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.

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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 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.

SECTION 2

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 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

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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

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“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.

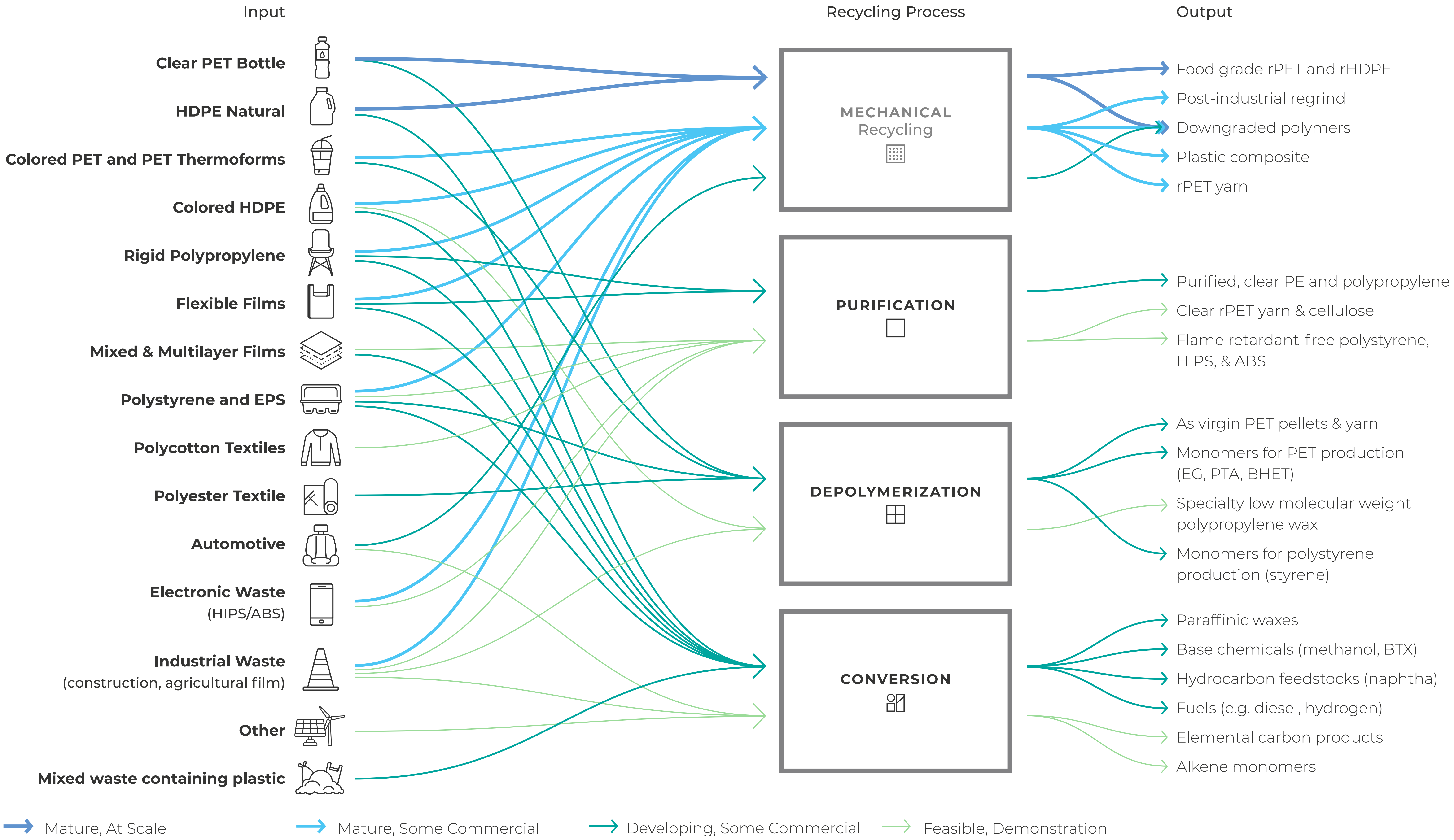
- Molecular recycling is a diverse sector that encompassess dozens of technologies that use solvents, heat, enzymes, and even sound waves to purify or break down plastic waste to create polymers, monomers, oligomers or hydrocarbon products. The sector is made up of purification, depolymerization, and 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



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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 an area that comprises the complete cycle of activities in the solid waste services process, from collection to transfer operations and recycling to disposal in either landfills or waste-to-energy facilities, some of which may be owned and operated by third parties

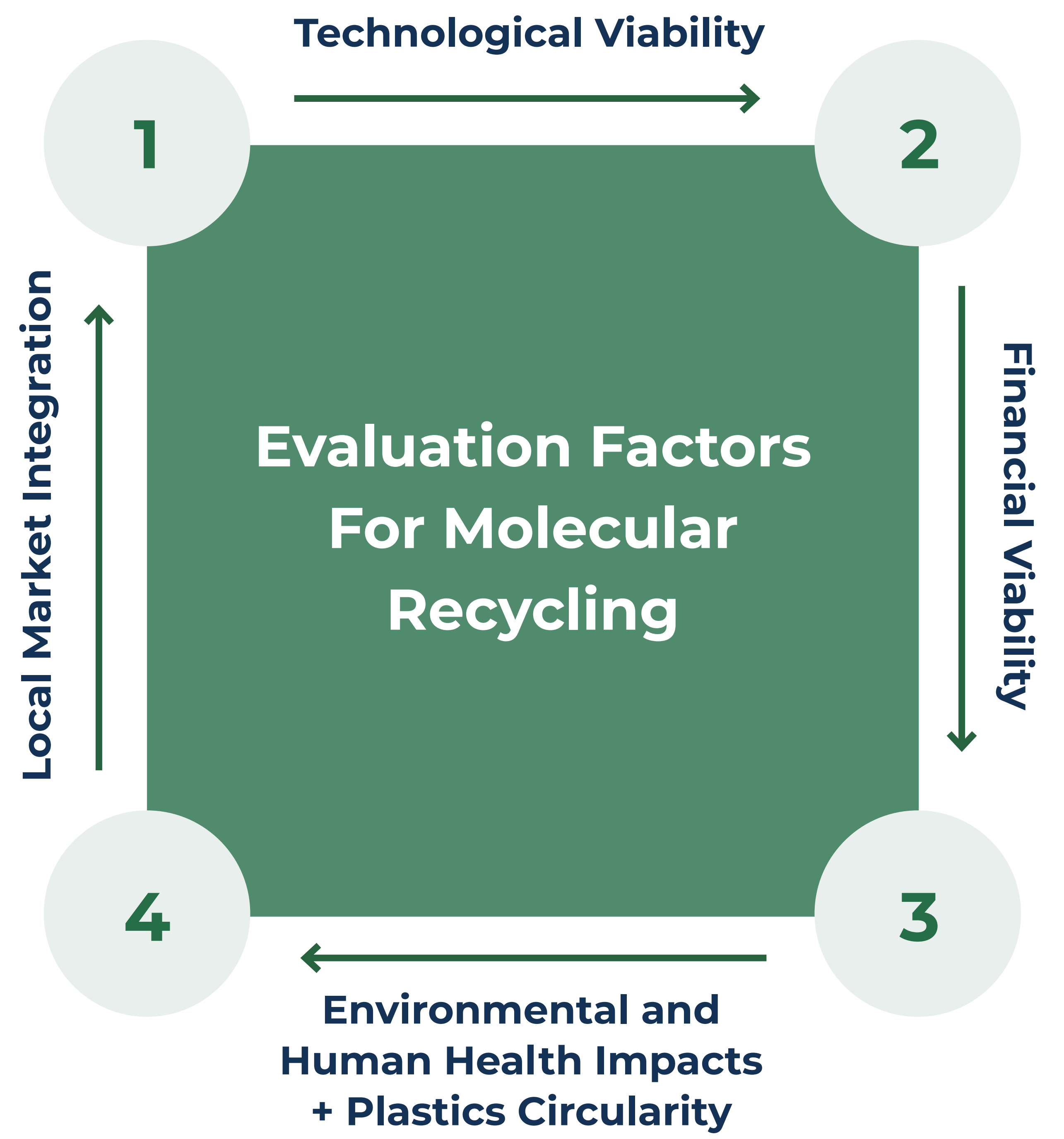
8 Closed Loop Partners' evaluation checklist can help investors and corporate partners execute the comprehensive diligence an early-stage sector this complex requires.

- 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.

CLOSED LOOP partners

SUPPLEMENTAL RESOURCES INCLUDING CASE STUDIES, THE GLOBAL DIRECTORY FOR MOLECULAR RECYCLING TECHNOLOGY COMPANIES, AND THE FULL REPORT ARE AVAILABLE ONLINE. VISIT CLOSED LOOP PARTNERS' WEBSITE **FOR MORE.**

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