protecting people and nature. This research brings us a step closer to understanding whether advanced recycling technologies can be implemented in such a way that they support the true transformation of our materials system and complement efforts to reduce and reuse plastic."
>
> – **ERIN SIMON, HEAD, PLASTIC WASTE + BUSINESS,** WORLD WILDLIFE FUND

FIGURE 25. OUR UNDERSTANDING OF WASTE AND RECYCLING OPTIONS TODAY: KEY FACTORS AND BENEFITS ACROSS MECHANICAL RECYCLING AND MOLECULAR RECYCLING

MECHANICAL Recycling

	Single polymer · Single colors	Single polymer · Mixed colors
Input	HDPE natural; Post-industrial; Clear PET Bottle	Colored HDPE; Colored PET and PET Thermoforms; PE Films
Output	• Single color recycled flake or pellets	• Mixed color pellets • Plastic composite
Key factors	• Enables post-industrial recycling • Closes the loop on PET bottles and HDPE bottles • Output is often downcycled • Typical capacity[1]: ~50,000 metric tons per year	• Provides low-impact recycling route which can produce long-lasting products (e.g. plastic lumber, buckets etc.)
Benefits	Possible to maintain plastic output quality via specific upgrading processes, e.g. increasing intrinsic viscosity 88 % lower CO_2 emissions than virgin[2]	Stable end markets for recycled content Value added per metric ton[2]: $520 88 % lower CO_2 emissions than virgin[2]

PURIFICATION

	Single polymer · Mixed colors	Single polymer Flame retardants	Polycotton blended textiles Mixed colors
Input	Rigid Polypropylene; PE Films; Polystyrene and EPS	Electronic Waste (HIPS/ABS); EPS insulation	Polycotton blend textiles
Output	• Single color, food grade recycled pellets	• Single color recycled pellets	• Clear rPET pellets • Powdered cellulose
Key factors	• Removes dye & additives • Produces high quality pellets • Typical capacity[1]: 8,000 - 50,000 metric tons per year	• Extracts & isolates specific persistent organic pollutants from priority waste streams (e-waste and insulation)	• Removes dye • Separates mixed fibers (synthetic & natural)
Benefits	Shortest supply chain route back to polymer capable of removing additives and color from feedstock Value added per metric ton[2]: $670 Average 20 % lower CO_2 emissions than virgin[2]	Human health benefits from removing pollutants from circular economy[2] Out of scope for Closed Loop Partners study	Enables recovery of both synthetic and natural fibers in blended feedstocks Out of scope for Closed Loop Partners study

DEPOLYMERIZATION

	Single polymer · Single colors	Synthetic textiles
Input	Colored PET and PET Thermoforms	Polyester and Polyamide Textiles
Output	• Monomers • Virgin-like clear pellets	• Monomers • Virgin-like clear pellets
Key factors	• Creates high quality clear polymer from mixed colored waste • Typical capacity[1]: 8,000 - 50,000 metric tons per year	• Creates high-value outputs from hard-to-recycle synthetic fibers
Benefits	Route processes feedstocks that are not major targets for the mechanical recycling system Value added per metric ton[2]: $385 Average 10 % lower CO_2 emissions than virgin[2]	PET and polyamide make up ~60 % of global fiber production[3] Out of scope for Closed Loop Partners study

CONVERSION

	Mixed polymers · Mixed colors	Hard-to-recycle products
Input	Rigid Polypropylene; Polystyrene and EPS; Mixed & Multilayer Films	Other
Output	• Hydrocarbon products • Syngas • Base chemicals	• Hydrocarbon products • Syngas • Base chemicals
Key factors	• Creating valuable end-products from mixed & contaminated waste streams • Typical capacity[1]: ~20,000 - 400,000 metric tons per year	• Creates solutions for difficult waste streams such as thermosets
Benefits	Highest throughput potential of all technologies with trade-off of lower processing efficiency[2] Value added per metric ton[2]: $60 Average 4 % lower CO_2 emissions than virgin[2]	Composite materials are a rapidly growing waste stream with few treatment pathways Out of scope for Closed Loop Partners study

Notes:
Data from Global Directory of Molecular Recycling Companies
1. "Capacity" refers to typical waste throughput capacity
2. Source: Closed Loop Partners study, 2021
3. Source: Textile Exchange PFMR, 2020

Collaborate

Collaboration across the plastics value chain is critical in order to drive circular, safe and profitable outcomes. In this chapter, we examine the diverse stakeholders, including brands, recyclers, petrochemical companies, investors and policymakers, and recommend how each could play a unique role in shaping the development of the molecular recycling sector to align with sustainability goals.

1

All stakeholders have a role to play in increasing transparency and disclosure around plastic usage and recycling in order to help expedite innovation and investment to drive the commercialization of molecular recycling technologies that are high-performing, safe and circular.

Industry and government must make efforts to collect reliable, complete data to fully understand the flow of plastics through our economy.

We cannot fix what we do not measure. With detailed information on the volume, chemistry and format of plastic waste, we can collectively identify and optimize solutions to capture plastic, recover its economic value, and reduce the need for virgin plastic production.

Today, the best available data on plastic production, collection, recycling and applications of recycled content are focused on single-use packaging. Even then, the data is limited, outdated and imprecise, relying on average production figures and scaling those on a per capita basis to estimate the volumes and types of plastics in a region. There is virtually no data on the flow of other types of plastic waste, like healthcare plastics, textiles and apparel, construction and automotive plastic waste, even though these plastics make up two-thirds of the plastics put into use in the U.S.[55]

More and better quality data on plastic volumes and flows across industries will support a transition towards a circular economy, identify market needs and opportunities, and expedite investment and progress to solving plastic waste. Industry and federal agencies like the U.S. Environmental Protection Agency are best positioned to lead a multi-industry effort to develop a more robust picture of how plastics flow through our economy, which in turn will help set the stage for plastics waste reduction and increased plastics recovery.

2 Molecular recycling companies should disclose data on the economic, social and environmental viability of their technologies and adhere to global standards to create clarity, assurance and trust for diverse stakeholders.

Companies must be transparent about if and how molecular recycling is contributing to circularity.

The outputs of molecular recycling processes have uses outside of the plastics supply chain; thus, the use of molecular recycling technologies does not guarantee a circular outcome (except in the case of purification). For example, a pyrolysis technology process can produce maritime diesel, which is not part of the plastics value chain, or it can produce naphtha, which can be mixed into many products or looped back into the plastic supply chain. Closed Loop Partners does not consider plastics-to-fuel to be circular, or an optimal use case of molecular recycling technologies. Producing fuels from plastic waste is more sustainable than virgin fuel production and captures the economic value of those resources. But it does not maximize the potential of molecular recycling to build circular supply chains, close the loop on more types of plastic waste, and decrease the need for fossil fuel extraction.

Molecular recycling technology operators should be transparent about when and where their process is being implemented in ways that drive circularity. More data on the viability and impact of molecular recycling processes and their associated supply chains, would help molecular recycling operators, the petrochemical industry, and the brands and retailers who want a greater supply of recycled plastics support investment in the sector. More data would also help address the concerns and questions raised by environmental and community groups.

Three Ways for Molecular Recycling Companies to Increase Transparency Around Their Circularity

1. Molecular recycling companies who release Life Cycle Assessments (LCA) should share the assumptions that went into the analysis.

Many molecular recycling and petrochemical companies release Life Cycle Assessments (LCA) about a process or product without supplemental data or any explanation of the LCA's assumptions. Assumptions like the energy source or the base case end-of-life fate for materials processed (e.g. incineration) can drastically alter LCA results (See page 70).

We recommend using the latest accredited LCA methodologies (i.e., ISO 14440 and ISO 14046), which include a peer review process by a panel. Credible and transparent life cycle assessments include the full set of assumptions and data sources that went into the modeling (e.g. energy grid mix, credits given to a process for avoidance of specific end-of-life fates) as we have done for this study (see Appendix 4.1). The goal is to provide transparency and build trust without overcommunicating company IP or trade secrets. Investors or other stakeholders who are evaluating a technology process or potential project must use data relevant to the specific market and region where a potential company or project will be sited, and understand the limitations of the LCA they are reviewing.

2. Purification, depolymerization, and conversion technologies should disclose information that verifies the safety and limitations of their process, facility, and products.

There are consistent references to the high polymer recovery rates and quality of solvent-based purification and depolymerization processses in the literature and research about the sector. But, it is not clear how effectively solvent processes remove chemical additives (i.e., colorants, plasticizers, anti-oxidants, flame retardants etc.) from polymers. Residual additives in the recycled content must be low in order for plastic compounders to buy recycled polymers. This issue is a central concern for all solvent-based molecular recycling manufacturers, but especially true for those intending to sell food-grade finished products made from plastic feedstock that is non-food grade. Solvent-based molecular recycling technology companies who wish to sell food-grade resins or resins for human-contact uses should test their outputs and final products to ensure they meet regulated thresholds and share results with regulators, investors, and brands. Other non-food or human-contact applications may merit similar testing; this subject bears further study, but is outside the report scope.

Lastly, technology companies should disclose the limitations of their processes. For thermal processes, understanding the purity of the output is often an early step in a petrochemical company's evaluation process; this test determines if integration is viable from a cost and volume perspective. For purification and depolymerization technologies, there is little to no public data on the degradation levels of the polymer when comparing plastics produced from these systems to plastics produced from mechanical recycling. It is well-accepted that mechanical recycling can technically recycle plastic up to seven times, though one to two cycles is most realistic.[56, 57] Understanding the technical limits of purification and depolymerization is an important area of public research.

3. Molecular recycling companies should use credible measurement standards, like mass balance, to help track recycled content and build visibility and trust with stakeholders.

There is a great deal of consumer pressure and corporate commitment to increase the sustainability of plastics around the world, particularly through the inclusion of recycled content. As a result, there is a strong market need for internationally recognized and trusted standards against which recycled content can be measured. There are standards that use a mass balance approach where strict records are kept of the materials used in the formulation of a product and product outputs, and this data is transferred, monitored and controlled as the products move through the relevant supply chain. A mass balance approach could enable manufacturers and users to quantify amounts of recycled content using a recognized method and with the accompanying certification to build consumer confidence. The mass balance approach has previously been successful in developing high levels of transparency and consumer trust for tracking other kinds of recycled content, such as paper, and in sectors like renewable energy.

Mass balance is particularly relevant for molecular recycling and also introduces some interesting considerations when accounting for recycled content and process efficiency. Purification, depolymerization, and conversion technologies are likely to need distinct mass balance approaches because of the different chemical reactions that occur in each type of process and because they produce such a wide range of outputs. New and existing mass balance standards should account for the nuances that occur across different molecular recycling technology processes.

Plastic waste recycled by purification technologies can be easily tracked by mass, similar to mechanical recycling, since neither process changes the molecular structure of the polymer. Tracking mass balances is more complex for depolymerization and conversion. For example, water is a key component of depolymerizing PET and its mass is incorporated into the monomers. Therefore, it is possible for the weight of the monomer products to be heavier than the plastic waste entering the process. This water (i.e., mass) is lost if these monomers are repolymerized. Mass balance standards may not account for these nuances—and comparing between various depolymerization processes that produce monomers versus finished resin will likely require additional analysis to create a valid comparison.

For conversion, which can produce elemental products from plastic waste, carbon balancing (i.e., effectively tracking the carbon atoms only) can be an extremely useful tool to track these chemical processes. This method can also help to track carbon retention at a systemic level, indicating where material carbon is lost in a process as carbon dioxide (e.g. through combustion), and identifying which process routes have the greatest potential for retaining carbon in the system over multiple material lifetimes.

DEEP DIVE

Policies that Regulate Molecular Recycling Facilities

Molecular recycling facilities can be regulated as either waste operations or manufacturing operations. Groups like the American Chemistry Council (ACC) have lobbied states to regulate molecular recycling facilities as manufacturing facilities[58], rather than waste facilities, which would allow them to operate with fewer regulatory constraints. Public data on specific facility emissions is limited, but petrochemical and environmental groups have published their own perspectives and studies on the impacts of molecular recycling operations.[59, 60, 61]

A nuanced regulatory framework for this sector that keeps up-to-date with technological progress should be able to appropriately regulate the molecular recycling facilities and protect community health. Molecular recycling operators should be regulated, based on the inputs received and outputs produced at a particular facility. For example, gasification technologies will take in municipal solid waste with plastics in it, while purification technologies will often take in clean plastic feedstock that has been baled from a MRF or industrial manufacturer. The first facility should adhere to a regulatory regime of a waste management facility; regulations that apply for a manufacturing site could be sufficient in the second example. A one-size-fits all regulatory approach will either over- or under-regulate these technologies since they can cut across more than one sector (i.e. onsite waste preparation operations with methanol upgrading manufacturing at the same facility).

Policymakers are working to understand molecular recycling technologies and how to regulate them. In September 2021, the U.S.

Environmental Protection Agency (EPA) released an advanced notice of proposed rulemaking, seeking comments and data to inform whether to regulate pyrolysis and gasification units differently from solid waste incineration units subject to section 129 of the Clean Air Act.

Environmental justice and advocacy groups' primary concerns around specific molecular recycling technologies (i.e. pyrolysis and gasification) stem from the unknown of how facilities are operated and the often undisclosed air emissions of the facilities. They seek increased transparency from the molecular recycling operators to ensure that the emissions from each facility are not atypical from that of a plastics manufacturing facility. Disclosure and transparency are critical to build shared understanding between industry and community groups and to build trust in molecular recycling technologies, particularly the ones that have historically been focused on waste-to-fuel production. Other policies that indirectly regulate molecular recycling facilities are linked to extended producer responsibility schemes (EPR) and recycling mandates; these can regulate the format that plastic waste and other feedstock need to take and influence recycling facility design and on-site technology choices.

> Policies that foster innovation in science and technology, support a circular economy, and incorporate life cycle thinking can create opportunities that capture the true value of plastics while aligning with decarbonization and sustainability goals.
>
> **– RACHEL MEIDL, FELLOW, ENERGY AND ENVIRONMENT,** BAKER INSTITUTE FOR PUBLIC POLICY, CENTER FOR ENERGY STUDIES, RICE UNIVERSITY

3 Investment and funding from government, industry, and private equity actors are critical to scale this sector in line with circular principles and in time to reach industry goals for sustainability.

The public sector and impact investors play an important role in bridging gaps in capital to develop high-performing technologies that are aligned with circular and market needs. Their early investments create market signals that trigger mainstream investors to scale best-performing technology solutions.

As with any technological advancement, it takes time and considerable investment to improve and optimize new technologies that can alter the course of material flows, and the systems and lifestyles built around them. Historically, federal funding has supported new technology development and system shifts through supply side incentives, such as tax incentives and credit support, as well as R&D funding and demand mandates.[62] Government funding and state and federal policies have stimulated supply and demand for industries like oil and gas, solar, and wind, which commercialized across regional markets.

Following the devastating global impacts of the Covid-19 pandemic, there is tremendous interest in “building back better” and a potential windfall of capital allocated to achieve this ideal, with bills like President Joe Biden’s $1.2 trillion USD infrastructure package.[63] We can build our communities back in ways that support people, business and the planet by transitioning our plastics supply chain to a circular one and keeping these resources in circulation to limit the need for virgin resource extraction. Molecular recycling technologies have a unique value proposition to support this goal, but need federal support to scale safe and circular technologies. Federal support in the form of low-risk funding and grants can help accelerate technological advances. The federal government has played this role historically, most recently investing more than $4 billion dollars in R&D for wind and solar energy technology between 2005 and 2015.[64]

There is currently an investment gap in the United States and Canada for catalytic technologies, particularly if they are capital-intensive and require longer time-horizons to commercialize. A molecular recycling technology company needs to be well capitalized as it navigates from pilot stage to commercialization stage, because piloting feedstock and outputs can take several years and tens of millions of dollars. Venture capital tends to come in at later stages, once the technology is proven at scale. Traditional project finance will not typically invest until after the first commercial facility has proven successful. Thus, federal funding is critical to bridge the gap as earlier stage technologies go through proof of concept demonstration stages. The federal government can also support later-stage companies with financing products that de-risk molecular recycling projects; for example, loan guarantees, capital exemptions and incentives that encourage investment into key areas of system change. The solar and wind energy sectors benefited from this type of credit support, receiving $11.7 billion dollars in loans and loan guarantees from the U.S. Department of Energy between 2005 and 2015.[65]

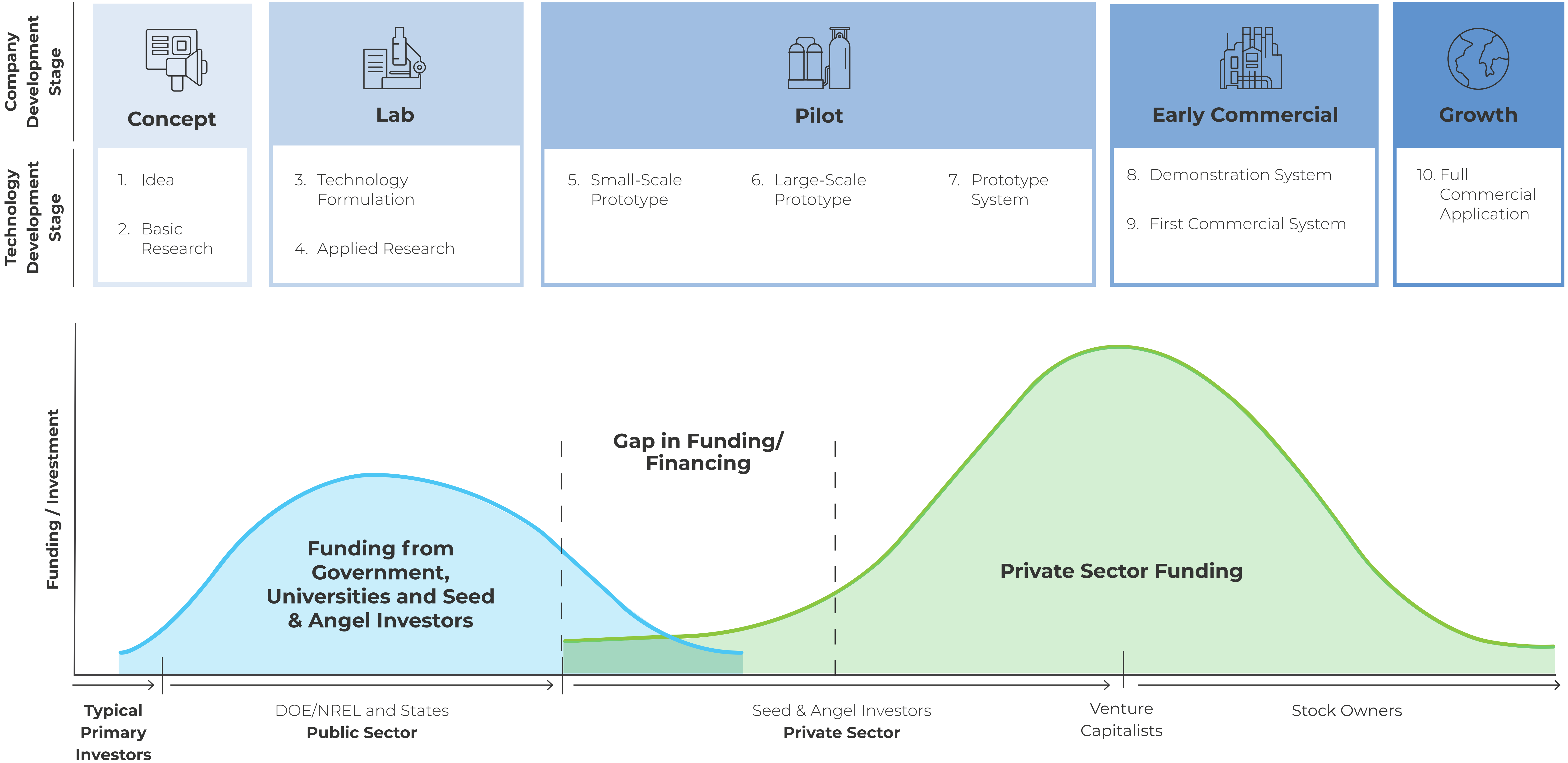
Participation from impact, ESG, and strategic corporate investors to scale high-performing molecular recycling solutions aligns with corporate, environmental, social, and climate objectives.

The second wave of funding for commercialization of molecular recycling technologies, after federal funding for development and testing, should come from investors interested in ESG opportunities, the transition towards a circular economy and addressing the negative environmental impact of plastic waste. This includes strategic investors and grant making entities who stand to either gain proprietary interest from early-stage engagement in the sector or are willing to support climate-friendly technology development.

Integrating molecular recycling into the existing plastics recycling system requires investment in collection and sortation systems, as well as molecular recycling technologies. Our study estimates that investment of less than two billion dollars into collections, sortation, and secondary processors (i.e. reclaimers) could successfully integrate a mix of molecular recycling technologies into our current plastics recycling system. Setting up the molecular recycling facilities would require an additional $5 billion USD and could increase plastic packaging recycling rates to 30% across all common resins (i.e. PET, PP, LDPE, etc.) in ways that do not compete with mechanical recycling. Of that $5 billion, a fraction of that would be needed as 'seed' funding to build out the first tranche of commercial plants, which will then enable plant operators to access mainstream infrastructure funding.

Investment across the recycling value chain to integrate molecular recycling solutions would result in the recycling of an additional 2.5 million pounds of plastic packaging per year in the U.S. and Canada, and yield more than $970 million USD per year in economic activity with a net benefit of $1.4B compared to landfilling, as soon as 2030 (see *Reaching a 30% Recycling Rate across all Packaging Types Deep Dive)*.

FIGURE 26. DEVELOPMENT MILESTONE FOR MOLECULAR RECYCLING AND CAPITAL NEEDS THROUGH COMMERCIALIZATION



4 Waste collectors, recyclers, and the petrochemical industry should collaborate to create standards that optimize material flows and scale their symbiotic processes.

Integrating molecular recycling into the existing supply chain will require localized solutions and testing through regional collaborations.

Recycling is local. The spectrum of outputs represented across the molecular recycling technologies provides considerable opportunity for circularity and distinct needs for collaboration. Large brands, petrochemical producers and waste management service providers should engage with molecular recycling innovators in an effort to scale more holistic regional waste management systems.

Working at the subnational or regional level would allow partners to aggregate sufficient feedstocks across a larger population, leverage existing infrastructure for collecting, sorting, and mechanically pre-processing materials, and keep economic constraints, such as transportation and logistics costs, in check. Doing so diversifies feedstock sources and could change the unit economics of a particular recycling technology. For example, a depolymerization technology that processes PET packaging and polyester textiles or carpets can access much more material in a given region (e.g. ~200 miles from the facility). But it will take transparency and collaboration between stakeholders to uncover the market opportunities and match them to what is technically feasible. These strategic partnerships would allow for hard-to-recycle plastics that are landfilled or incinerated at a cost today to become revenue-generating opportunities that can find new end-markets.

Additionally, strategic supply chain stakeholder collaborations can have considerable impact on project and product viability. They can test outputs to provide regulatory reassurance on product safety and compliance with existing or new standards; support the development of new processing aids (e.g. solvents, enzymes etc. to reduce process costs at initial development stages); and agree to longer-term offtake contracts to reduce project risk and reduce financing costs. Similarly, they can represent and showcase molecular recycling technologies to policy and decision makers to support systems change and the development of circular supply chains.

Molecular recycling technology companies and their investors are best positioned to address local plastic waste challenges when the local wasteshed[i] is understood. Most plastics sustainability initiatives, like the U.S. Plastics Pact, focus on closing the loop on post-consumer plastic packaging waste. However, identifying both post-consumer and post-industrial sources of plastic waste is especially important for earlier-stage technology companies who typically have lower contamination tolerances and therefore benefit from post-industrial sources. Beyond evaluating a technology process and company, project developers and investors supporting facility expansion or upgrade projects should consider access to feedstock and policy effects.

Molecular recycling technology companies should align with and incentivize the existing recycling value chain to support cost-efficient operations and feedstock acquisition.

In the current market some molecular recycling companies are paid to take plastic waste from municipalities or private companies, but in general, they should expect to pay for this feedstock in order to better control the quality and volume they need. If and when molecular recycling companies receive payment for feedstock via a tipping fee, they will need to compete with the low cost of landfilling for untreated mixed solid waste, or at least cover the costs of transportation to the molecular recycling facility.

Molecular recycling technologies will also have to invest in pre-processing equipment and vertically integrate these activities into their operations if they do not provide the adequate economic incentive for the existing collections and sorting infrastructure to integrate with their operations.

To date, the main driver for integrating on-site feedstock preparation seems to be the lack of adequately prepared feedstock from the existing waste infrastructure, which is solely focused on mechanical recycling needs. The technology companies that we evaluated reported 'paying too much for overly prepared feedstock' (e.g. washed, color-sorted or only being able to source mixed baled or shredded feedstock of certain polymers not suitable for mechanical recycling), which then required further size reduction and extrusion on-site before processing. In the future, collection, separation and sorting infrastructure targeted at molecular recycling might provide more cost-efficient input and create additional revenue opportunities for the existing mechanical recycling system.

i. A wasteshed is a geographic area that serves as supply of post-consumer and post-industrial feedstock for recycling technologies.

5 Brands who generate recycled plastic demand should support its sustainable growth.

Brands can act on their public commitments to using recycled plastic content, and help stabilize demand for recycled plastics, by entering into long-term supplier contracts, supporting investment into the existing collections and sortation infrastructure in the U.S. and Canada, and collaborating across sectors and with peers to create new product standards that align and scale end markets.

Until fully commercialized, molecular recycling will command premium prices for its outputs. The need for premium prices reflects both the higher production costs of these early-stage technologies from not yet being fully scaled up and the difference in cost between recycled content and virgin prices, which do not fully reflect all negative externalities or the subsidies received by the oil and gas industry. Even so, premium pricing is typical of early-stage sectors with long technology development curves; for example, solar energy cost $100 per watt in 1975 and came down to less than $0.50 per watt by 2016.[66]

Based on our study, petrochemical companies, brands, and retailers should expect to pay premiums between 10% and 40% in the short-term to scale molecular recycling in line with their time-bound public commitments. Premiums in conversion are usually needed to create positive returns on the business model while premiums in purification and depolymerization more often reflect the difference between market demand and supply for their outputs. Premiums resulting from demand supply imbalance are expected to reduce over the next 5 to 15 years while the supply of recycled content from molecular recycling technologies increases. However, premium pricing based on the added value that recycled content provides can prevail if virgin pricing increases to include externalities, and industry recognizes the circular impact of these materials or the carbon emission reduction benefit of “waste”-derived products. Meanwhile, brands can support the early growth of molecular recycling by both allocating the budget to account for these premiums, and by signing long-term offtake contracts which help a company stabilize their revenue, lower the cost of capital, and invest in improving operations. Historically, the apparel sector has used long-term offtake contracts to secure the majority of recycled content (i.e. rPET) away from food and beverage industry who typically source recycled content on the spot market.

6 Policymakers should help guide development of circular technologies.

The molecular recycling sector has historically been shaped by cultural and economic forces that drive toward linear outcomes, but a collective desire for a waste-free future is now pushing the industry towards circularity. Policymakers should include molecular recycling in legislation that pertains to downstream material management if they intend to support a circular future for plastics.

Thoughtfully-constructed extended producer responsibility (EPR) policies can support the investment in new infrastructure that drives circularity.

Extended producer responsibility (EPR) is an environmental policy approach which levies a fee from waste producers— for example, packaging manufacturers— for not meeting recycled content targets in products, effectively taxing them for the use of virgin resources.[67] These collected fees are used to fund collection, sortation and recycling infrastructure. Thus, EPR encourages designers, procurers and manufacturers to increase the recyclability of their products, as well as their use of recycled content, and prioritize efficient resource use.[68] EPR is increasingly regarded by policymakers and the consumer packaged goods industry as a necessary part of the solution to end plastic waste when the details of the policy dictate how material flows are measured and when funding flows directly to increasing collections, sortation, and processing infrastructure rather than a general state fund.[69]

EPR schemes have generally been considered successful in contributing to funding recycling infrastructure development, lowering the amounts of waste sent to landfill or incinerators, and reducing public costs of waste management.[70] When EPR is thoughtfully designed, it provides a long-term policy framework that has a significant impact on increasing resource efficiency in target waste streams.

There is considerable policy uncertainty regarding the definition of molecular recycling processes and their place in the waste management hierarchy and circular economy. For example, the U.S. Environmental Protection Agency released a recycling strategy in the fall of 2020 which does not mention molecular recycling.[71] For EPR to support all downstream recycling solutions, the definition of recycling needs to be expanded to include those molecular recycling technologies that lead to circular outcomes. Molecular recycling operators that produce energy or fuel from plastic waste should not qualify for EPR funding. Better-defined policy and market incentives could support and accelerate plastics recycling in the United States and Canada.

In the United States, Maine and Oregon were the first states to pass EPR. Maine's program enlists an eco-modulated approach, where fees for different material types will create market incentives for using materials that are easier to recycle, contain higher recycled content, and reduce the number of materials used, amongst other considerations.[72, 73, 74] Oregon's EPR bill targets paper, packaging, and foodservice ware and requires producers to join producer responsibility organizations (PROs) that will charge annual membership fees based on the environmental impacts of the producer's products.[75] Other states following the wave of EPR policies include California, Hawaii, Massachusetts, Maryland, and New York, which all have EPR bills on plastic packaging for review in 2021-2022.[76]

In contrast, Canada has more than 200 EPR Programs and 30 categories of materials are targeted under various frameworks. These programs vary from packaging and printed paper (PPP) to electronics, household hazardous materials, special waste and automotive material, across 10 Canadian provinces.[77] Five out of the ten provinces currently have PPP ERP programs.[78] As EPR scales across these two markets, key factors that could affect the position and role of molecular recycling in the future include:

- Definitions of recycling include molecular recycling based on each molecular recycling technology's greenhouse gas impact assessment, type of waste processed, and/or outputs produced that replace virgin petrochemicals

- Building a collections and sortation infrastructure that can adequately meet the specifications of both mechanical and molecular recycling (i.e. ensuring non-target plastics for mechanical recycling are sent to molecular recycling; and that the feedstock for molecular recyclers is not overly processed)

- Implementation of fees based on the recyclability of the product/material

The most effective fee structure is one that is tiered to reflect brands' progress toward policy goals and takes into account the actual recyclability of products. The incentives could be in the form of a fee waiver, fee reduction, or special designation (e.g. 'green seal') to consumers or other incentives. The policy and fee structure must be designed to motivate brands to ensure that their product is:

(1) recyclable (based on local, state, or federal definitions):
(2) recycled; and
(3) uses all or mostly recycled content in the manufacturing of their products.

Policy can stimulate private sector investment in local recycling programs and circular economy infrastructure to spur demand.

Similar to the subsidies provided to renewable energy investors and producers, public policy tools could help support physical infrastructure development and stimulate demand for products with recycled content. The U.S. granted more than $45 billion USD in tax abatements to support the scale up of solar and wind energy between 2005 and 2015.[79] This achieved remarkable results in terms of dollars attracted to alternative energy sources which in turn led to solar reaching electricity cost parity with fossil fuel sources. Similar incentives relevant to molecular recycling could include:

- Investment Tax Credits (ITC): An ITC Program would encourage investment immediately, as the credit is applied upon construction. Such a credit could be applied to new facilities or equipment that demonstrate circular outcomes and environmental impact benefits. To encourage investment in the entire recycling system, investment tax credits could also apply to ancillary infrastructure like sorting and feedstock preparation, which would benefit both mechanical recycling and molecular recycling;
- Production Tax Credits (PTC): Similar to those provided to renewable energy producers, a PTC program would encourage

> "Three considerations are key to make EPR successful. First, stakeholders should gain consensus on the goal for EPR and incentivize brands to achieve it. Second, we should update the definition of "recyclable" to ensure that only products that are profitable for municipal recycling programs are designated as recyclable. Third, we must allocate funds from an EPR program directly to municipal recycling programs and empower local leaders to invest the funds in the infrastructure required to achieve their waste reduction goals."
>
> **– RON GONEN, FOUNDER & CEO,**
> CLOSED LOOP PARTNERS

investment in large-scale project development and could be structured to be applied only to facilities producing a minimum output of certain material types, such as those most in demand by industry or prioritized by government. Production tax credits should not be applied to plastics-to-fuel outcomes, since this does not support material circularity or climate change mitigation;

- Advanced Market Commitments: These are commitments to acquire certain materials that lack any or robust secondary markets, in order to encourage their acceptance by MRFs. These would likely be best applied to electronic waste, textile waste, and organics;
- Pay for Performance Rewards: Additional grant capital could be made available to municipalities that reach certain recycling thresholds across material types for at least a two-year period to demonstrate sustained (systemic) improvement, with funds used to support product design and commercialization for lower-waste, reusable, and recyclable products;
- Research grants: Grants could fund research on topics related to consumer behavior, product design and durability, and product commercialization for increased reuse and recyclability.

The public sector can support the transition from a linear plastics economy to a circular one through federal or state-level green procurement practices.

Public procurement practices have been successful to support the development of markets for other recycled materials, most notably recycled paper for use as office paper. In the U.S. and Canada, there is or has been precedent of green procurement practices for plastics. Canada's Strategy on Zero Plastic Waste promotes procurement of more reusable, recyclable or compostable plastics and renewable or recycled plastic content.[80] In the United States, green procurement mandates that require federal agencies to use recycled products to the extent practical and competitive have started and stopped with changing administrations.[81, 82]

Procurement policies that require recycled plastic content can contribute to a stability in demand in the market when used with long-term procurement contracts or strategies, which would then enable long-term investment in molecular recycling and infrastructure for recycling plastics. The increased market could also provide economies of scale for plastic recycling.

Invest

Molecular recycling encompasses distinct and diverse technology processes that, under the right conditions, can generate positive impact outcomes for people, the planet and profitability. Investors can help shape and commercialize the winning technology companies that will represent best performing operations. In this chapter, we dig into four critical factors — technological viability, financial viability, environmental and human health impact measurement, and integration into local markets — to help ensure that investors and other stakeholders are asking the right questions in assessment of investable opportunities around molecular recycling companies and technologies.

In the first two sections of this report, Closed Loop Partners provides a macroanalysis summary of molecular recycling in the context of the circular economy and plastics production. This summary is based on our review of nine distinct recycling technology processes. In this Invest section, we focus on the microeconomic view of molecular recycling, with the objective of supporting investors, partners, and other stakeholder groups who may be evaluating molecular recycling technologies at the company or deal level. We have created evaluation checklists that frame the factors that support the evaluation of a technology and company in combination with standard commercial due diligence.

Disclaimer: This section and report is not intended to replace a standard technical economic analysis or due diligence process, nor do they serve as investment recommendations or promises. This information is intended to be a framework for how investors might evaluate molecular recycling technologies. The considerations presented here represent but a piece of what would be required for full financial due diligence in support of an investment.

Four Factors for Evaluating Molecular Recycling Technologies

1. **Technology Viability:** Assess how efficiently a given technology does or can operate, its feedstock requirements and limitations, output quality, and local and international end markets.

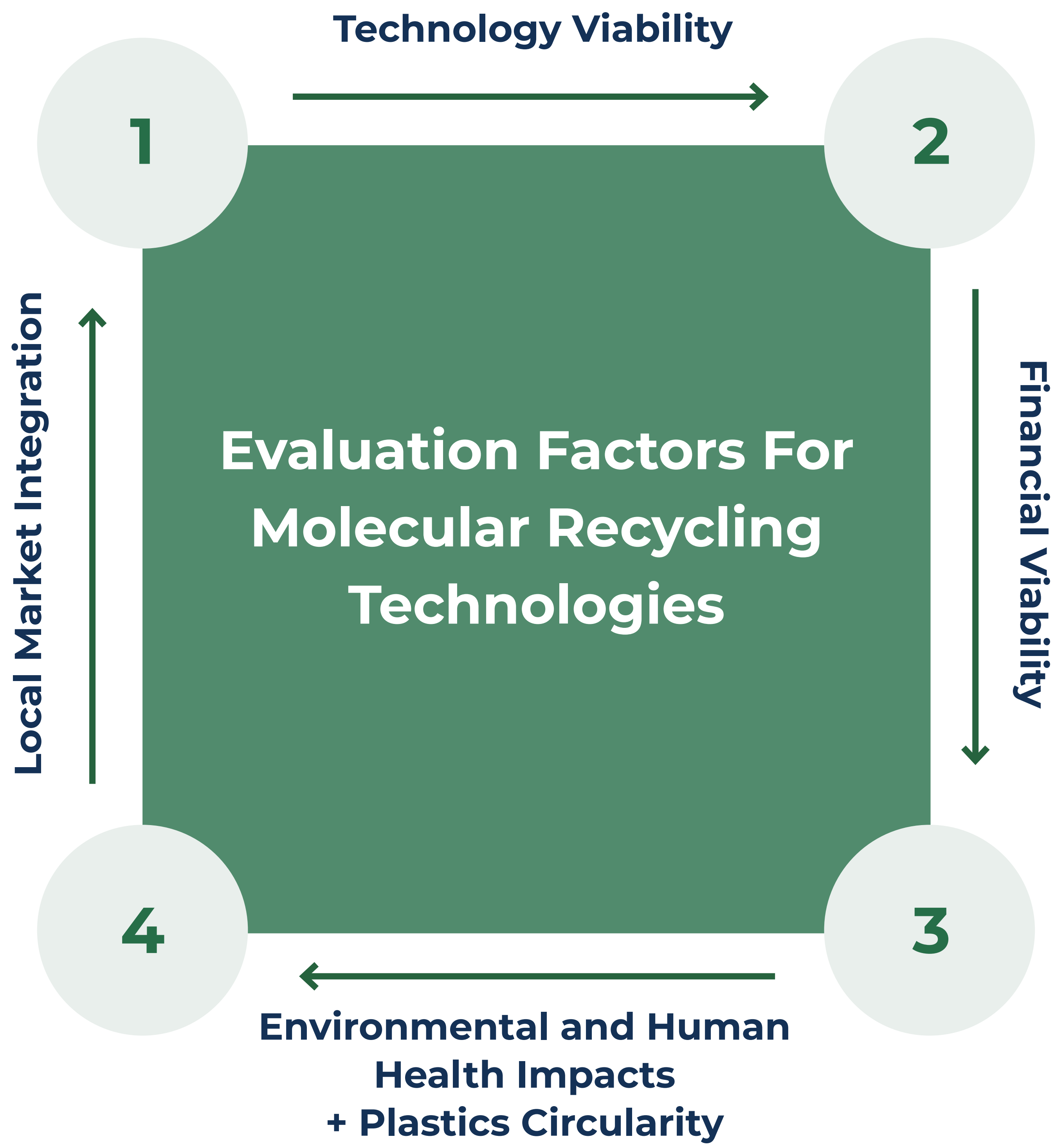
2. **Financial Viability:** Assess cost and revenue drivers, and how these determine the overall payback period, growth, and profit stability for a given technology.

3. **Environmental and Human Health Impacts & Contributions to Circularity:** Assess the extent to which an individual technology can reduce energy use, fresh water consumption, greenhouse gas emissions, and human health risks *relative* to virgin plastic production.

4. **Integration into Local Markets**: Assess the impacts of a particular technology in the local operating environment and market context, including waste and recycling infrastructure, feedstock availability, and policy.

Note: Closed Loop Partners has used these four factors to evaluate purification, depolymerization, and conversion technologies, based on the study of nine molecular recycling technology companies evaluated for this study. We recognize that the technologies in this sector are highly nuanced, and the sector is evolving quickly. Closed Loop Partners developed these resources with the goal of supplementing existing due diligence practices with sector-specific information to ensure stakeholders are asking the right questions and driving towards scaling molecular recycling technologies with the greatest potential for net-positive impacts outcomes

FIGURE 27. FOUR FACTORS FOR EVALUATING MOLECULAR RECYCLING TECHNOLOGIES



1 Technology Viability Checklist

Technology Classification and Efficiency

CLASSIFICATION

- [ ] Which technology category and technology type is it? See Figure 6 for descriptions and definitions of molecular recycling technology types.
- [ ] Is the technology licensed or does the company own and operate facilities?
- [ ] What inputs and outputs is the company currently using and producing? See Figure 7 for general overview of inputs and outputs across industry.
- [ ] What is the designed capacity of a commercial scale facility? See Appendix 2.8 for average and range of facility sizes from our study.
- [ ] Does the technology process have built-in optionality to meet market needs in the future (i.e. change processing temperature to transition from producing fuels to intermediaries, or monomers)?

MARKET READINESS

- [ ] What is the technology readiness level? What stage of maturity is the company? See Figure 2 for an example and definitions.
- [ ] How many demonstration or commercial facilities are operational? For how many hours does each operate? What are the company's assumptions around market readiness? If pre-commercial, what is the evidence that the technology can effectively scale (e.g. processing post-consumer feedstock)?

- [ ] Has the company tested processing and producing feedstock and outputs it does not process now? If yes, why do they not process that feedstock or produce those outputs anymore?

EFFICIENCY

- [ ] Is the process continuous or batch?
- [ ] What is the weight or quantity of material received at the facility? What proportion of that is processed by the technology? Learn to calculate the process reject rate in Appendix 4.3. Understand the fate of reject material. What proportion goes to disposal, what proportion has demonstrated end markets?
- [ ] What is the total volume of output product(s) produced per year? If more than one output product is produced, what proportion of total output does each product make up and how and when do those proportions change? (i.e., changes in feedstock composition, process temperature). See Appendix 4.3 to learn how to calculate processing efficiency.
- [ ] How has facility throughput changed over time as the technology has matured?
- [ ] How does this technology perform on key metrics compared to others in the market (i.e.,material processing efficiency, feedstock reject rates, uptime, contamination tolerance). See *Figures 31, 35, and 39* for environmental impact metrics across the three molecular recycling technology categories. See Appendix 4.4 for technology processing efficiency data from our study.
- [ ] Pursue third party feedback from their feedstock suppliers; Engineering, Procurement and Construction partners; pilot off-take partners; current/past customers; and/or environmental impact life cycle evaluators.
- [ ] What percentage of the total inputs processed by this company can mechanical recycling process? Will optimizing a mechanical recycling system achieve the desired output quality with less overall CapEx, OpEx, and overall environmental impact?

Feedstock (Process Inputs)

- [ ] What are the feedstock specifications that the company requires of its feedstock suppliers? How much of the company's feedstock is post-consumer? Post-industrial? Post-commercial?
- [ ] What is considered non-target material (i.e., contamination) for the process? What is the tolerance for contamination levels across all non-target materials (e.g. 20% natural fibers in textile feedstock, 1% PVC)? Are there any other upstream constraints and requirements of the process?
- [ ] What stakeholders in the waste management value chain can supply feedstock consistently? Will feedstock suppliers need to retrofit or adapt their systems to meet specifications? See Appendix 6.0 for summary of feedstock needs across technology processes.
- [ ] Does their technology process scale match the plastic waste/feedstock typically available in the market? See Figure 22 for information on how technology processes match to plastic packaging waste volumes in the U.S. and Canada.
- [ ] How secure is the feedstock over the investment period? Does the company have an established and strong network of suppliers for feedstock where they operate? If there are contracts with feedstock suppliers, what are the length and terms of those contracts? See Feedstock Supply Case Study.
- [ ] Will the company be competing with mechanical recycling markets for feedstock? See Figure 25 for our understanding of optimized recycling solutions for different types of plastics.
- [ ] To what extent is their total feedstock at risk from a policy perspective (i.e., plastic bag or single-use plastic bans, consumer brand switch to other materials)?

Offtake (Process Outputs)

- [ ] Does the output replace a commodity in the market (e.g. naphtha), and if so, which one? If yes, how is demand trending for that output, and what supply chains can that output link to? If no, what do offtakers need to do in order to use the product (i.e., post-processing)?
- [ ] Are there product standards for the outputs the company is producing? If yes, how consistently does that company achieve that output standard? If no, do they have a realistic roadmap for reaching accepted standards?
- [ ] What evidence exists to test and confirm the process efficiency, material outputs, and safety of outputs and/or facility? Where does evidence exist to support claims (e.g., proxy technologies, lab tests, pilots, independent studies)?
- [ ] Does the company have defined, demonstrated sales channels for the outputs? Who are their current buyers? Do they have long-term contracts with them, or other agreements (e.g. Memorandum of Understanding, Letter of Intent)?

2 Financial Viability Checklist

Developmental Costs

- [ ] What are the technology development costs to date? Does that align with the stage of maturity and technology type? Read the financial analysis summaries that follow this checklist for information on development costs by technology category.

Capital Expenses

- [ ] How much capital is required to set up a facility? If commercial, how have the capital costs changed with new projects? Read the financial analysis summaries that follow this checklist for information on CapEx costs by technology category.

Cost Drivers

FEEDSTOCK COSTS AND CONTRACTS

- [ ] What are the biggest assumptions currently made about the quality and quantity of feedstock? How sensitive is the business model to increases in feedstock costs due to competition or changes in quality?
- [ ] Does the company have long-term contracts with feedstock suppliers? To what extent do long-term contracts protect the business model from short-term fluctuations in feedstock or output costs (i.e locking in a floor price for products)?

OPERATING EXPENSES

- [ ] What are the different components of operational costs? How does the company foresee their operating costs changing over the next 5 years (i.e. labor, transportation costs)? Are those assumptions based on significant market changes or their incremental efficiencies?
- [ ] What insurance is required for their type of operations? How do those costs compare to industry averages and why (i.e. operating in fire-prone area, etc.)?

Revenue Drivers

SOURCES OF REVENUE

- [ ] What are types and amounts of projected revenue (i.e. tipping fees, product sales, technology licensing)?
- [ ] Does the company receive any national, state, or local subsidy for municipal solid waste? To what extent is that subsidy at risk (i.e. expires in 2030)?

PRICING

- [ ] To what extent does the company compete against virgin petrochemical commodity prices (i.e. virgin naphtha, virgin PET)? To what extent does the company compete against a recycled commodity price (i.e. food-grade rPET)?
- [ ] To what extent is the business model dependent on near-term and/or long-term price premiums or subsidies? To what extent are these assumptions defensible, given existing contracts, or broader demand and pricing trends?

- [ ] How does the return on investment (ROI) fluctuate with changes in output pricing?
- [ ] How do changes in feedstock or output pricing influence the expected payback period on the project?

ADDRESSABLE MARKETS

- [ ] What are the specific markets for the outputs produced and share of that market linked to the company's specific project location/s, buyers, and/or strategic partnerships? If pre-revenue, does the defined market opportunity reflect appropriate assumptions (e.g., consideration of short-term versus long-term premium pricing)? What are the market demand projections for the outputs produced?
- [ ] What has the company done to anticipate the evolution of their end markets?

EXIT STRATEGIES

- [ ] Is the company planning for optimal exit timing and early identification of potential exit issues (reason for exit or refinancing, IP, feedstock, off-take contract renewal, planning and permits, market conditions and future growth expectations, regulatory framework)?
- [ ] Does the management understand the exit processes to maximize value for existing assets and future pipeline?

3 Impact Measurement: Environmental, Human Health, and Circularity Checklist

Life Cycle Assessments

- [ ] Has the company conducted a life cycle assessment (LCA) of its process or a specific facility? Is the company transparent regarding its methods and assumptions used to feed into its LCA (e.g., disclosed energy source, accurate feedstock processed, avoided impact credits)? See *Life Cycle Assessment Deep Dive* and download Closed Loop Partners LCA Methodology in **Appendix 4.1**.

- [ ] Does that assessment disclose demonstrated savings or efficiency over virgin production of its outputs for the three fundamental environmental key performance indicators: energy use, water (bluewater)use, and carbon emissions (CO_2e)?

Management and Standard Operating Procedure

WORKER AND COMMUNITY SAFETY

- [ ] What operational health and safety risks are there in each facility?

- [ ] Who will be operating the process/facility (i.e., company staff vs. third party staff)? What level of operational expertise is needed to safely operate? Does the company provide adequate training to ensure the safety of its workers and surrounding communities?

- [ ] Has the technology company defined potential hazards relevant to sources of feedstocks? Have they created the processes to minimize processing of feedstock known to cause human health impacts (e.g. polystyrene)?

WORKER AND COMMUNITY SAFETY

- [ ] Is the operator in compliance with local and national environmental and public health and safety regulations (i.e. OSHA, Clean Water Act, Clean Air Act, regional and national EPA regulatory requirements)?

OPERATIONAL RISK MANAGEMENT

- [ ] Has the company analyzed and defined potential hazards relevant to process byproducts or residuals?
- [ ] What is the downstream fate of residuals or byproducts? Are they considered to be hazardous or chemicals of concern? Do they need to be treated in a dedicated facility, or can they go straight to landfill?
- [ ] Are there standard operating practices put in place to appropriately deal with technology process' residues?
  - For conversion technologies, are responsible pollution control practices in place?
  - For purification and depolymerization processes, are their products tested to ensure residual solvent does not remain in the final output product? Chem21 has created a solvent selection guide to support safe and sustainable solvent choices.
- [ ] What pollution controls are mandated, and to what extent are they enforced? How often?

Facility Siting

- [ ] Where is this molecular recycling project proposed to be sited or where is it located? Is the proposed or existing facility listed in an region/area impacted by climate change?

- [ ] Does the company have plans to engage local community groups to support local hiring, transparent communication, and local manufacturing and resource development?
- [ ] What is the makeup of the local grid in the region (or state, county)? What is/would be the underlying energy source for the facility?
- [ ] Does the proposed/existing site have sufficient access to hazardous waste or wastewater treatment infrastructure, when relevant?
- [ ] Is the proposed or existing facility listed in an environmental justice "hot spot" as identified by tools such as the Environmental Protection Agency's EJSCREEN? How does the company plan to engage historically disenfranchised communities to ensure their health, safety, and trust?

Business Model Support of Circularity

- [ ] What percentage of the company's feedstock processes single-use plastics or plastics that can be processed by mechanical recycling (e.g. PET bottles)? Will this molecular recycling project be more efficient (i.e. $ per metric ton of output) than building out a system to support mechanical collection to process the same feedstock, if that is possible?
- [ ] What hard-to-recycle plastics can this technology address that today have limited end-of-life solutions? (i.e. textiles, bulky rigid plastics, wind turbines, etc.)
- [ ] Where does the technology sit in the plastics value chain (See Figure 9). How many process steps are required to convert the process outputs back into a plastic or product? What are the losses in the system?
    - See material processing yields across purification, depolymerization, and conversion technologies in Appendix 4.4.
    - See the human health impact analysis summary which starts on page 76 of this report and the human health impact benefits and risks Table 5, Table 6, and Table 7 which summarize the benefits and risks of depolymerization, and conversion processes.

4 Local Market Integration Checklist

Infrastructure

- [ ] How robust is the local collections and sortation infrastructure to support the feedstock requirements and supply needs of the company? See Closed Loop Partners' Plastic Waste and Infrastructure map.

Policy Barriers

- [ ] Are there local policies that would impact the operations or viability of a particular technology (e.g. plastic bans that positively/negatively impact feedstock supply)? To what extent does local policy present barriers to setting up molecular recycling facilities or technologies in a market?

Market Incentives or Mandates

- [ ] To what extent are specific technologies identified in existing and proposed local regulations? Are technologies likely to benefit from incentives or credits, or subject to fees?
- [ ] Are there any national, state, or local incentives or mandates that drive the company toward more circular markets (e.g. tax credit for producing recycled plastic content (PCR), California's recycled content minimum mandate)?

Local Benefit

- [ ] Does the project help reduce waste sent to landfill while delivering a net environmental benefit that is demonstrated by one or more environmental impact factors when compared to virgin plastics production? (e.g. carbon emission reductions compared to virgin)
- [ ] How many local jobs are created by this operation? and skill development in the local economy?

SUMMARY

Viability & Impact of Purification Technology

The following information is based on our study of two purification technologies (i.e. n=2), which each have demonstration plants in the United States and Germany. Both companies are at technology readiness level (TRL) 7, which means that the technology is still being piloted and has yet to be commercialized. With a sample size of two in this technology category, our analysis yields helpful data points but should not be taken as a comprehensive assessment of the entire sector.

Technological Viability

Purification technologies are the only group of technologies in the molecular recycling landscape that work at the physical level, meaning they do not break polymeric bonds. These technologies process single-stream or mixed plastic waste and work by separating and extracting unwanted chemicals (e.g. color, additives) from the target polymer by:

1) deploying a “strong solvent” that purifies or breaks a polymer bond;

2) deploying a “weak solvent” to precipitate the target polymer for extraction; and

3) purifying the extracted polymer through a series of steps.

Figure 28 shows sample purification process steps. The type of solvents used may be considered proprietary or part of a company’s intellectual property since these choices can considerably alter operational costs and performance. Table 3 shows common solvents for target polymers used in the dissolution and reprecipitation process (i.e. purification) which have been adapted from the Zhao et al 2018 study[83]. Best performing technologies have low solvent replacement rates; lower replacement costs reduce operational costs and lower the environmental and human health impacts associated with those solvents. Three-fourths of solvent-based technologies that Closed Loop Partners evaluated, which include purification technologies, had annual solvent replacement rates below 3%.

FIGURE 28. TYPICAL PURIFICATION PROCESS FLOW DIAGRAM

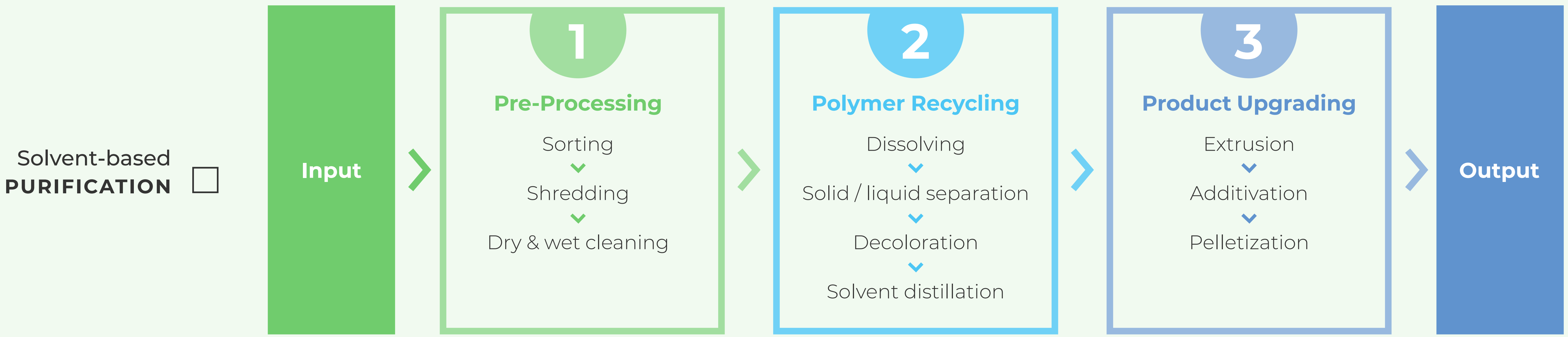


TABLE 3: COMMONLY USED SOLVENTS FOR PURIFICATION TECHNOLOGIES

Polymer	Strong Solvents	Weak Solvents (“anti-solvent” or precipitator”)
Polystyrene (PS)	Dichloromethane (DCM), toluene	Methanol
	Toluene	n-hexane
	Xylene	Methanol
	Limonene, terpene, cymene, phellandrene	-
	Cyclic monoterpenes	Water
	L-limonene	-
	Benzene, toluene	Water
	Methyl ethyl ketone (MEK)	Methanol, n-hexane
Polycarbonate (PC)	DCM	Methanol
Polyethylene (PE)	Xylene	Propanol
	Xylene	n-hexane, methanol
Polypropylene (PP)	Xylene	Acetone, n-hexane
	Tetrachloroethylene	Acetone
Polyester Terephthalate (PET)	Benzylalcohol	Methanol
	N-methyl-2-pyrolidone (NMP)	-
	NMP	n-octane + n-hexane
Acrylonitrile Butadiene Styrene (ABS)	Acetone	Methanol
	Acetone	-
Polyvinyl Chloride (PVC)	85/15 xylene + cyclohexane	-
	Cyclohexane	n-hexane
	DCM, toluene	Methanol

Market Readiness

The purification companies in our study were at the early commercial stage, running demonstration facilities at full capacity, and in the process of expanding their commercial footprint. The purification technology category is generally less commercialized than conversion technologies (average TRL 8) but more mature than the average depolymerization technologies (TRL 7) which process novel feedstock like textiles and multilayer packaging. The two purification companies in our study were processing both post-consumer and post-industrial feedstock, and producing like-new recycled plastic content including recycled polypropylene (rPP) and recycled polyethylene (rPE) destined for consumer packaged goods, cosmetic and industrial application.

Efficiency

Because the polymer bonds are not broken through purification, purification technologies have higher material yields, on average, than depolymerization and conversion technologies. Purification technologies in our study had an average of 90% material processing yields with a minimum of 85% material processing efficiency.

Financial Viability

Capital Expenses (CapEx) and Development Costs

Across molecular recycling technologies in our study, purification technologies have the highest capital expenses (CapEx) per metric ton of output produced. The average purification technology facility had a 34,000 metric ton capacity and CapEx of $150 million USD (i.e. $2,300 to $4,500 USD per metric ton of output).

It is important to note that development costs are not static and may follow some efficiency function as technologies scale. We provide these development cost figures as proxies for investors. Purification technologies in our study have the second highest development costs per metric ton of output ($900 - $1,300/metric ton output) which aligns to their position as the second-most commercialized technology category in the molecular recycling sector. Purification is approximately 3x more expensive per metric ton processed than depolymerization, which is in earlier stages of technology development; purification's technology development costs per metric ton are, on average, $450 USD lower than conversion technologies, which are most commercialized and have spent more time and R&D capital improving technology processes.

See how the CapEx and Facility Capacity compare across the three technology categories in **Appendix 2.8**

Cost Drivers, Revenue, and Margins

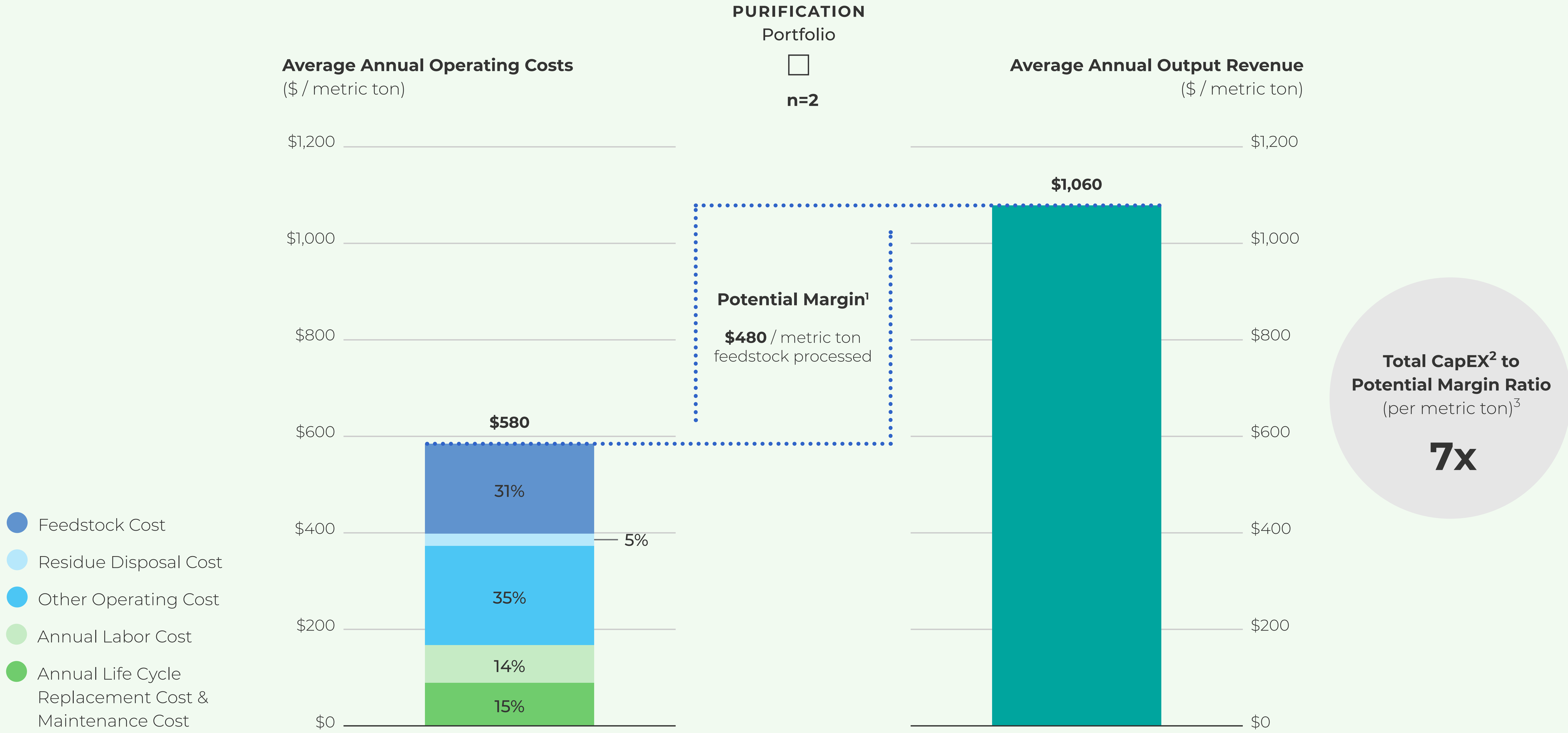
The biggest portion of operating costs for purification technologies was the "Other" category, which included utility costs for water, electricity, gas and any other additives required for the recycling process (Figure 29). Payment for feedstocks, on average, also makes up a large proportion of operational costs (31%), though we also observed that some purification processes receive tipping fees (i.e., revenue) if they can accept mixed and contaminated material for processing on site. Purification technologies in this study demonstrate the potential to be profitable operations despite higher CapEx and development costs because of their ability to produce high-value application outputs like rPP for food grade applications and rPE film. This ability to tap into the recycled plastic markets, where demand far outstrips supply, allows for the purification technologies to operate at higher margins compared to other technology categories (Figure 29).

Return on Investment

Despite the additional operating costs relative to other technology groups, purification technologies seem to still be able to achieve positive returns and reasonable payback periods. At 2021 market prices, the average purification technology in our study generated positive IRRs of between 14 to 23%.

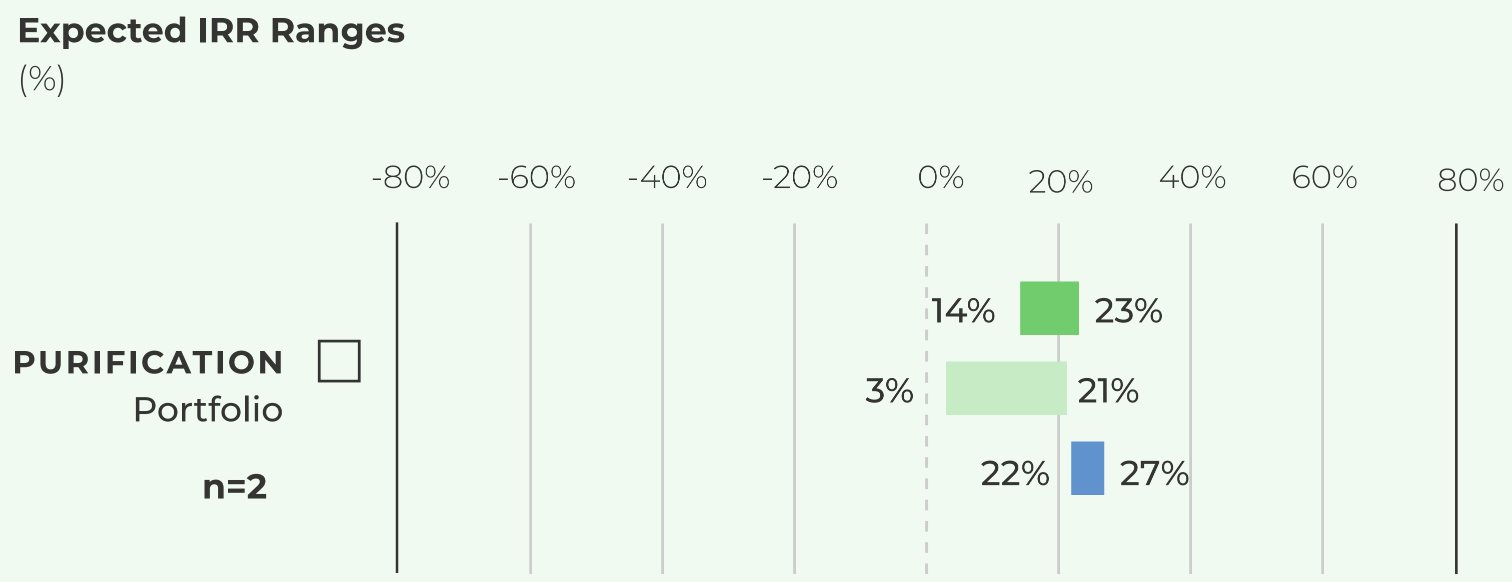
Not all financial scenarios modeled with the purification technologies yielded both positive Net Present Value (NPV) and positive internal rates of return over the lifetime of the project, which was reported by each technology company and ranged between 20-30 years. Across the three molecular recycling categories, our study implies that purification is the most sensitive to discount rate changes as high capital intensity means large upfront costs need to be offset by operating revenues. At 10% discount rates, both purification technologies achieve positive returns over the lifetime of the plant (e.g. 20 years) and a payback period between 7 and 12 years, which is typical of other waste management infrastructure projects like waste-to-energy and large scale waste material sortation facilities. Figure 30 summarizes how purification rates of return and payback period change across four different output price scenarios.

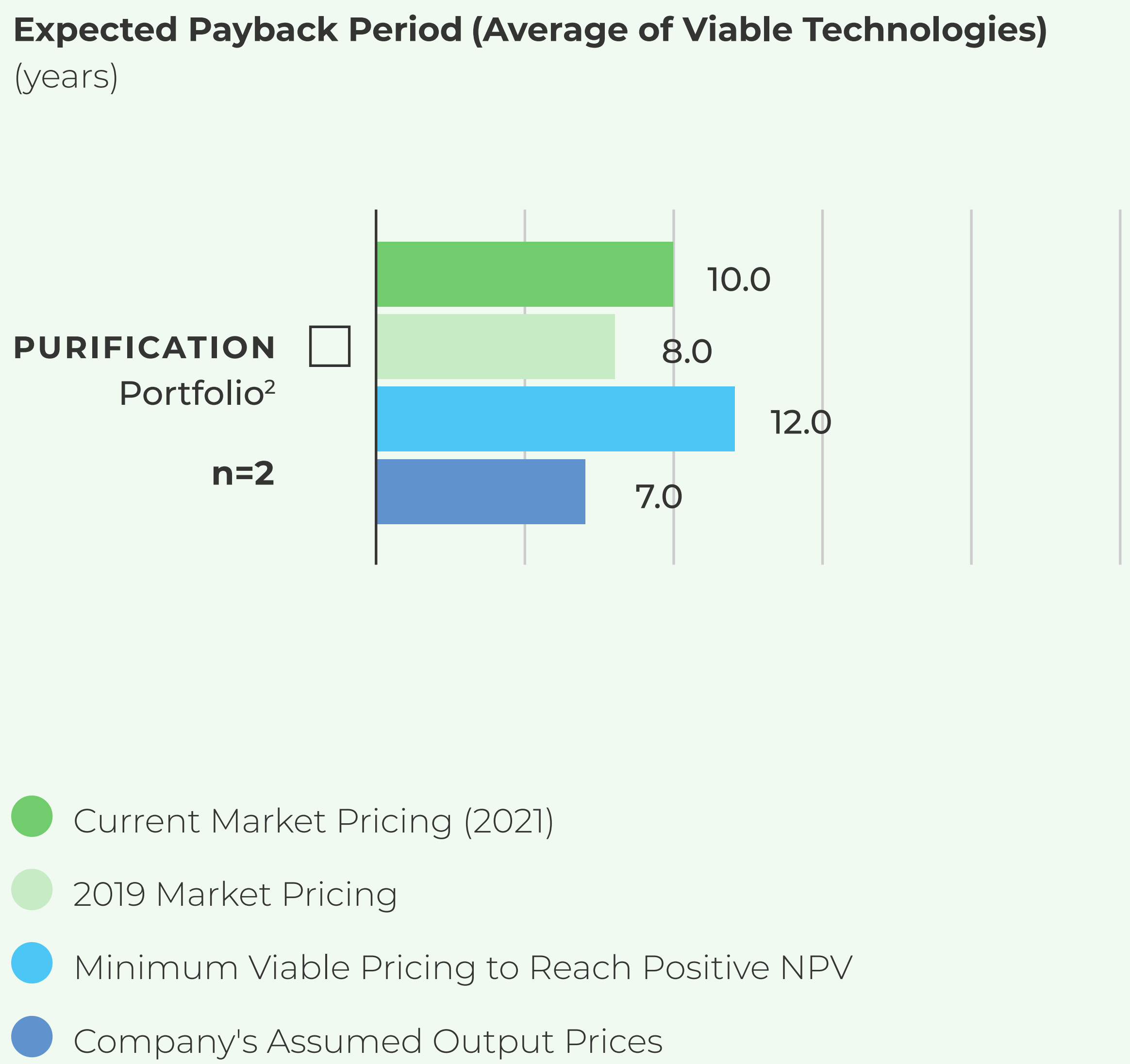
FIGURE 29. AVERAGE OPEX, POTENTIAL MARGIN, AND REVENUE PER METRIC TON PROCESSED IN PURIFICATION PORTFOLIO



Notes:
Graphic represents technology cost model based on average of multiple technologies included in the study which may include both high and low performing examples. Averages have been derived from individual financial modeling of each technology based on input data from technology providers and market valuation of output products. The base case depicted utilizes 2021 market prices for revenue generation and supplier provided assumptions on operating costs. All costs/revenues are normalized per ton of input to the facility to provide a comparable unit of measure.
1. Potential margin = Average operating revenue per metric ton - average operating costs per metric ton
2. CapEx per metric ton expressed as a multiple of margin. In the study, the average capital cost (CapEx)per metric ton processed in the purification portfolio is $3,400
3. Ratio of total CapEx per metric ton of the facility to the potential margin per ton of feedstock processed.

FIGURE 30. EXPECTED INTERNAL RATE OF RETURN (IRR) AND EXPECTED PAYBACK PERIODS OF PURIFICATION ACROSS MULTIPLE OUTPUT PRICE SCENARIOS





Notes:

Current Market Pricing: IRR results when primary product output prices are set to 2021 market prices. Appendix 2.1 details these market prices.

2019 Market Prices: IRR results when primary product output prices are set to 2019 market pricing.

Company's Assumed Output Prices: IRR results when prices for primary product outputs set to technology company's expectations.

Impact Assessment: Environmental, Human Health, and Contributions to Circularity

Life Cycle Impact Analysis Results

Across the board, purification technologies utilize fewer fossil fuels compared to the virgin system by avoiding the need for the extraction of raw materials for plastic production (i.e., MJ/kg of primary product). Figure 31 summarizes the average energy, greenhouse gas emissions, and bluewater results of purification processes of the companies within our study and compares that to the avoided virgin system. Appendix 4.1 details the boundaries of our analysis and our LCA methodology. Across the purification portfolio, we observed energy savings of 47% to 70% compared to the equivalent virgin supply chain. From an emissions reduction perspective, purification demonstrated the highest potential, with the biggest reductions in greenhouse gas emissions achieved by any technology category compared to the avoided virgin system, but the technology category also had one example that performed marginally worse than virgin. Purification processes in our study each reduced bluewater consumption by 15% to 70% compared to the virgin system (Table 1).

Because purification processes produce finished polymers, the process-level impact also represents the system-level impact. It also means that of all the technology processes in the molecular recycling sector, purification technologies are the only ones that contribute to plastics-to-plastics outcomes every time, driving circularity and maintaining resources at their highest value.

Human Health Impacts

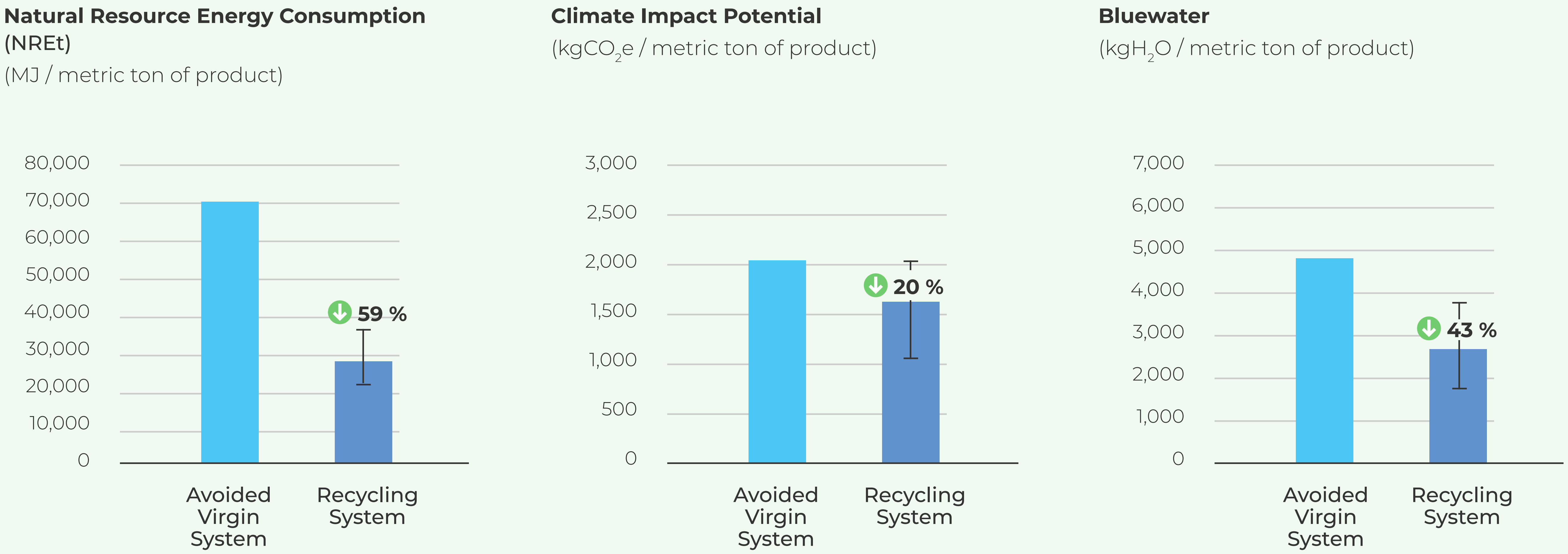
Purification technologies' differentiating characteristic (i.e. keeping the polymer intact) is also its biggest advantage from a human health perspective among the molecular recycling technologies. If the purification process itself is safe to human health, this category of technology has the highest potential to mitigate human health impacts compared to virgin plastic production and other molecular recycling technologies since these technologies eliminate the need for virgin chemicals or depolymerizing steps to remake recycled plastic. See the summary of our human health impact analysis.

However, since these technologies are processing plastic waste as feedstock, technology providers, investors, and regulators evaluating purification technologies must understand the different hazard profiles of the feedstock, including the potentially hazardous contaminants that may be a part of the commonly sourced feedstock, the hazard of the reaction solvents (i.e. strong and weak solvents), and the effectiveness of the process in removing them from the polymers. Investors should inquire about the total solvent used per ton of product produced and have an understanding of the fate of spent solvents and their contaminants. Table 4 summarizes the results of our qualitative assessment of solvent-based purification technologies and lists their benefits and risks.

FIGURE 31. AVERAGE PURIFICATION ENVIRONMENTAL IMPACT RESULTS (PROCESS ONLY)

PURIFICATION
Portfolio
☐
n=2

Outputs in Portfolio
PP & PE pellets



Notes:
For each molecular recycling technology, the environmental impact was calculated in comparison to an equivalent virgin system producing the same product. The referenced virgin system for each molecular recycling technology is specific to that technology category and is considered to reflect real-world operating considerations. Therefore, comparisons between technologies are not made on the basis of a single reference input or output (e.g. considering a single feedstock or a single product basket for all technologies).

For each technology category, environmental results were aggregated using a portfolio approach. To enable comparison between technology categories, each portfolio is set to produce 1000 kg of product, with each technology contributing an equal share of products (e.g. for a technology portfolio of 2 technologies, each technology contributes 500 kg of product; for 3 technologies, each technology contributes 333.3 kg; etc.). Advanced process outputs were considered as a basket of products to account for technologies producing multiple products. The environmental impact for each of these technologies (or virgin reference systems) were summed to produce the aggregate portfolio impact.

Bluewater - The total of all water evaporated during production or physically incorporated into the product. Thus, blue water does not include non-contaminated water returned to the environment (i.e. from steam heating or cooling water systems) or contaminated water that is returned to the environment via a wastewater treatment process (i.e. from a manufacturing plant or municipal wastewater treatment plant).

Natural Resource Energy, Total (NREt) - The sum of Natural Resource Energy Combusted (NREc) and Natural Resource Energy for Materials (NREm). It is the total energy value of fossil fuels extracted from the ground. This is similar to the non-renewable fossil component of the Cumulative Energy Demand (CED) metric that is widely used in life cycle assessment.

TABLE 4. BENEFITS AND RISKS OF PURIFICATION TECHNOLOGIES

Benefits	Risks	Best Performing Technologies
• Produce high quality polymers (i.e. food grade, cosmetic grade) by sequestering contaminants by separating and extracting unwanted chemicals (i.e. color, performance additives) from target polymer or monomers • Ensure circular outcome since these processes do not break the polymer bonds and produce recycled polymer • Highest potential for reducing human health risks associated with the virgin production of plastics • May be used as first stage for recycling waste plastics with known problematic substances (e.g. chlorinated pigments, brominated flame retardants) • May be used as a last stage to upgrade outputs (i.e. purifying recycled PTA from depolymerization process)	• **Air Emissions:** Closed Loop Partners study found a mix of worse-than-virgin and better-than -virgin carbon emission results when modeled on the US average grid (Table 1) • **Water Emissions:** Unclear whether solvent losses can be found in the wastewater effluent[1] • **Occupational exposures** from fugitive emissions of process should be measured [1] • **Residuals in Outputs:** Unclear how effectively solvent processes remove chemical additives from polymers; residual additives in the PCR must be low enough to not prohibit the sale of recycled polymers to compounders, especially for high-quality applications like food-grade[1]	• Have low solvent replacement rate[2]; Closed Loop Partners observed <3% among the technologies we evaluated • Have at least one stage in their process where non-target contaminants are filtered out (e.g. dyes, non-target polymers, inorganics); company discloses how these are treated and disposed of • Test their outputs to ensure their process removes solvents or additives from the final products in line with health standards (i.e REACH) • Disclose the facility-specific environmental impact analysis results (i.e. LCA) with full assumptions stated. • Evaluate and understand their facility's fugitive emissions[1]

Notes:
1. Out of scope in Closed Loop Partners 2021 study
2. Solvent replacement rate is the amount of solvent that is needed to be replaced in a given year due to losses in the system or damage to the solvent. The lower the solvent replacement rate, the lower the operational costs and environmental footprint other company. replaced in a ould have to have over the course of their reproductive years in order to replace themselves

SUMMARY

Viability & Impact of Depolymerization Technology

The following information is based on our study of four depolymerization technologies which operate in the North American, Asian, and European markets. Environmental and financial data have been normalized and modeled to fit the U.S. and Canadian market realities. Within the depolymerization cohort, we have two companies who are at early commercial stages (TRL 8) and two companies who are at pilot stages (TRL 5). The average technology readiness level (TRL) in the depolymerization group is TRL 7. With a sample size of four in this technology category (i.e. n=4), our analysis yields helpful data points but should not be taken as a comprehensive assessment of the entire sector.

Technological Viability

Depolymerization technologies are often categorized as "chemical recycling" technologies. These processes chemically alter the structure of the polymer by breaking bonds in the main polymer chain. These technologies process single-stream plastic waste, enabling the extraction of non-target polymers, dyes, and other additives. Unlike conversion processes, depolymerization processes are tailored to produce specific chemical outputs, as opposed to mixtures of chemicals. Process approaches to depolymerization depend on the target polymer.

1A) Solvent-based processes are used to recycle condensation polymers (such as PET and PA) to monomers or oligomers using a chemical reaction called hydrolysis. The waste plastic is heated with a chemical solvent (i.e., water, acid, or ethylene glycol) to initiate the reaction.

1B) Biological-based processes usually work on similar principles to solvent-based processes, but use a biological agent (i.e., enzyme) to catalyze the reaction.

2) Thermal processes use heat and catalysts to break the bonds in the polymer chain. These processes are usually used to recycle polymers such as polystyrene and acrylics (i.e. poly(methyl methacrylate)).[j]

Figure 32 shows sample depolymerization process steps. For the "wet" processes outlined in 1A and 1B, there are a variety of different reaction agents and chemical routes that may be used to depolymerize a given polymer. Different routes have different reaction requirements (e.g. solvent, temperature) which can considerably alter operational costs, performance, and reaction time. Many best performing technologies feature closed loop systems which recycle solvents and have low replacement rates, which may lower operation costs and environmental and human health impacts associated with them.

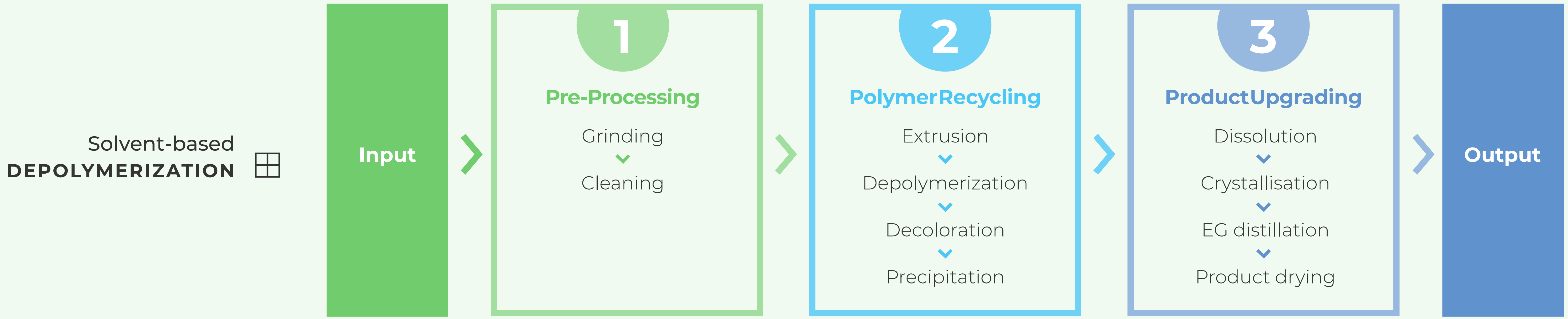
Efficiency

The initial products of depolymerization technologies, specifically ones that target PET, will have high mass yields (>90 %, or over 100 % in some cases) as mass from water is incorporated into the products (monomers) in the depolymerization process. Investors should note that if PET-linked monomer products are repolymerized, the overall mass yield will drop as the surplus water is removed from the polymer products during the repolymerization reaction. At the system level (i.e. feedstock to plastic pellet), our study of the four depolymerization technology processes showed that this group has a similar average mass yield (87 %) to purification technologies.

Thermal depolymerization technologies do not process PET, focusing instead on plastic feedstock which includes polypropylene (PP), polystyrene (PS), or PMMA resins. These thermal processes also generally have high yields above >90%. Polystyrene feedstock depolymerizes the quickest since breaking the PS bonds to form styrene monomer is more straightforward than depolymerizing PET or PA; depolymerizing PS also produces the most side reactions.

j. These thermal processes may be similar in nature to conversion processes but produce specific chemical products.

FIGURE 32. TYPICAL DEPOLYMERIZATION PROCESS FLOW DIAGRAM



Financial Viability

Capital Expenses (CapEx) and Development Costs

The capital costs (CapEx) of decomposition technologies are the lowest average of all technology categories at $1,585 per metric ton when removing a single outlier technology; the average range excluding this outlier is $1,300 to $1,900 per metric ton. One company skewed the average slightly higher to $2,300; however, it is unclear if this is a factor of the datasets provided by these companies or possibility for high variability in CapEx in this technology category.

Depolymerization technologies have the smallest capacity of all three technology categories in our study, at 29,500 metric tons througput capacity per year. These markers, combined with the lower technology development costs of (i.e., $400 - $600 per metric ton managed) may reflect their group's position at an early stage of technology development compared to, for example, conversion technologies, where technology has already undergone several development cycles with associated development costs incurred.

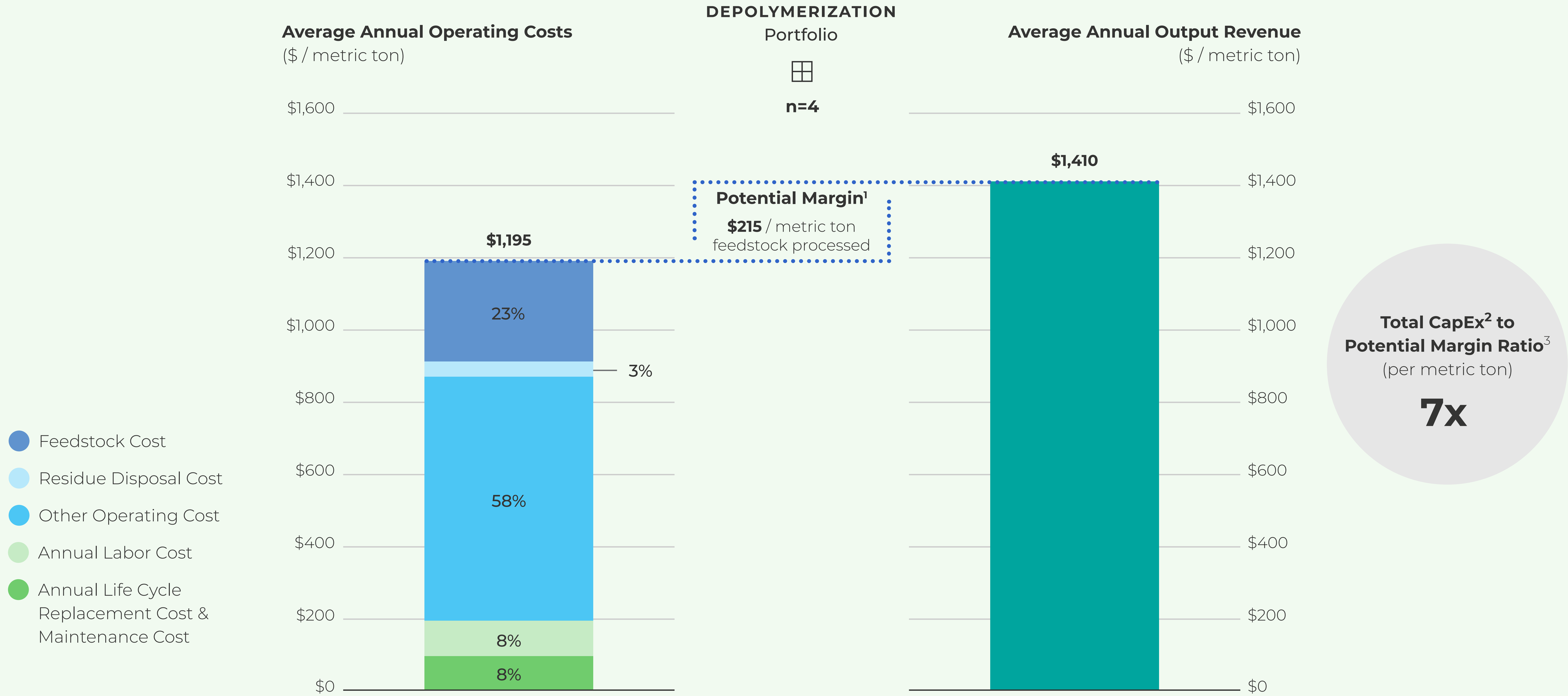
See how the CapEx and Facility Capacity compare across the three technology categories in **Appendix 2.8**

Cost Drivers, Revenue, and Margins

Operating costs for depolymerization technologies are driven predominantly by "other operating costs" (58%), which within our modeling includes utility costs for water, electricity, gas and any other additives required for the recycling process. Feedstock costs also make up a large proportion of the category's total operational costs (23%), but despite paying the most, on average, for feedstock, there are strong examples of viable business models.

Because this study's depolymerization portfolio is made of a mix of early commercial and pilot technologies, this category demonstrated the widest range of operational costs, margins, and returns on investment. Figure 33 shows the average across these metrics, but it is important to note that within this group, there are some technologies that are not yet benefitting from the lower cost of accessing and processing more difficult-to-recycle feedstock (e.g., colored, non-bottle rigids and textiles) while others have developed very efficient processes, which could be profitable even at discounted market pricing.

FIGURE 33. AVERAGE OPEX, POTENTIAL MARGIN, AND REVENUE PER METRIC TON PROCESSED IN DEPOLYMERIZATION PORTFOLIO



Notes:
Graphic represents technology cost model based on average of multiple technologies included in the study which may include both high and low performing examples. Averages have been derived from individual financial modeling of each technology based on input data from technology providers and market valuation of output products. The base case depicted utilizes 2021 market prices for revenue generation and supplier provided assumptions on operating costs. All costs and revenues are normalized per metric ton of input to the facility to provide a comparable unit of measure.
1. Potential margin = Average operating revenue per metric ton - average operating costs per metric ton
2. In the study, the average capital cost (CapEx)per metric ton processed in the decomposition portfolio is $1,585
3. Ratio of total CapEx per metric ton of the facility to the potential margin per metric tonof feedstock processed

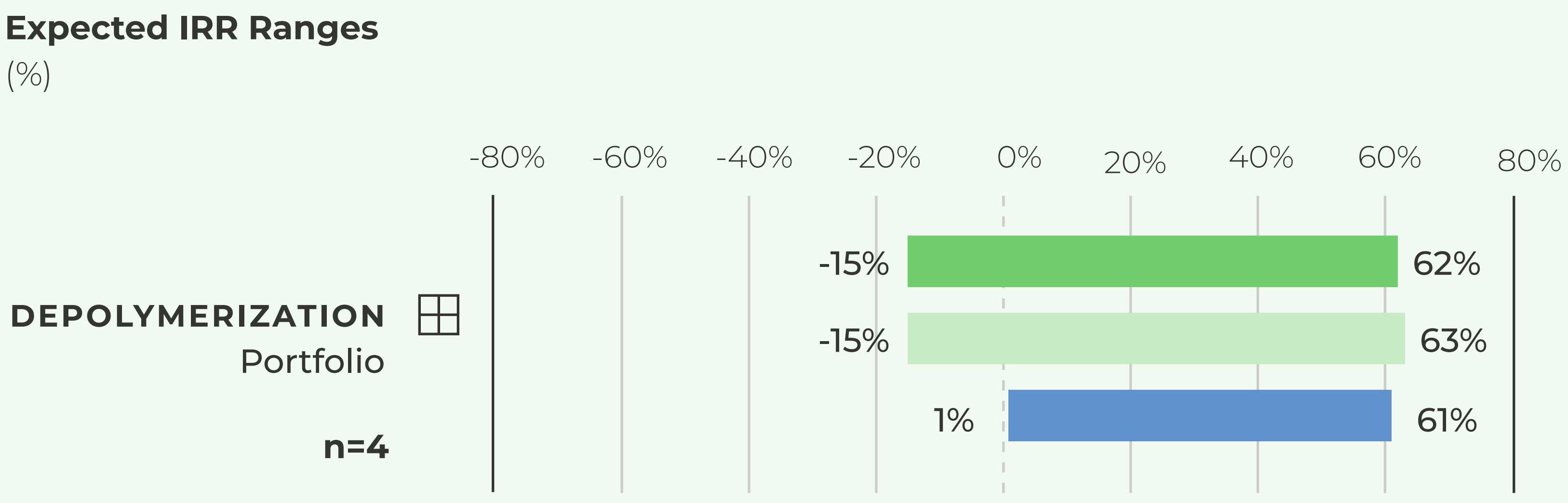
Return on Investment

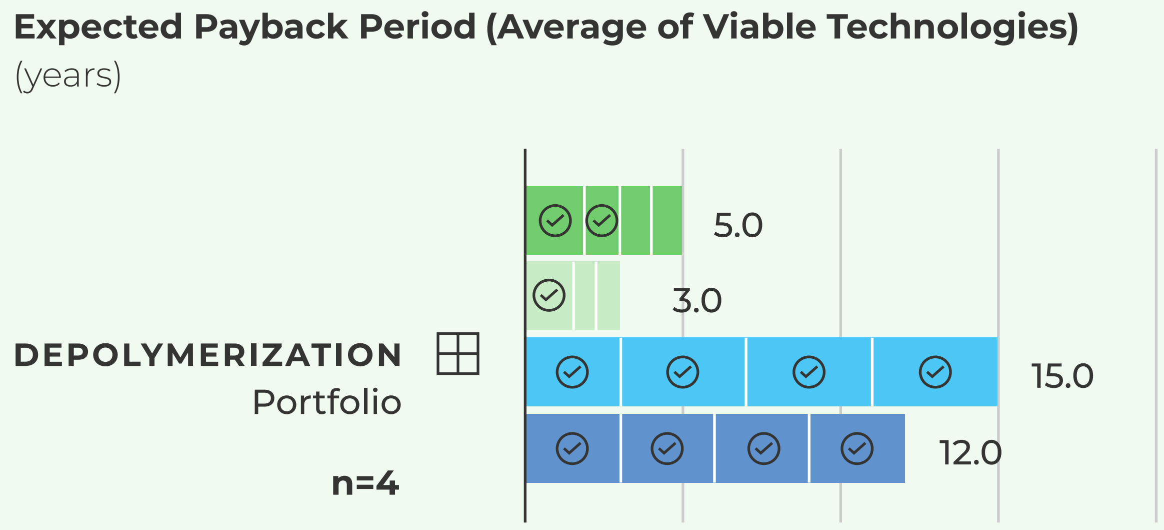
Monomer prices between 2019 and 2021 have remained relatively stable as compared to recycled resin prices and even petrochemical prices. This difference illustrates the disconnect between demand and price for oil and the cost of monomers and may also reflect that fluctuations in oil prices are absorbed by different parts of the value chain. It also reflects that, to date, the market for monomers is less well-defined, with less of the differentiation between virgin and recycled content that is seen in the market for resins.

Decomposition technologies in general have the potential to produce high-value application outputs from the recycling process that are more circular in nature. These include food grade polymers and speciality waxes that generate both high revenues and high margins per unit of throughput. Using 2021 commodity prices, we observed that two of the four depolymerization technologies we studied operate viable business models with an internal rate of returns (IRR) above 20%. For those two technologies, the payback period ranges from 2 to 8 years at a 10% discount rate and between 3 to 12 years at a 20% discount rate. This demonstrates that depolymerization technologies can be investable even for venture capital type investment with the expectations of paid returns within reasonable investment cycles. It also demonstrates significant potential for financial returns with these same two technologies offering net present values (NPVs) of up to $200 million USD over the lifetime of the plant at a discount rate of 10% and $88 million USD at 20% discount rate. Figure 34 summarizes the results of our IRR and expected payback period analysis of depolymerization technologies. Appendix 2.7 summarizes our methodology.

On the other hand, our analysis also showed two examples of technologies that are not financially viable (i.e. low or negative IRR) based on current market prices and/or information provided by the company. This may be the result of current operating costs being too high, or expected pricing premiums for outputs being higher than anticipated and as compared to benchmarks from recycled polymers. When we used output prices assumed by the companies, all companies had positive IRRs, but the extent to which this pricing is realistic is yet to be seen, as recycled content markets are still developing. In these cases, achieving positive IRR may be more realistic through developing operational efficiencies and more efficient technology.

FIGURE 34. EXPECTED INTERNAL RATE OF RETURN (IRR) AND EXPECTED PAYBACK PERIODS OF DEPOLYMERIZATION ACROSS MULTIPLE OUTPUT PRICE SCENARIOS





Notes:
Current Market Pricing: IRR results when primary product output prices are set to 2021 market prices. Appendix 2.1 details these market prices.

2019 Market Pricing: IRR results when primary product output prices are set to 2019 market pricing.

Company's Assumed Output Prices: IRR results when prices for primary product outputs set to technology company's expectations.

- Current Market Pricing (2021)
- 2019 Market Pricing
- Minimum Viable Pricing to reach Positive NPV
- Company's Assumed Output Prices
- Number of companies in technology portfolio that meet a minimum of 10% return on investment (IRR) under this scenario

Impact Assessment: Environmental, Human Health, and Contributions to Circularity

Life Cycle Assessment Results

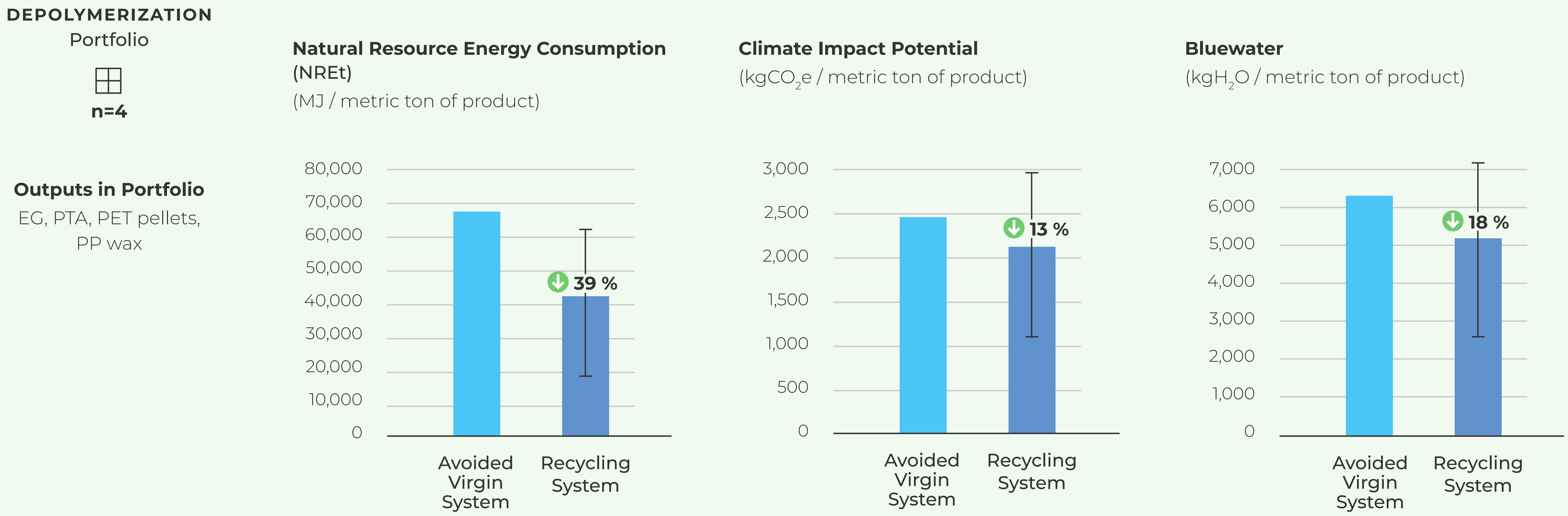
Depolymerization had the widest range of performance across environmental key metrics; the reason for this is multifactorial and includes the stage of development across the depolymerization companies in our study and the differences of their outputs (i.e. some companies sell finished resin while others produce monomers or oligomers and do not repolymerize on-site). Three of the four depolymerization technologies in this study utilize fewer fossil fuels compared to the virgin system by avoiding the extraction of raw materials for plastic production (i.e., MJ/kg of primary product); savings ranged between 17 to 72% energy per metric ton of primary product compared to the virgin system. Of the four technologies evaluated, there was one technology that showed worse than virgin greenhouse gas emissions results. The other three processes show reductions between 0% to 36% compared to the equivalent virgin system. Figure 33 summarizes the average energy, greenhouse gas emissions, and bluewater results of depolymerization processes only and compares that to the equivalent virgin system.

Human Health Impact Results

Like all recycling technologies, depolymerization can reduce the human health risks associated with producing virgin plastic since it avoids the impacts associated with fracking and manufacturing processes for producing monomers or oligomers. Depolymerization technologies may also have a potential advantage over purification since the processes have a higher tolerance for contaminants contained in feedstocks such as polyester-based textiles that can contain mixed fibers, dyes, pigments, dye auxiliaries, fabric backings and finish coatings. Depolymerization can remove all of these contaminants and sequester them for further purification into products, ideally, or in preparation for safe disposal.

Understanding types of solvents used, total amounts used and fate of spent solvents for both depolymerization and purification processes is an important aspect of environmental due diligence. Our study was not set up to draw conclusions between different types of depolymerization technologies (i.e. ones that use solvents and ones that use enzymes). Future studies should examine whether biological depolymerization processes, if proven to scale efficiently and profitably, could have fewer environmental and human health impacts than more traditional solvent-based depolymerization methods.

FIGURE 35. AVERAGE DEPOLYMERIZATION ENVIRONMENTAL IMPACT RESULTS



Notes:
For each molecular recycling technology, the environmental impact was calculated in comparison to an equivalent virgin system producing the same product. The referenced virgin system for each molecular recycling technology is specific to that technology category and is considered to reflect real-world operating considerations. Therefore, comparisons between technologies are not made on the basis of a single reference input or output (e.g. considering a single feedstock or a single product basket for all technologies).

For each technology category, environmental results were aggregated using a portfolio approach. To enable comparison between technology categories, each portfolio is set to produce 1000 kg of product, with each technology contributing an equal share of products (e.g. for a technology portfolio of 2 technologies, each technology contributes 500 kg of product; for 3 technologies, each technology contributes 333.3 kg; etc.). Advanced process outputs were considered as a basket of products to account for technologies producing multiple products. The environmental impact for each of these technologies (or virgin reference systems) were summed to produce the aggregate portfolio impact.

Bluewater - The total of all water evaporated during production or physically incorporated into the product. Thus, blue water does not include non-contaminated water returned to the environment (i.e. from steam heating or cooling water systems) or contaminated water that is returned to the environment via a wastewater treatment process (i.e. from a manufacturing plant or municipal wastewater treatment plant).

Natural Resource Energy, Total (NREt) - The sum of Natural Resource Energy Combusted (NREc) and Natural Resource Energy for Materials (NREm). It is the total energy value of fossil fuels extracted from the ground. This is similar to the non-renewable fossil component of the Cumulative Energy Demand (CED) metric that is widely used in life cycle assessment.

TABLE 5. BENEFITS AND CONSIDERATIONS OF DEPOLYMERIZATION MOLECULAR RECYCLING TECHNOLOGIES

Benefits	Considerations	Best-in class technology companies will
• Can create high-quality monomers by sequestering contaminants by separating and extracting unwanted chemicals from target polymer or monomers • Technology’s capacity to depolymerize to the monomer-level and then repolymerize indicates maximum flexibility to alter or manipulate polymer properties to achieve exact same quality as original polymer • Primary target feedstocks for depolymerization technologies (i.e., PET, PA, PMMA) do not compete with pyrolysis or purification feedstocks	• Can have a significant water footprint • Solvent-based depolymerization processes can require several steps, increasing the overall process time and the overall energy required for the process. Additionally, facilities may produce necessary reaction agents (e.g. reagents or enzymes) on-site which can contribute to the overall energy requirement and environmental impact[1].	• Understand the hazard profiles of reaction solvents, especially when used at elevated temperatures, and whether these are recycled in the system • Have at least one stage in their process where non-target contaminants are filtered out (e.g. dyes, non-target polymers, inorganics); company discloses how these are treated and disposed of • Have low solvent replacement rate[2]; Closed Loop Partners observed <3% among the technologies we evaluated

Notes:
1. Out of Scope in Closed Loop Partners 2021 study
2. Solvent replacement rate is the amount of solvent that is needed to be replaced in a given year due to losses in the system or damage to the solvent. The lower the solvent replacement rate, the lower the operational costs and environmental footprint other company. replaced in a ould have to have over the course of their reproductive years in order to replace themselves

SUMMARY

Viability & Impact of Conversion Technology

The following information is based on our study of three conversion technologies which operate in the North American, Asia, and European markets. Environmental and financial data have been normalized and modeled to fit the U.S. and Canadian market realities. Within the conversion cohort, there are two growth stage companies and one early commercial company. The average TRL of this group is above 8. With a sample size of three in this technology category (i.e. n=3), our analysis yields helpful data points but should not be taken as a comprehensive assessment of the entire sector.

Technological Viability

Conversion technologies is a term that describes two of the most common thermal-chemical processes in molecular recycling: pyrolysis and gasification. Both types of technologies differentiate themselves from other technology categories by being able to process mixed plastics or mixed solid waste with plastics to produce hydrocarbon products like naphtha and methanol*. Conversion technologies typically follow three steps:

1) metals and other non-target materials are removed from feedstock;

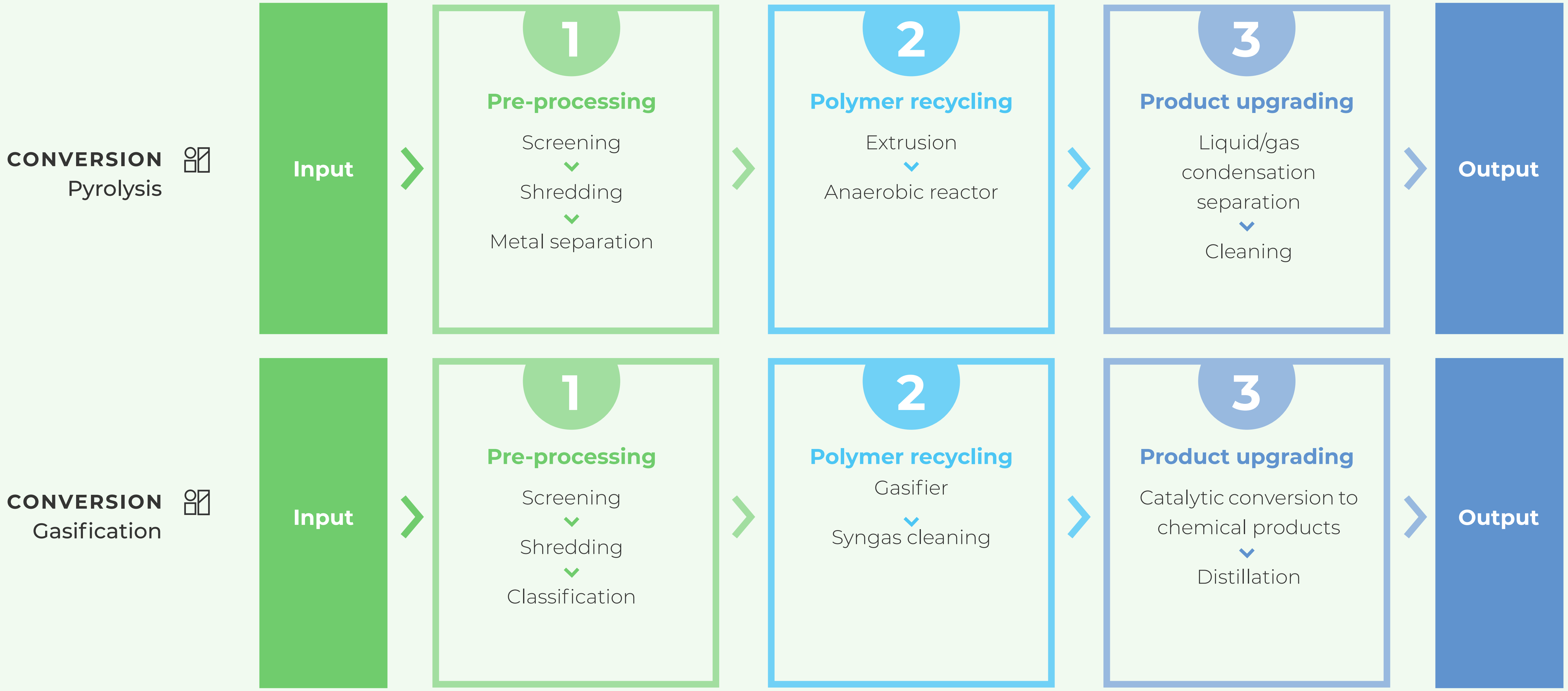
2) plastic waste goes into the reactor where temperatures reach between 600-1300 degrees Celsius;

3) residual gasses are collected or condensed; sometimes the product is distilled for quality purposes.

Most conversion processes have been designed to consume some of the embedded energy in the feedstock (i.e. 5 to 15% of the total energy in the feedstock), which limits the energy pulled from the grid to run its process. Best performing conversion technologies, from a circularity standpoint, will consume as little of the plastic waste for energy as possible, yielding larger volumes of sellable product(s).

While conversion technologies are less selective about feedstock compared to purification and depolymerization technologies, the processes are not optimized to process any and all waste. Rather, conversion processes should have a feedstock screening process or specific feedstock specifications for its suppliers to limit problematic materials in the feedstock which impact the quality of the products or damage equipment (e.g. feedstock with chlorine, like PVC, corrodes metal materials, erodes machinery and is a contaminant in outputs). For processes that take in biomass with plastic waste in feedstock, there is likely a target ratio between biomass and inert material (e.g. plastics) that maximizes output yields. Figure 36 shows two sample conversion processes.

FIGURE 36. TYPICAL PROCESS FLOW DIAGRAM OF TWO MOST-COMMON CONVERSION TECHNOLOGIES (PYROLYSIS AND GASIFICATION)



Financial Viability

Capital Expenses (CapEx) and Development Costs

The capital expenditures (CapEx) for the three conversion technologies in our study range from $2,000 to $2,700 per metric ton of throughput capacity. Compared to purification and depolymerization, the conversion technologies in our study have the widest range of facility sizes, ranging from 25,000 metric tons per year to 270,000 metric tons per year. The average processing capacity was 140,000 metric tons per year and average CapEx per facility was $280 million.

Conversion technologies had development costs between $2,200 to $2,500 per metric ton of output, which is the highest development costs of all technology groups. This is logical, since this is the most mature technology category in the market, and companies have already injected research and development (R&D) capital during their demonstration and pilot development phases. It also follows that conversion technologies have the highest CapEx on an absolute basis, since the facilities can have throughputs up to 10x of some purification and depolymerization facilities.

See how the CapEx and Facility Capacity compare across the three technology categories in **Appendix 2.8**

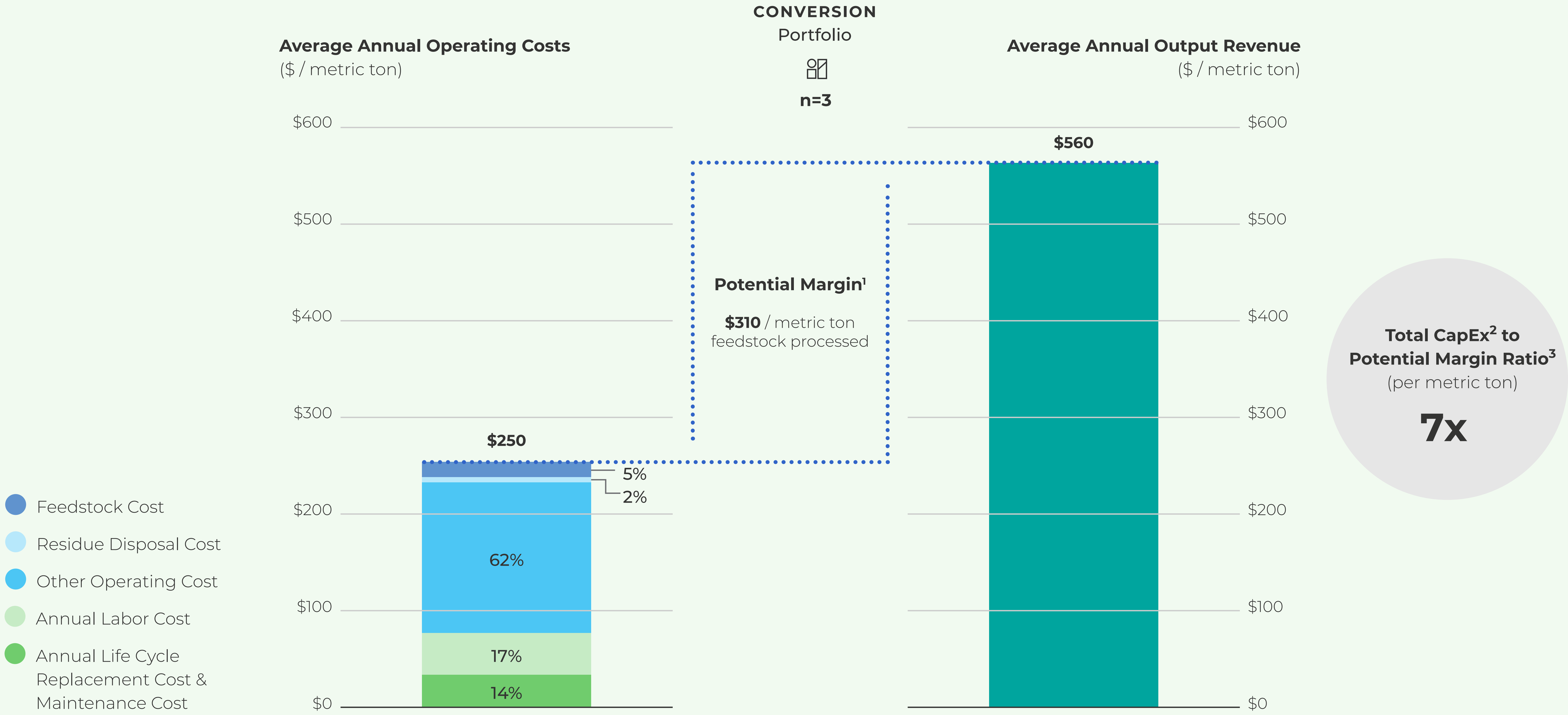
Cost Drivers, Revenue, and Margins

The largest category of operating costs for a conversion technology is "Other," which within our model includes utility costs for water, electricity, gas and any other additives required for the recycling process. In general, conversion technologies are the only category that are paid to take feedstock, although in our study, only one of the conversion companies was receiving payments, which amounted to a small revenue stream of less than 10% of total revenue. For the other two companies, which were paying for feedstock, feedstock costs were just 2% of total operating costs (Figure 37).

On an absolute basis, the conversion technologies in our study are producing outputs (e.g. methanol, naphtha, diesels and waxes) that have lower price points compared to other technology categories' outputs (e.g. monomers, recycled plastic resin). Conversion technologies can integrate at the start of a plastics supply chain (Figure 9), and command a premium price above virgin naphtha or methanol produced from its recycling processes. This premium reflects the value-added service of retaining natural resources in the economy for at least one more cycle as well as the demand and supply imbalance in the market[k]. To date, most conversion technologies have prioritized end markets with the strongest economic case: tax credits and subsidies are most abundant in renewable, low carbon fuels for road and aviation, especially in European markets, which as we have noted, we do not consider a circular application. It's important to note that our financial modeling does not include any tax credit or market subsidy since these do not exist at scale across the U.S. and Canada. Market incentives will play a big role in how the outputs of conversion technologies will be applied in the long run, and policymakers are encouraged to align incentives to climate goals to ensure that these technologies are leveraged to support circularity in supply chains.

k. None of the technology companies in this study provided information on the average premiums they are receiving today. Therefore, financial analysis compares the outputs from conversion technologies to an average 2021 US commodity price.

FIGURE 37. AVERAGE OPEX, POTENTIAL MARGIN, AND REVENUE PER METRIC TON PROCESSED IN CONVERSION PORTFOLIO



Notes:
Graphic represents technology cost model based on average of multiple technologies included in the study which may include both high and low performing examples. Averages have been derived from individual financial modeling of each technology based on input data from technology providers and market valuation of output products. The base case depicted utilizes 2021 market prices for revenue generation and supplier provided assumptions on operating costs. All costs and revenues are normalized per metric ton of input to the facility to provide a comparable unit of measure.

1. Potential margin = Average operating revenue per metric ton - average operating costs per metric ton
2. In the study, the average capital cost (CapEx)per metric ton processed in the conversion portfolio is $2,400
3. Ratio of total capex per metric metric ton of the facility to the potential margin per metric ton of feedstock processed

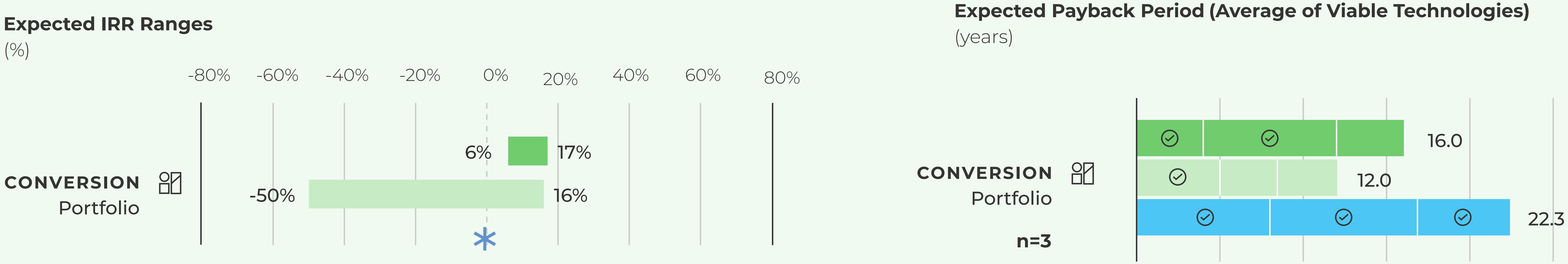
Return on Investment

Even though conversion technologies often receive a tipping fee to process materials, the majority of the category's revenue, based on our study of three companies, is generated through the sale of their outputs. In the waste supply chain this lower reliance on gate fees could support their business models by allowing them to be more competitive in accessing feedstock than conventional technologies. Their operating models currently rely on low operating costs and high volume and lower priced outputs relative to other technology groupings. In order to recover the capital investment in large scale infrastructure, operating margins per ton appear higher than other technology groups (on a % basis), although revenue generation per metric ton of output is still considerably lower. The business models for the the conversion technologies analyzed are most closely aligned with the petrochemical sector and fluctuations in commodity prices. This is demonstrated in the difference between modeling scenarios with 2019 and 2021 (base case) prices. In the timeframe between our study's analysis of 2019 and 2021 prices, there was a significant recovery for methanol, naphtha and diesel prices which many of the outputs from conversion technologies are benchmarked against. This recovery in market prices provides conversion technologies with a more positive outlook, with all technologies offering positive IRRs.

Based on the modeling undertaken, conversion technologies can be viable without market incentives, but the payback periods for these projects reflect the timeline and return profile of real asset and infrastructure investors. At 10% discount rates, two of the three technologies reviewed presented returns on investment within payback periods of between 11 and 21 years, a long-term investment. At 20% discount rates, none of the conversion companies presented positive returns (NPV). Based on this analysis it appears that producing lower value application outputs without market based incentives, the ability to differentiate products from petrochemical commodities, or long-offtake contracts that support a conversion project's business model appears to be risky. This is likely why conversion technologies are concentrating in markets with incentive schemes that support drop-in fuels[I] or low carbon fuels (such as sustainable aviation fuels) as conversion technology outputs can be used to produce these products from waste-derived fuels.

I. Drop in fuels is a term used to describe a range of comparable fuel products (which may be produced more sustainably) that can be interchanged or blended with conventional fossil fuel products in use without need for significant change to existing technology/infrastructure

FIGURE 36. EXPECTED INTERNAL RATE OF RETURN (IRR) AND EXPECTED PAYBACK PERIODS OF CONVERSION TECHNOLOGIES ACROSS MULTIPLE OUTPUT PRICE SCENARIOS



* Output prices not given by conversion suppliers

Notes:
Current Market Pricing: IRR results when primary product output prices are set to 2021 market prices.

2019 Market Prices: IRR results when primary product output prices are set to 2019 market pricing.

Company's Assumed Output Prices: IRR results when prices for primary product outputs set to technology company's expectations

- Current Market Pricing (2021)
- Market Pricing (2019)
- Minimum Viable Pricing to reach Positive NPV
- Number of companies in technology portfolio that meet a minimum of 10% return on investment (IRR) under this scenario

Impact Measurement of Conversion: Environmental and Human Health Impacts and Contribution to Circularity

Results of our Life Cycle Analysis

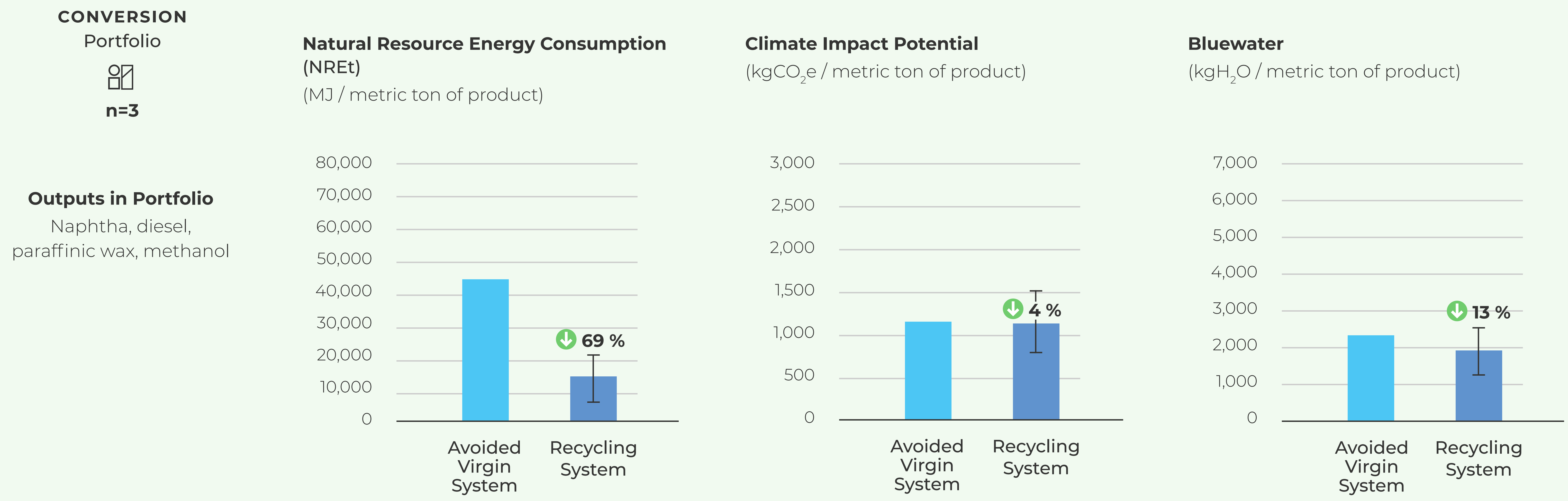
On average, conversion demonstrated the largest energy savings per metric ton of output produced compared to other molecular recycling technology categories. Individual conversion processes show energy savings between 25 and 88% compared to the virgin system. There was a small (4%) reduction of generated greenhouse gases ($CO2_e$) when comparing the conversion average to the virgin equivalent supply chains. But, $CO2_e$ generated is 34% less through conversion compared to the avoided virgin supply chain, if we only look at best performing technologies. This illustrates a key finding of our study: that careful due diligence is critical to ensure that the strongest performing technologies scale across all three molecular recycling categories. Conversion processes had the widest range of water use, from 16% more water usage compared to the virgin system to a 50% savings reduction compared to the virgin system.

Human Health Impacts

Molecular recycling technologies mitigate human health risks in different ways depending on the type of process they use. A summary of the benefits and risks of thermal conversion technologies is presented in Table 8. At the highest levels, investors and technology operators must understand how potentially problematic feedstock inputs (e.g. nitrogen, chlorine, bromine, and metals from non-target materials) are minimized or diluted, or how these are scrubbed from emissions. It was out of scope for our study to collect residue samples from the companies in evaluation. Part of our human health impact analysis, which is summarized in Appendix 5.0, was a literature review.

The literature cites various potential direct emissions from pyrolysis and gasification of waste plastics. It is important to understand the variables that affect the types and amounts of toxic substances that are generated and that may be may be released to air, water or as solid residues: feedstock composition (homopolymers and additives), use of catalysts in the reactor, temperature ranges and the amount of oxygen present during processing. Hazardous emissions to air and solid waste (mostly as char or fly ash) seem to be the most frequently cited.[84, 85, 86, 87, 88]

FIGURE 37. SUMMARY OF ENVIRONMENTAL IMPACT RESULTS ACROSS CONVERSION CATEGORY (TECHNOLOGY PROCESS ONLY)



Notes:
For each molecular recycling technology, the environmental impact was calculated in comparison to an equivalent virgin system producing the same product. The referenced virgin system for each molecular recycling technology is specific to that technology category and is considered to reflect real-world operating considerations. Therefore, comparisons between technologies are not made on the basis of a single reference input or output (e.g. considering a single feedstock or a single product basket for all technologies).

1. For each technology category, environmental results were aggregated using a portfolio approach. To enable comparison between technology categories, each portfolio is set to produce 1000 kg of product, with each technology contributing an equal share of products (e.g. for a technology portfolio of 2 technologies, each technology contributes 500 kg of product; for 3 technologies, each technology contributes 333.3 kg; etc.). Advanced process outputs were considered as a basket of products to account for technologies producing multiple products. The environmental impact for each of these technologies (or virgin reference systems) were summed to produce the aggregate portfolio impact.
2. **Bluewater** - The total of all water evaporated during production or physically incorporated into the product. Thus, blue water does not include non-contaminated water returned to the environment (i.e. from steam heating or cooling water systems) or contaminated water that is returned to the environment via a wastewater treatment process (i.e. from a manufacturing plant or municipal wastewater treatment plant).
3. **Natural Resource Energy, Total (NREt)** - The sum of Natural Resource Energy Combusted (NREc) and Natural Resource Energy for Materials (NREm). It is the total energy value of fossil fuels extracted from the ground. This is similar to the non-renewable fossil component of the Cumulative Energy Demand (CED) metric that is widely used in life cycle assessment.

TABLE 8. BENEFITS AND RISKS OF CONVERSION TECHNOLOGIES

Benefits	Risks	Best-in class technology companies will
• Produce high quality outputs able to compete with virgin (may require hydrotreating) • Convert heterogeneous feedstock into useful end products, like reducing overall operational cost of recycling system • Similar technologies (e.g. waste-to-energy) laid the groundwork for conversion technologies and are better equipped with pollution control technologies that can be applied to conversion technology processes	• **Air Emissions:** Problematic chemicals in plastic feedstock create problematic emissions. Inputs of concern (e.g. sulfur, phosphorus, chlorine, bromine) need to be diluted or eliminated from the feedstock as these can affect the output quality potential dioxin/ furan generation risks; especially important if operating in countries/regions with inadequate regulations or pollution control technologies • **Air Emissions:** occupational exposures from fugitive emissions • **Climate Risk:** Some technology processes in the Closed Loop Partners' study performed worse-than-virgin on climate impact metrics ($CO2_{e)}$	• Sort out problematic plastics such as PVC and styrenic plastics • Evaluate and disclose the facility fugitive emissions • Test char for metals and run a toxicity characteristic leaching procedure • Equip facility with the appropriate pollution control technologies

Conclusion

A comprehensive, circular plastics system should eliminate unnecessary plastics early in the supply chain, reuse those that are needed, and invest in downstream solutions that support the extended use of existing plastics over multiple generations, if not in perpetuity. There is no panacea to address the diversity of plastic waste in our economy, even if we optimize for reduction and reuse, but integrating molecular recycling into the toolkit of downstream solutions provides a significant and unique opportunity to recover plastics that currently have limited to no end-of-life solutions. Molecular recycling is not a monolith; rather, it is a sector marked by distinct and diverse technology processes that, under the right conditions, have the potential to positively impact people, planet and business. To achieve this potential, we need to foster the conditions that will help bring safe and circular technologies to scale:

- Investment in technology development and integration into the existing recycling system, for technologies that drive toward circular outcomes and support decarbonizing our plastics economy;
- Collaboration between incumbents and innovators across the plastics value chain, from production to recovery and recycling; and
- Policies inclusive of molecular recycling, to set a new, holistic regulatory and market environment.

In the long term, molecular recycling's full potential—in both impact and financial terms—is limited by the extent to which stakeholders across the plastics value chain collaborate and support the adoption of complementary molecular recycling technologies. Given the scale of global commitments on plastics and climate made by consumer brands and governments, molecular recycling can play an important role, alongside other plastic waste mitigation strategies, in a larger trend in which virgin plastic production is de-emphasized in the coming decades. We look forward to the continued dialogue, questions, and exploration that are critical as stakeholders across the value chain work to evaluate how molecular recycling fits into a circular plastics supply chain.Policies inclusive of molecular recycling, to set a new, holistic regulatory and market environment.

Molecular Recycling Technology Case Studies

Dive deeper into the molecular recycling companies included in our research, where we highlight insights and lesson learned from their development process.

APK AG ↗
How Meeting Safety Standards Can Help Keep Plastics in Play at Their Highest Value

Brightmark ↗
How Partnerships Between Molecular and Mechanical Recycling Can Strengthen Plastics Recycling

Carbios ↗
How Molecular Recycling Can Strengthen Plastic Flows Between Textiles and Packaging

Gr3n ↗
How Collaboration Can Catalyze the Commercialization of Molecular Recycling Technologies

GreenMantra ↗
How Molecular Recycling Is Increasing Resource Efficiency in New Sectors

JEPLAN ↗
How Vertical Integration Opens Access to Hard-to-Recycle Plastic Feedstock for Molecular Recycling Technologies

Plastic Energy ↗
How Collaborations Can Drive Closed-Loop Plastics Supply Chains

PureCycle Technologies ↗
How Strategic Investments Can Scale Emerging Technologies

Modularity ↗
Opportunities and Challenges in Scaling Distributed Molecular Recycling Network

Glossary

Finance Terms

1. **Abatement Cost**
A cost borne by firms when they are required to remove and/or reduce undesirable nuisances or negative byproducts created during production. As businesses shift towards pursuing environmental, social, and governance (ESG) means, abatement costs play a large role in discouraging companies from leniency on their environmental, greenhouse gas emissions. (Investopedia)
2. **Capital Expenses (CapEx)**
Funds used by a company to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology or equipment. (Investopedia)
3. **Economies of Scale**
Cost advantages reaped by companies when production becomes efficient. Companies can achieve economies of scale by increasing production and lowering costs. (Investopedia)
4. **Feedstock/Input Costs**
The price of the raw material. (Science Direct)
5. **Floor Price**
The lowest acceptable limit as restricted by controlling parties, usually involved in the management of corporations. (Investopedia)
6. **Internal Rate of Return (IRR)**
A metric used in financial analysis to estimate the profitability of potential investments. The internal rate of return is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis. (Investopedia)
7. **Net Benefit**
The estimated benefit of diverting plastic waste from landfill to recycling. This is the cumulative net benefit for the whole supply chain and not for any single party in the supply chain. Instead, it is the aggregated net benefit of recycling compared to landfilling. (Closed Loop Partners)
8. **Net Present Value**
The difference between the present value of cash inflows and the present value of cash outflows over a period of time. (Investopedia)
9. **Operating Expenses (OpEx)**
Expenses a business incurs through its normal business operations. Often abbreviated as OpEx, operating expenses include rent, equipment, inventory costs, marketing, payroll, insurance, step costs and funds allocated for research and development. (Investopedia)
10. **Output Prices**
Market price of the final product created by a molecular recycling process. (Closed Loop Partners)
11. **Output Revenue**
Total revenue gained from the sales of the final product created by a molecular recycling process. (Closed Loop Partners)
12. **Payback Period**
The amount of time it takes to recover the cost of an investment. (Investopedia)
13. **Price Premium**
When a current value or transactional value of an asset is above its fundamental value. (Investopedia)
14. **Profit Margin**
One of the commonly used profitability ratios to gauge the degree to which a company or a business activity makes money. It represents what percentage of sales has turned into profits. (Investopedia)
15. **Revenues**
The income generated from normal business operations, including discounts

Glossary

and deductions for returned merchandise. It is the top line or gross income figure from which costs are subtracted to determine net income. (Investopedia)

16. **Threshold Pricing**
    The price needed to achieve breakeven Net Present Value (NPV). (Investopedia)
17. **Tipping/Gate Fee**
    A fee charged for accepting recyclable materials or solid waste at a solid waste management facility (such as a transfer station, solid waste combustor, MRF, IPC or sanitary landfill). (SWANA)
18. **Venture Capital (VC)**
    A form of private equity and a type of financing that investors provide to startup companies and small businesses that are believed to have long-term growth potential. (Investopedia)

General Plastics and Recycling Terms

1. **Acrylonitrile butadiene styrene (ABS)**
   ABS plastic is a terpolymer formed by the polymerization process of styrene & acrylonitrile in the presence of polybutadiene. Usually, the composition comprises the half amount of styrene with the remaining balance divided between acrylonitrile and butadiene. (Plastic Insight)
2. **Additives**
   Additives can either be fillers, such as calcium carbonate or chemicals, added to polymers in small amounts to achieve desired characteristics in use or during processing. These may be flame retardants, UV stabilizers, plasticizers, colorants, etc.
3. **Avoided Virgin System**
   Because waste plastics are recycled, the avoided virgin system is the sum of the avoided manufacture and supply chain of the equivalent virgin products plus the avoided U.S. municipal waste management of 83% landfill and 17% incineration.
4. **Brominated Flame Retardants (BFRs)**
   Mixtures of man-made chemicals that are added to a wide variety of products, including for industrial use, to make them less flammable. They are used commonly in plastics, textiles and electrical/electronic equipment. (EFSA)
5. **Bulky Rigids (also referred to as Durable Plastics)**
   Solid waste comprised of large discarded materials, such as appliances, furniture and automobile parts. (SWANA)
6. **Char**
   The finer component of the gasifier solid residuals, composed of unreacted carbon with various amounts of siliceous ash. It can be recycled back into the gasifier to increase carbon usage and has been used as a supplemental fuel source for pulverized coal combustion. The irregularly shaped particles have a well-defined pore structure and have excellent potential as an adsorbent and precursor to activated carbon. (DOE)
7. **Compostable**
   Describes a material which: disintegrates into smaller pieces with less than 10% of the product’s mass remaining larger than 2mm after 12 weeks; biodegrades greater than 90% of the organic carbon into carbon dioxide within 180 days; leaves no residual heavy metals and fluorinated chemicals exceed regulatory limits; and, does not contain any byproducts that have harmful effects in the resulting compost. (Closed Loop Partners)
8. **Construction Debris/Waste**
   Materials resulting from the construction and demolition (C&D) of buildings and other structures, including materials such as metals, wood, gypsum, asphalt shingles, roofing, concrete, rocks, rubble, soil, paper, plastics and glass,

Glossary

but excluding putrescible wastes. (SWANA)

9. **Conversion**
   Similar to depolymerization in that the process involves breaking the molecular bonds of the plastic. A key difference is that the output products from conversion processes are often liquid or gaseous hydrocarbons similar to the products derived from petroleum refining. These raw materials may enter different supply chains, such as fuels for combustion, and/or petrochemicals (e.g., naphtha) that can be made into intermediates and monomers for new plastics. (Closed Loop Partners)
10. **Curbside Collection**
    System of waste collection from households, where each house or building has their own waste and recycling bins. (Plastic Recyclers Europe)
11. **Depolymerization**
    A process that involves breaking molecular bonds of the plastic to recover the simple molecules (“monomers”) from which the plastic is made. Monomers may be single molecules or short fragments of molecules bound together called “oligomers,” both of which are often reconstructed into plastics.
    This process, sometimes referred to as “decomposition”, can be biological, chemical, or thermal, and in some cases, a combination of two or three of these methods (Closed Loop Partners)
12. **Dioxins**
    Highly toxic chemicals that can be formed in small amounts from forest fires or volcanoes but more often are produced unintentionally from industrial activities and from incinerating waste and burning fossil fuels. (EPA)
13. **Downstream Solutions**
    Interventions related to the recovery infrastructure to recapture the value of plastics already in circulation. (Closed Loop Partners)
14. **Expanded Polystyrene (EPS)**
    A white foam plastic material produced from solid beads of polystyrene. It is primarily used for packaging, insulation, etc. (Omnexus)
15. **Elemental Carbon Products**
    During conversion, a solid product referred to as char or solid inert residue is formed. This residue may contain ash or other inserts, as well as elemental carbon. Elemental carbon is a group of carbon atoms bonded to other carbon atoms as in charcoal. (Environmental Clarity)
16. **Extrusion**
    A process of forming continuous shapes by forcing a molten plastic material through a die. (Plastics Recyclers Europe)
17. **Flash Joule Heating**
    An advanced material synthesis technique, has been used for the production of high-quality carbon materials (ACS Publications)
18. **Food Grade Plastic/Resins**
    A resin that has been certified approved safe for contact with food by the Food and Drug Administration (FDA). These plastics are known as food contact substances (FCS)
19. **Furans**
    Any of a class of organic compounds of the heterocyclic aromatic series characterized by a ring structure composed of one oxygen atom and four carbon atoms. The simplest member of the furan family is furan itself, a colorless, volatile, and somewhat toxic liquid that boils at 88.45° F. (Britannica)
20. **Gasification**
    A conversion technology type using gasification (controlled-oxygen) thermal concepts producing syngas, ash and need a liquidation technology (Fisher-Tropsch, supercritical water) to convert the gas to liquids and chemical precursors.

Glossary

21. **Healthcare Plastics**
Medical plastic itself is designed to be temperature, chemical and corrosion resistant. That way, it can handle frequent sterilization cycles and any other medical or bodily fluids it comes into contact with. Medical grade polypropylene and medical grade polycarbonate are two common polymers used in several applications, from MRI casings to surgical tools (A&C Plastics Inc.)

22. **High-density polyethylene (HDPE)**
A plastic used to make a variety of products including milk jugs and landfill liners. HDPE containers are often identified by the number "2" inside the recycling arrows stamped on the container. Natural HDPE refers to a clear or semi-translucent colored plastic which has FDA approval to be used for food and beverage (i.e milk jug). (SWANA)

23. **Hydrocarbons**
Any of a class of organic chemical compounds composed only of the elements carbon (C) and hydrogen (H). The carbon atoms join together to form the framework of the compound, and the hydrogen atoms attach to them in many different configurations. Hydrocarbons are the principal constituents of petroleum and natural gas. They serve as fuels and lubricants as well as raw materials for the production of plastics, fibers, rubbers, solvents, explosives, and industrial chemicals. (Britannica)

24. **Hydrolysis**
Hydrolysis is a chemical reaction where water is used to break a bond. For example, depolymerization of PET by reacting water with PET to form ethylene glycol and terephthalic acid is a hydrolysis reaction.

25. **Incineration and Waste to Energy**
Controlled combustion of solid waste in solid waste combustors having state-of-the-art pollution controls, and energy recovery there from. Types of Waste-to-Energy facilities include mass burn units that incinerate mixed solid waste with little or no prior separation, and RDF (Refuse Derived Fuel) units that separate combustible solid waste from noncombustible solid waste prior to combustion. (SWANA)

26. **Landfill**
Specially engineered site for disposal of solid waste on land. The waste is generally spread in thin layers which are then covered with soil. (Plastics Recyclers Europe)

27. **Low-density polyethylene (LDPE)**
Polyolefin usually used for films like shopping bags or cheese wrapping. (Plastics Recyclers Europe)

28. **Materials Recovery Facility (MRF)**
A plant that separates and prepares single-stream recycling materials to be sold to end buyers. (Rubicon)

29. **Mechanical Recycling**
An operation aiming to recover plastics waste via mechanical processes (i.e. grinding, washing, separating, drying, re-granulating and compounding), thus producing recycled content that can be converted into new plastics products, often substituting virgin plastics. For mechanical recycling, only thermoplastic materials are of interest (i.e. polymeric materials that may be re-melted and re-processed into products via techniques such as injection molding or extrusion). Thermosets cannot be reprocessed in this way, but maybe chemically recycled back to feedstock or used as a carrier (e.g. cement kilns). (Plastics Recyclers Europe)

30. **Mixed Solid Waste**
Consists of a mixture of waste from all kinds of places. It includes general household waste, office waste, waste from retail stores or other businesses, other miscellaneous, and non-hazardous waste. (Blue Earth County)

Glossary

31. **Molecular Recycling**
Refers to several different technology processes that purify or break down plastic to create virgin-quality outputs through a number of different biological, thermal and/or catalytic processes including dissolution, enzymatic depolymerization, glycolysis, pyrolysis and gasification. (Closed Loop Partners)

32. **Molecular Recycling Technology Category**
Refers to the purification, depolymerization and conversion technology classes. (Closed Loop Partners)

33. **Molecular Recycling Technology Platform**
Each technology category uses a range of platforms in which enzymes, solvents, soundwaves, or thermal heat are used to purify or break the bonds in the plastic polymer, creating several dozen technology types and distinct outputs. (Closed Loop Partners)

34. **Monoethylene glycol (MEG)**
Also known as ethylene glycol, MEG is one of the important commercially available glycol. It is produced industrially from ethylene or ethylene oxide. In this process of manufacturing MEG two co-products are obtained, diethylene glycol (DEG) and triethylene glycol (TEG). (Plastics Insights)

35. **Monomer**
A molecule that binds chemically with other molecules to form polymeric substances for example. (Plastics Recyclers Europe)

36. **Multilayer Films**
Used in the high-volume packaging industry. including food and medical packaging. The combination of several polymer layers significantly increases shelf-life by controlling the transmission rate of oxygen, carbon dioxide and moisture as well as the concentration of oxygen inside the package which is key in preserving the freshness of fresh produce for longer periods of time. (Polymer Properties Database)

37. **Naphtha**
Any of various volatile, highly flammable liquid hydrocarbon mixtures used chiefly as solvents and diluents and as raw materials for conversion to gasoline. (Britannica)

38. **Oligomers**
Oligomers are low molecular weight polymers comprising a small number of repeat units whose physical properties are significantly dependent on the length of the chain. (Science Direct)

39. **Oxygen Scavengers**
An oxygen scavenger is a material in which one or more reactive compounds can combine with oxygen to reduce or completely remove oxygen in fluids and enclosed packaging. (SAES Group)

40. **Pellet**
Standard raw material used in plastic manufacturing. Pellets are tablets or granules of uniform size, consisting of resins or mixtures of resins with compounding additives which have been prepared for moulding operations by extrusion and chopping into short segments. (Plastics Recyclers Europe)

41. **Plastic Compounders**
Machines or companies that mix additives into polymers to produce polymers with desired characteristics.

42. **Polyamide (PA)**
Polymers with amide groups, notably nylon 6 or nylon 6,6.

43. **Polyester**
A class of synthetic polymers built up from multiple chemical repeating units linked together by ester (CO-O) groups. Polyesters display a wide array of properties and practical applications. Permanent-press fabrics, disposable soft-drink bottles, compact discs, rubber tires, and enamel paints represent only a few of the products made from this group. (Britannica)

Glossary

44. **Polyethylene (PE)**
Polyolefin polymer based on ethylene. It is used in a variety of bottles, lids, trays, thin flexible films in pouches and flow wrap applications. Two variants exist: Low-density (LDPE) and high-density (HDPE). (Plastics Recyclers Europe)

45. **Polyethylene terephthalate (PET)**
Plastic commonly used to make containers such as soft drink bottles. PET containers are often identified by the number "1" inside the recycling arrows stamped on the container. (SWANA)

46. **rPET**
Term used to refer to recycled PET. (Closed Loop Partners)

47. **Polylactic acid (PLA)**
Perhaps the best-known biopolymer family. It is typically made from corn and its byproducts, but PLA can also be made from anything with high starch content like cassava, beets and sugarcane bagasse. (Closed Loop Partners)

48. **Polymer**
A chemical made of many repeating units. (Closed Loop Partners)

49. **Polymerization/Repolymerization**
Thermal and chemical depolymerization of organic waste in a furnace operated without sufficient oxygen to allow combustion. Pyrolitic products include combustible gases, oils, charcoal and mineral matter. Contrast Incinerator. (SWANA).

50. **Polyolefins**
A group of polymer thermoplastics consisting of only PP and PE. (Plastics Recyclers Europe)

51. **Polypropylene (PP)**
Polymer used in bottles, trays, and as a thin flexible film in pouches and flow wrap applications. (Plastics Recyclers Europe)

52.

53. **Polystyrene (PS)**
A hard, stiff, brilliantly transparent synthetic resin produced by the polymerization of styrene. It is widely employed in the food-service industry as rigid trays and containers, disposable eating utensils, and foamed cups, plates, and bowls. (Britannica)

54. **Polyvinyl chloride (PVC)**
Polymer most often used in construction (pipes, windows, doors), sometimes also used for non-food packaging. (Plastics Recyclers Europe)

55. **Post-Consumer Recycled Content (PCR)**
When consumers recycle their products and packaging, the resulting recycled content manufactured from those recycled materials are considered post-consumer. Legislative trends, such as minimum content requirements, might encourage companies to package their products using higher percentages of post consumer content. (Closed Loop Partners)

56. **Post-Industrial**
Polymer scrap (such as cut-off waste) that was collected from an industrial system and was never included in a consumer product.

57. **Pre-Processing**
The process of improving waste plastic recycling by increasing the target polymer content through the removal of unwanted impurities from the feed prior to entering the recycling process, typically a reactor or vessel. (Closed Loop Partners)

58. **Processing Efficiency**
Performance effectiveness divided by the processing resources invested in the task. Thus, processing efficiency declines in situations where performers maintain performance levels by investing additional resources in the task. (Science Daily)

Glossary

59. **Purification**
    A process that involves dissolving plastic in a solvent, then separating and purifying the mixture to extract additives and dyes to ultimately obtain a "purified" plastic. The purification process does not change the polymer on a molecular level. (Closed Loop Partners)
60. **Pyrolysis**
    A conversion technology type that uses no-oxygen, anaerobic thermal concepts to produce oils, chemical precursors and char products (i.e. carbon black). (Closed Loop Partners)
61. **Recycled Plastics Content (Recycled Content)**
    A portion of a product's or package's weight that is composed of materials remanufactured from a recyclable product or packaging material, including pre-consumer materials or post-consumer materials. (SWANA)
62. **Residue**
    Typically, a heavy byproduct of an oil refinery. Conversion processes often produce a solid byproduct, which could be a waste or could be used as a byproduct This is often referred to as a residue.
63. **Side reactions**
    Reactions other than intended reactions within a reactor. These typically make a range of chemicals in small quantity.
64. **Single-Stream Recycling**
    Type of recycling in which all recyclables are collected in the same container and then sorted by the deposit facilities, before entering the recycling process. (Plastics Recyclers Europe)
65. **Single Resin Feedstock**
    Typically, polymers with one repeating unit, like ethylene or propylene for polyethylene and polypropylene.
66. **Solvent-Based Platforms**
    Technologies using chemical catalysts or depolymerization agents. (Closed Loop Partners)
67. **Steam Cracker Kit**
    Steam cracking converts naphthas or light petroleum gases into light polyolefins such as ethylene and propylene and produces hydrogen as a byproduct.
68. **Syngas**
    A gas composed primarily of carbon monoxide, hydrogen, methane, carbon dioxide, and water vapor. Syngas can be used to form a variety of chemicals, and it is often produced industrially from natural gas.
69. **Thermal Platforms**
    Encompasses pyrolysis, gasification, or other conversion technology types using other thermal concepts such as microwaving etc. (Closed Loop Partners)
70. **Thermo-Chemical Processes**
    These processes encompass both pyrolysis or gasification. Under temperatures between 600-1300 degrees Celsius, residual gasses are collected or condensed; sometimes the product is distilled for quality purposes. Thermal-chemical processes typically link to petrochemical infrastructure which efficiently upgrades advanced recycling outputs through a steam cracker or chemical synthesis process. (Closed Loop Partners)
71. **Thermodynamic**
    As applied in this report, a set of physical laws that determine energy flows, such as heat released on incineration or chemical reaction.
72. **Thermoform**
    To give a final shape to a material, such as a plastic with the aid of heat and usually pressure. (Merriam-Webster)

Glossary

73. **Thermoset**
A polymer that hardens during curing and cannot be melted and reshaped. Common examples are epoxy and polyurethane.

74. **Wasteshed**
A geographic area that serves as supply of post-consumer and post-industrial plastics for a recycling technology.

Environmental and Human Health Terms

1. **Bluewater**
The total of all water evaporated during production or physically incorporated into the product (Aviso et al., 2011). Thus, bluewater does not include non-contaminated water returned to the environment (i.e. from steam heating or cooling water conditions) or contaminated water (i.e. from manufacturing) that is returned to the environment via a permitted wastewater treatment process. (Closed Loop Partners)

2. **Carbon Dioxide Equivalents (CO2e)**
A unit of comparison for chemicals that result in global warming. Different chemicals have different warming potentials and also different reactivities (persistence) in the environment. Therefore, a timeframe must be used to compare warming potential. The TRACI methodology used is based on a time frame of 100 years. If two alternatives are more than 20% different, there is higher confidence that one is substantively better than the other. (Closed Loop Partners)

3. **Climate Impact Potential**
See global warming potential.

4. **Cumulative Energy Demand (CED)**
Represents the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials. (American Chemical Society)

5. **Energy Grid**
A network of electrical transmission lines connecting a multiplicity of generating stations to loads over a wide area. (Merriam-Webster)

6. **Fugitive Emissions**
Greenhouse gas emissions that are not produced intentionally by a stack or vent and stipulates that they may include leaks from industrial plants and pipelines. (Energy)

7. **Global Warming Potential**
The global warming impact due to chemical emissions expressed as carbon dioxide equivalents (CO2eq). The relative impact of different gasses such as CO2 and methane (CH4) depend on the time frame used as a basis of comparison. This report uses the US EPA's TRACI 2.1, which is based on 100 years. (Closed Loop Partners)

8. **Greenhouse Gas Emissions**
Any gas that has the property of absorbing infrared radiation (net heat energy) emitted from Earth's surface and reradiating it back to Earth's surface, thus contributing to the greenhouse effect. Carbon dioxide, methane, and water vapour are the most important greenhouse gases. (Britannica)

9. **Hazard Category Ratings**
The Globally Harmonized System (GHS) is an internationally adopted system for the classification and labeling of hazardous chemicals that (1) includes established criteria for classifying hazards and for further categorizing (or rating) the hazards according to their relative risks, (2) provides established language and symbols for each hazard class and each category within a class. The hazard categories are numbered from 1 to 5. The lower the number, the greater the severity of the hazard. (ACS Institute)

Glossary

10. **Life Cycle Assessment (LCA)**
Cradle-to-grave or cradle-to-cradle analysis techniques to assess environmental impacts associated with all the stages of a product's life. (Closed Loop Partners)
11. **Material Processing Efficiency (%)**
Total amount of materials entering the reactor that is converted into saleable products expressed as a percent. This is a more direct measure of the efficiency of each technology to convert waste plastics into saleable products. (Closed Loop Partners)
12. **Material Rejection Rate (%)**
Total material rejected from the waste plastic received at the plant prior to the recycling reactor, expressed as a percent. The input streams for each technology are highly variable with some technologies taking in more heterogeneous and contaminated materials streams while others have undergone more pre-processing to create cleaner, more homogeneous streams of materials. (Closed Loop Partners)
13. **Natural Resource Energy Combusted (NREc)**
The energy value (HHV) of fossil resources extracted from earth to supply the process energy (electricity, heat, etc.) through all activities. This includes energy used to extract, transport, generate, and deliver energy to the point of use. Combustion of fuels leads directly to impacts such as global warming, blue water, and human health.
14. **Natural Resource Energy for Materials (NREm)**
The energy value (HHV) of fossil resources extracted from earth and used for material purposes as the product mass. This includes oil and gas that ultimately end up in the product or exits as process emissions. NREm results in resource depletion and process emissions, but not combustion emissions.
15. **NREtotal**
The sum of NREm and NREc, a measure of the total energy value of all extracted fossil fuel materials regardless of use. This metric is used as an indicator of fossil circularity.
16. **Waste Reduction Model (WARM)**
A model created by the EPA to help solid waste planners and organizations track and voluntarily report greenhouse gas (GHG) emissions reductions, energy savings and economic impacts from several different waste management practices. WARM calculates and totals these impacts from baseline and alternative waste management practices—source reduction, recycling, anaerobic digestion, combustion, composting and landfilling. (EPA)
17. **Water Emissions/Pollution**
Occurs when harmful substances—often chemicals or microorganisms—contaminate a stream, river, lake, ocean, aquifer, or other body of water, degrading water quality and rendering it toxic to humans or the environment. (NRDC)

Policy Terms

1. **Advanced Market Commitments**
Commitments to acquire certain materials that lack any or robust secondary markets, to encourage their acceptance by Material Recovery Facilities. Likely best applied to electronic waste, textile waste, and organics. (Closed Loop Partners)
2. **CO2 Taxes**
Taxation systems applied across high energy and carbon intensive industries. Application to the waste sector is relatively new. (Closed Loop Partners)
3. **Extended Producer Responsibility**
Fee-based schemes place financial liability on producers with regard to the collection and sorting of the goods they put on the market. Extended

Glossary

producer responsibility legislation aims to hold producers responsible for the waste they create through establishing stewardship programs, and requiring all single-use products be made recyclable or compostable. Landmark examples include California's AB1080 and Washington's SB5397. (The Ellen MacArthur Foundation)

4. **Incineration Taxes**
   Taxes on either energy from waste in general or the use of waste incineration or mass combustion plants in particular. (Closed Loop Partners)
5. **Investment Tax Credits**
   Similar to those provided to renewable energy producers, an ITC Program would encourage investment immediately, as the credit is applied upon construction. Such a credit could be applied to new facilities, equipment, or software to improve efficiency. (Closed Loop Partners)
6. **ISCC Plus**
   International Sustainability and Carbon Certification offers a global sustainability certification system covering all sustainable feedstocks, including circular materials. (Closed Loop Partners)
7. **ISO 14041**
   Environmental management standard set by the International Organization for Standardization, measuring a product's life cycle assessment. This standard has since been revised by ISO 14040:2006 and ISO 14044:2006. (ISO)
8. **ISO 14044**
   ISO 14044:2006 specifies requirements and provides guidelines for life cycle assessment (LCA) including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements. The standard covers life cycle assessment (LCA) studies and life cycle inventory (LCI) studies. (ISO)
9. **Mass Balance**
   Strict records are kept of the materials used in the formulation of a product and product outputs and this data is transferred, monitored and controlled as the products move through the relevant supply chain. The units of the mass balance can vary with examples using mass, energy and carbon and this approach has previously been successful in developing high levels of transparency and consumer trust for other materials such as paper and renewable energy. (Closed Loop Partners)
10. **Pay for Performance Rewards**
    Additional grant capital available to municipalities that reach certain recycling thresholds across material types for at least a two-year period, to be used to support product design and commercialization for lower-waste, reusable and recyclable products. (Closed Loop Partners)
11. **Production Tax Credits**
    Similar to those provided to renewable energy producers, a PTC program would encourage investment in large-scale project development and could be structured to be applied only to facilities producing a minimum output of certain material types, such as those most in demand by industry or government. (Closed Loop Partners)
12. **Research Grants**
    Funding for research organizations to study topics related to consumer behavior, product design and durability, and product commercialization for increased reuse and recyclability. (Closed Loop Partners)
13. **Recycled Plastics Traceability Certification**
    Allows manufacturers to have the recycled content of their products certified via a third-party verification whether the material is from pre and/or post-consumer sources. (Closed Loop Partners)

Bibliography

1. UN Environmental Programme. (2018). *Our planet is drowning in plastic pollution—it's time for change!* Retrieved June 15, 2021, from https://www.unep.org/interactive/beat-plastic-pollution/#:%7E:text=Only%209%25%20of%20all%20plastic,dumps%20or%20the%20natural%20environment.
2. Plastics News. (2021, June 2). *APR wants chemical recycling limited to plastics-to-plastics*. https://www.plasticsnews.com/news/apr-wants-chemical-recycling-limited-plastics-plastics
3. Closed Loop Partners. (2021, November). *Transitioning to a Circular System for Plastics: Assessing Molecular Recycling Technologies In the United States and Canada.* Appendix 4.0
4. Arkin, C. (2021, April 21). *All Talk and No Recycling: An Investigation of the U.S. "Chemical Recycling" Industry.* Global Alliance for Incinerator Alternatives. https://www.no-burn.org/chemical-recycling-us/
5. Closed Loop Partners. (2020, May). *Building a Circular Path Forward: Closed Loop Partners 2020 Impact Report.* https://www.closedlooppartners.com/wp-content/uploads/2021/02/Closed-Loop-Partners-2020-Impact-Report-3.pdf
6. *Press Release: El Dorado of Chemical Recycling, State of play and policy challenges.* (2021, August 29). Zero Waste Europe. https://zerowasteeurope.eu/press-release/press-release-el-dorado-of-chemical-recycling-state-of-play-and-policy-challenges/
7. Greenpeace. (2020, September). *Deception by the Numbers: American Chemistry Council claims about chemical recycling investments fail to hold up to scrutiny.* https://www.greenpeace.org/usa/research/deception-by-the-numbers
8. World Economic Forum. (2016, January). *The New Plastics Economy Rethinking the future of plastics.* https://www3.weforum.org/docs/WEF_The_New_Plastics_Economy.pdf
9. University of Michigan. (2020, August 25). *Plastics, waste and recycling: It's not just a packaging problem.* ScienceDaily. Retrieved November 13, 2021 from www.sciencedaily.com/releases/2020/08/200825113621.htm
10. Becqué, R., & Sharp, S. (2020, September). *Phasing out plastics: The automotive sector.* ODI. https://cdn.odi.org/media/documents/odi-et-cp-automotive-report-sep20-proof02_final2.pdf
11. *Electronic waste is destroying the planet, but we can fix that.* (2021, April 27). U.S. PIRG. Retrieved November 13, 2021, from https://uspirg.org/blogs/blog/usp/electronic-waste-destroying-planet-we-can-fix#:%7E:text=E%2Dwaste%20contains%20harmful%20toxins,waste%20or%20its%20environmental%20impact.
12. *MATERIALS INDEX.* (2021). CFDA. Retrieved November 13, 2021, from https://cfda.com/resources/materials/detail/polyester#:%7E:text=Polyester%20is%20the%20most%20widely,at%2052%20million%20metric%20tons.
13. Closed Loop Partners. (2021, January 27). *A Data Visualization Tool Identifying Opportunities to Recapture Plastic in the US & Canada.* https://www.closedlooppartners.com/research/us-and-canada-recycling-infrastructure-and-plastic-waste-map/
14. Closed Loop Partners. (2021, January 27). *A Data Visualization Tool Identifying Opportunities to Recapture Plastic in the US & Canada.* https://www.closedlooppartners.com/research/us-and-canada-recycling-infrastructure-and-plastic-waste-map/
15. Closed Loop Partners. (2021, January 27). *A Data Visualization Tool Identifying Opportunities to Recapture Plastic in the US & Canada.* https://www.closedlooppartners.com/research/us-and-canada-recycling-infrastructure-and-plastic-waste-map/
16. UN Environmental Programme. (2018). *Our planet is drowning in plastic pollution—it's time for change!* Retrieved June 15, 2021, from https://www.unep.org/interactive/beat-plastic-pollution/#:%7E:text=Only%209%25%20of%20all%20plastic,dumps%20or%20the%20natural%20environment.
17. Closed Loop Partners. (2021, January 27). *A Data Visualization Tool Identifying Opportunities to Recapture Plastic in the US & Canada.* https://www.closedlooppartners.com/research/us-and-canada-recycling-infrastructure-and-plastic-waste-map/
18. Closed Loop Partners. (2021, January 27). *A Data Visualization Tool Identifying Opportunities to Recapture Plastic in the US & Canada.* https://www.closedlooppartners.com/research/us-and-canada-recycling-infrastructure-and-plastic-waste-map/

Bibliography

19. Bagaria, R. (2021, June). *FDA Regulation Surrounding Food Packaging Plastic Resin.* Closed Loop Partners.
20. 2019 PET Recycling Report National Association for PET Container Resources (NAPCOR). (2020, November). *2019 PET Recycling Report.*
21. Domina T., Koch K. The Textile Waste Lifecycle. Cloth. Text. Res. J. 1997;15:96–102. doi: 10.1177/0887302X9701500204. https://journals.sagepub.com/doi/abs/10.1177/0887302x9701500204
22. RRS. (2021, April 21). *Data Corner: The importance of decoupling recycled and virgin plastic prices.* Resource Recycling News. https://resource-recycling.com/recycling/2021/04/18/data-corner-the-importance-of-decoupling-recycled-and-virgin-plastic-prices/
23. Closed Loop Partners. (2021, January 27). *A Data Visualization Tool Identifying Opportunities to Recapture Plastic in the US & Canada.* https://www.closedlooppartners.com/research/us-and-canada-recycling-infrastructure-and-plastic-waste-map/
24. The Ellen MacArthur Foundation. (2019). *Completing the picture: How the circular economy tackles climate change.* https://ellenmacarthurfoundation.org/completing-the-picture
25. Rahimi, A., García, J. Chemical recycling of waste plastics for new materials production. *Nat Rev Chem* 1, 0046 (2017). https://doi.org/10.1038/s41570-017-0046
26. Closed Loop Partners. (2019, April). *A Landscape Mapping of the Advanced Plastics Recycling Market. Closed Loop Partners.* (2021, May 25). http://www.closedlooppartners.com/research/advancing-circular-systems-for-plastics/.
27. Naviroj, Pensiri et al. (2019). Chemical Recycling of Plastics by Dissolution. University of Pennsylvania Scholarly Commons. Department of Chemical & Biomolecular Engineering.
28. Abdelaal, M. Y., Sobahi, T. R., & Makki, M. S. I. (2011). *Chemical transformation of pet waste through glycolysis. Construction and Building Materials, 25(8)*, 3267–3271. https://doi.org/10.1016/j.conbuildmat.2011.03.013
29. Vollmer, I., Jenks, M. J. F., Roelands, M. C. P., White, R. J., Harmelen, T., Wild, P., Laan, G. P., Meirer, F., Keurentjes, J. T. F., & Weckhuysen, B. M. (2020). *Beyond Mechanical Recycling: Giving New Life to Plastic Waste.* Angewandte Chemie International Edition, 59(36), 15402–15423. https://doi.org/10.1002/anie.201915651
30. Braun, D., Cherdron, H., Rehahn, M., Ritter, H., & Voit, B. (2021). *Polymer Synthesis: Theory and Practice: Theory and Practice: Fundamentals, Methods, Experiments by Dietrich Braun (2014–04-13).* Springer.
31. Panda, Achyut K. et al. (2010). *Thermolysis of waste plastics to liquid fuel A suitable method for plastic waste management and manufacture of value-added products—A world prospective, 14,* 233-248. Renewable and Sustainable Energy Reviews.
32. Vehlow, J. (2016) *Overview of the Pyrolysis and Gasification Processes for Thermal Disposal of Waste.* TK Verlag Karl Thomé-Kozmiensky.
33. *Conversion technology: A complement to plastic recycling.* April 2011. 4R Sustainability, Inc. Report prepared for the American Chemistry Council (ACC).
34. *Textiles: Material-Specific Data.* (2021, July 2). US EPA. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/textiles-material-specific-data
35. Martin, C. (2020, February 5). *Wind Turbine Blades Can't Be Recycled, So They're Piling Up in Landfills.* Bloomberg. Retrieved November 13, 2021, from https://www.bloomberg.com/tosv2.html?vid=&uuid=3ec921d8-44c4-11ec-ba6b-45514676556a&url=L25ld3MvZmVhdHVyZXMvMjAyMC0wMi0wNS93aW5kLXR1cmJpbmUtYmxhZGVzLWNhbi10LWJlLXJlY3ljbGVkLXNvLXRoZXktcmUtcGlsaW5nLWxhbmRmaWxscw==
36. Hopewell, J., Dvorak, R., & Kosior, E. (2009). *Plastics recycling: challenges and opportunities. Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1526), 2115–2126. https://doi.org/10.1098/rstb.2008.0311
37. *Functional Fillers and Specialty Minerals for Plastics.* (2021, September 15). Phantom Plastics. https://phantomplastics.com/functional-fillers/
38. ÜGdüler, S., van Geem, K. M., Denolf, R., Roosen, M., Mys, N., Ragaert, K., & de Meester, S. (2020). Towards closed-loop recycling of multilayer and coloured PET plastic waste by alkaline hydrolysis. *Green Chemistry*, 22(16), 5376–5394. https://doi.org/10.1039/d0gc00894j

Bibliography

39. Vollmer, I., Jenks, M. J. F., Roelands, M. C. P., White, R. J., Harmelen, T., Wild, P., Laan, G. P., Meirer, F., Keurentjes, J. T. F., & Weckhuysen, B. M. (2020). Beyond Mechanical Recycling: Giving New Life to Plastic Waste. *Angewandte Chemie International Edition, 59*(36), 15402–15423. https://doi.org/10.1002/anie.201915651

40. Thiounn, T., & Smith, R. C. (2020). Advances and approaches for chemical recycling of plastic waste. *Journal of Polymer Science, 58*(10), 1347–1364. https://doi.org/10.1002/pol.20190261

41. The European Commission. (2020). *Circular Economy Action Plan: For a cleaner and more competitive Europe*. European Union. https://ec.europa.eu/environment/pdf/circular-economy/new_circular_economy_action_plan.pdf

42. *European plastics manufacturers plan 7.2 billion Euros of investment in chemical recycling*. (2021, June 1). Waste Management World. https://waste-management-world.com/a/european-plastics-manufacturers-plan-72-billion-euros-of-investment-in-chemical-recycling

43. Closed Loop Partners. (2021, January 27). *A Data Visualization Tool Identifying Opportunities to Recapture Plastic in the US & Canada*. https://www.closedlooppartners.com/research/us-and-canada-recycling-infrastructure-and-plastic-waste-map/

44. Wood Mackenzie. Material and Application Platform.

45. Wood Mackenzie. Material and Application Platform.

46. The U.S. Plastics Pact. (2021, June 15). *The U.S. Plastics Pact Roadmap to 2025.* https://usplasticspact.org/roadmap/

47. Baca, J. (2021, October 22). *Big Companies. . . Big Advances for Plastics Recycling.* American Chemistry Council. https://www.americanchemistry.com/chemistry-in-america/news-trends/blog-post/2021/big-companies-big-advances-for-plastics-recycling

48. The Ellen MacArthur Foundation. (2019). *Completing the picture: How the circular economy tackles climate change*. https://ellenmacarthurfoundation.org/completing-the-picture

49. The U.S. Plastics Pact. (2021, June 15). *The U.S. Plastics Pact Roadmap to 2025.* https://usplasticspact.org/roadmap/

50. The Pew Charitable Trusts & SYSTEMIQ. (2020). *Breaking the Plastic Wave: A Comprehensive Assessment of Pathways Towards Stopping Ocean Plastic Pollution.* The Pew Charitable Trusts. https://www.pewtrusts.org/-/media/assets/2020/07/breakingtheplasticwave_report.pdf

51. IPCC. (2018). *Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press

52. DeBord, Gayle D. et al., Use of the “Exposome” in the Practice of Epidemiology: A Primer on -Omic Technologies. Am J Epidemiol. 2016 Aug 15; 184(4): 302–314.

53. Al-Sabagh, A., Yehia, F., Eshaq, G., Rabie, A., & ElMetwally, A. (2016). Greener routes for recycling of polyethylene terephthalate. *Egyptian Journal of Petroleum, 25*(1), 53–64. https://doi.org/10.1016/j.ejpe.2015.03.001

54. Ringer, M., Putsche, V., & Scahill, J. (2006, November). *Large-Scale Pyrolysis Oil NREL/TP-510-37779 Production: A Technology November 2006 Assessment and Economic Analysis.* National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy07osti/37779.pdf

55. University of Michigan. (2020, August 25). *Plastics, waste and recycling: It’s not just a packaging problem*. ScienceDaily. Retrieved June 24, 2021 from www.sciencedaily.com/releases/2020/08/200825113621.htm

56. Solis, M., & Silveira, S. (2020). Technologies for chemical recycling of household plastics – A technical review and TRL assessment. *Waste Management, 105,* 128–138. https://doi.org/10.1016/j.wasman.2020.01.038

57. Chung, E. (2020, January 7). *What really happens to plastic drink bottles you toss in your recycling bin.* CBC. Retrieved November 13, 2021, from https://www.cbc.ca/news/science/bottle-recycling-1.5416614

Bibliography

58. Chung, E. (2020, January 7). *What really happens to plastic drink bottles you toss in your recycling bin*. CBC. Retrieved November 13, 2021, from https://www.cbc.ca/news/science/bottle-recycling-1.5416614
59. Rollinson, A., Oladejo, J. (2020). Chemical Recycling: Status, Sustainability, and Environmental Impacts. Global Alliance for Incinerator Alternatives. doi:10.46556/ONLS4535
60. Cookson, C. (2021, October 1). *Advanced Plastics Recycling and the Air We Breathe*. American Chemistry Council. https://www.americanchemistry.com/chemistry-in-america/news-trends/blog-post/2021/advanced-plastics-recycling-and-the-air-we-breathe
61. Vahk, J. & Zero Waste Europe (ZWE). (2020, July). *CHEMICAL RECYCLING: 7 STEPS TO EFFECTIVELY LEGISLATE ON CHEMICAL RECYCLING*. https://rethinkplasticalliance.eu/wp-content/uploads/2020/07/rpa_chemical_recycling_statement.pdf
62. Jennings, C. E., Margolis, R. M., & Bartlett, J. E. (2008, December). *A Historical Analysis of Investment in Solar Energy Technologies (NREL/TP-6A2-43602)*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy09osti/43602.pdf
63. The White House. (2021, June 24). *FACT SHEET: President Biden Announces Support for the Bipartisan Infrastructure Framework*. https://www.whitehouse.gov/briefing-room/statements-releases/2021/06/24/fact-sheet-president-biden-announces-support-for-the-bipartisan-infrastructure-framework/
64. Jennings, C. E., Margolis, R. M., & Bartlett, J. E. (2008, December). *A Historical Analysis of Investment in Solar Energy Technologies (NREL/TP-6A2-43602)*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy09osti/43602.pdf
65. Scully Capital & Kutak Rock. (2018, October). *Examination of Federal Financial Assistance in the Renewable Energy Market: Implications and Opportunities for Commercial Deployment of Small Modular Reactors*. Scully Capital.
66. Jennings, C. E., Margolis, R. M., & Bartlett, J. E. (2008, December). *A Historical Analysis of Investment in Solar Energy Technologies (NREL/TP-6A2-43602)*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy09osti/43602.pdf
67. The Ellen MacArthur Foundation. (2021). *Extended Producer Responsibility a necessary part of the solution to packaging waste and pollution*. https://plastics.ellenmacarthurfoundation.org/epr#Position-paper
68. The Ellen MacArthur Foundation. (2021). *Extended Producer Responsibility a necessary part of the solution to packaging waste and pollution*. https://plastics.ellenmacarthurfoundation.org/epr#Position-paper
69. The Ellen MacArthur Foundation. (2021). *Extended Producer Responsibility a necessary part of the solution to packaging waste and pollution*. https://plastics.ellenmacarthurfoundation.org/epr#Position-paper
70. The Ellen MacArthur Foundation. (2021). *Extended Producer Responsibility a necessary part of the solution to packaging waste and pollution*. https://plastics.ellenmacarthurfoundation.org/epr#Position-paper
71. United States Environmental Protection Agency. (2020a, October 5). *EPA Releases Draft National Recycling Strategy*. US EPA. https://www.epa.gov/newsreleases/epa-releases-draft-national-recycling-strategy
72. *Maine Becomes First State to Sign Extended Producer Responsibility Law for Packaging, Other States with Plastics and Packaging Bills May Follow Shortly*. (2021, July 14). The National Law Review. Retrieved November 13, 2021, from https://www.natlawreview.com/article/maine-becomes-first-state-to-sign-extended-producer-responsibility-law-packaging
73. Okie, S. (2021, August 9). *The FAQs of EPR | Greenbiz*. GreenBiz. Retrieved November 13, 2021, from https://www.greenbiz.com/article/faqs-epr
74. Staub, C. (2021, July 14). *Nation's first packaging EPR bill is signed into law*. Plastics Recycling Update. https://resource-recycling.com/plastics/2021/07/14/nations-first-packaging-epr-bill-is-signed-into-law/
75. Staub, C. (2021, July 14). *Nation's first packaging EPR bill is signed into law*. Plastics Recycling Update. https://resource-recycling.com/plastics/2021/07/14/nations-first-packaging-epr-bill-is-signed-into-law/
76. Quinn, M. (2021, February 11). *2021 could be year for packaging EPR, nearly a dozen state bills in play*. Waste Dive. Retrieved November 13, 2021, from https://www.wastedive.com/news/2021-state-extended-producer-responsibility-recycling/594873/
77. GreenBlue. (n.d.). *The latest news on Canadian Extended Producer Responsibility*

Bibliography

(EPR) Programs | GreenBlue. Retrieved June 16, 2021, from https://greenblue.org/canadian-extended-producer-responsibility/

78. GreenBlue. (n.d.). *The latest news on Canadian Extended Producer Responsibility (EPR) Programs | GreenBlue*. Retrieved June 16, 2021, from https://greenblue.org/canadian-extended-producer-responsibility/
79. Jennings, C. E., Margolis, R. M., & Bartlett, J. E. (2008, December). *A Historical Analysis of Investment in Solar Energy Technologies (NREL/TP-6A2-43602)*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy09osti/43602.pdf
80. Government of Canada. (2021, November 2). *Zero plastic waste: Canada's actions - Canada.ca*. Retrieved November 13, 2021, from https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/reduce-plastic-waste/canada-action.html
81. Hasanbeigi, A., Becqué, R. & Springer, C. (2019). *Curbing Carbon from Consumption: The role of green public procurement*. San Francisco CS: Global Efficiency Intelligence. https://www.climateworks.org/wp-content/uploads/2019/09/Green-Public-Procurement-Final-28Aug2019.pdf
82. United States Environmental Protection Agency (2020). *About the Environmentally Preferable Purchasing Program*. https://www.epa.gov/greenerproducts/about-environmentally-preferable-purchasing-program
83. Zhao, Yi-Bo et al., Solvent-based separation and recycling of waste plastics: A review. Chemosphere 209 (2018) 707e720
84. Rollinson, A., Oladejo, J. Chemical Recycling: Status, Sustainability, and Environmental Impacts. Global Alliance for Incinerator Alternatives (GAIA). 2020
85. Cao, Bin et al. Synergistic effects of co-pyrolysis of macroalgae and polyvinyl chloride on bio-oil/bio-char properties and transferring regularity of chlorine. Fuel 246 (2019) 319–329
86. He, Zhigui et al., Pollution characteristics and health risk assessment of volatile organic compounds emitted from different plastic solid waste recycling workshops. Environment International 77 (2015) 85–94).
87. Lopez, Gartzen et al., Thermochemical routes for the valorization of waste polyolefinic plastics to produce fuels and chemicals. A review. Renewable and Sustainable Energy Reviews 73 (2017) 346–368
88. Wu, Zhihong et al., In-depth study on the effect of oxygen-containing functional groups in pyrolysis oil by P-31 NMR. Royal Society of Chemistry (RSC) Adv., 2019, 9, 27157

CLOSED LOOP partners

All inquiries can be directed to

molecularrecycling@closedlooppartners.com

closedlooppartners.com

twitter.com/loopfund

Certified B Corporation