Closing the Plastics Circularity Gap

Full Report

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Introduction

Humanity is consuming natural resources at an astonishing rate. During the 20th century, global raw material use rose at about twice the rate of population growth.[1] Every year, humanity consumes far more than what the planet can naturally replenish. In 2021, global demand for resources was 1.7 times what the earth's ecosystems can regenerate in a year.[2]

These statistics highlight the need to rethink the "take-make-waste" economic model—in which natural resources are taken from the earth, made into a product or burned for fuel, and eventually what remains is sent to the landfill as waste—that human societies have followed since the Industrial Revolution. The consequences of this model have contributed to significant global challenges, such as climate change, extreme weather events, and plastic pollution.

13 million metric tonnes of plastic leaks into the ocean every year

Plastic pollution has quickly become an existential threat to the health of people, the planet, and business. According to the UN, it is estimated that up to 13 million tonnes of plastic leaks into the ocean every year, which is equivalent to dumping the contents of one garbage truck into the ocean every minute.[3] Only a small fraction of the plastic produced since 1950—about 9%—has been recycled and returned back into the economy.[4] A study from the World Wildlife Fund found that the average person could be ingesting up to 5 grams of plastic each week, or the same amount of plastic found in the average credit card.[5] Without comprehensive and large-scale interventions, we should all expect that there will be more plastic than fish in the ocean by 2050.[6] Plastic pollution, in many ways, symbolizes the failures of the linear economic model and our collective inability to effectively manage a valuable resource.

While the linear economic model has generated tremendous progress for humanity in a short period of time, it has also created great disparities, injustice, and environmental harm. For example, the injustices are particularly acute for those in lower-income and disadvantaged communities who have been burdened by the differential concentration of industrial land uses where pollution is prevalent.[7] Creating a safe, equitable and circular economy requires that we all rebuild our relationship not only with the physical resources around us but also with each other and how we make, process, sell, and recycle those resources. One important way the world can address the unevenly distributed environmental inequities created through the linear economic model is by designing out waste and pollution and by choosing safe and healthy chemistry by design.

In 2018, Google published a white paper on The Role of Safe Chemistry and Healthy Materials in Unlocking the Circular Economy which describes a path to creating a safe and circular economy for physical resources.[8] Designing resources with safe chemistry from the start continues to be an important priority for material design and specification and is why Google continues to work with and support organizations like ChemForward on building a repository of robust, verified chemical hazard assessments and make them available to any industry. In the white paper, one of the calls to action is for innovation in the way materials are recycled such that molecules are broken down before they are returned back into commerce. This approach would emulate the way nature recycles materials today where one organism's waste becomes another organism's food. Additionally, it was recognized that all of the work to eliminate hazardous chemicals from materials and consumer products at the design stage is quickly lost when optimized materials enter the traditional mechanical recycling system and commingle with dirty, unoptimized materials prior to getting reintroduced back into consumer products as recycled content. For the vast majority of materials on the market, a separate dedicated recovery process – such as that used for PET bottles in some developed countries today – is not feasible. And even with the best performing mechanical recycling systems in the world, yields and material quality is reduced by complex mixtures of substances that are difficult to separate. This is why the future of recycling must be able to indiscriminately depolymerize, deconstruct, and dissociate the chemical makeup of materials so that the resulting by-products and constituents can be upcycled into higher value feedstocks for new materials. Chemical deconstruction serves to both tackle the toxic legacy of existing materials in the economy and enables the perpetual cycling of atoms and molecules, without the need for new fossil resources and without subjecting future generations to the design choices of linear systems, where human and environmental health are often not part of the objective.

As a continuation of this work in 2019, Google commissioned a first of its kind landscape assessment of chemical recycling technologies with Closed Loop Partners, AFARA, and GreenBlue.[9] The key objective of that study was to characterize the range of chemical recycling technologies including their inputs and outputs, where they sit on a relative technological maturity curve, and their classification as a technology (e.g., purification, decomposition, conversion). One of the insights from this study was that even if all of the 80+ identified technologies were completely capitalized to reach full market potential, that would still be insufficient to achieve a circular economy for plastics because there are several other structural and market conditions that aren't solved for yet including a lack of global infrastructure to collect and process waste plastics, supply chain logistics for recycled materials and re-integrating outputs of chemical recycling processes back into material production processes, unfavorable economics for chemically recycled plastics relative to that of fossil fuel based virgin plastics, and others.[10]

This led us to ask a big question–**Together, how could we create irreversible momentum towards a circular economy for plastics and simultaneously end our reliance on fossil fuel feedstocks?** To answer this question, we grounded our analysis in the economics of plastics production and recycling, brought together 20 years of supply-demand forecasts for plastics, and developed an intervention model that quantified the impacts of various potential solutions (e.g., technology, investment, procurement, policy). Finally, we prioritized potential solutions into 10 strategic interventions that are either low-risk or no-risk under multiple future scenarios.

At Google, we believe that realizing a sustainable world means that we must accelerate the transition to a safe, equitable, and circular economy where people, the planet, and business thrive. Creating a safe and equitable circular economy for plastics is a large and complex global challenge, but we've always viewed a challenge as an opportunity to be helpful and make things better for everyone. Our circular economy goal is to maximize the reuse of finite resources across our operations, products, and supply chains and enable others to do the same. Therefore, we seek to enable others to embrace circularity, which is why we share knowledge and insight through research and case studies with our partners, customers, and billions of users around the world.

Section 1
The Landscape Today

1.1 Plastics Circularity Gap

Plastics have a number of important characteristics – they are lightweight, affordable, waterproof, and durable. These characteristics make plastics an ideal material for packaging and consumer packaged goods. As global populations rise and consumer demand for products and packaging increase, these same qualities that make plastics so useful are also the reason that there is a growing global plastic waste problem.

Today, the overwhelming majority of plastics come from petrochemical sources, often called virgin[10] plastics, produced through a linear supply chain. These plastics also have low recycling rates. The most commonly recycled plastic in North America is polyethylene terephthalate (PET) with a recycling rate of 28% (Figure 1). Many other commonly used plastics are not recycled and have recycling rates in the low single digits.[11]

The purpose of this study is to establish a detailed understanding of the economic and business opportunities and challenges to create a future where plastic remains in the economy by identifying and quantifying the potential impact of strategic interventions (e.g. technology, investment, procurement, policy).

This study evaluated six polymers in three major regions of the world, representing 86% of global plastics demand.

The six polymers are:
Acrylonitrile-butadiene-styrene (ABS), Polycarbonate (PC), Polyester terephthalate (PET), Polyethylene (HDPE, LDPE, LLDPE), Polystyrene (PS), Polypropylene (PP)

Figure 1

North American Recycling Rates (2019)

In North America, plastics recovery through recycling is low for all polymers.

		Avg Recycling Rate	Collection
01	Polyethylene Terephthalate **PET**	28%	Curbside
02	High-Density Polyethylene **PE-HD**	20%	Curbside, grocery store
03	Polyvinyl Chloride **PVC**	0%	Direct to recyclers
04	Low-Density Polyethylene **PE-LD**	6%	Curbside, grocery store
05	Polypropylene **PP**	7%	Curbside
06	Polystyrene **PS**	2%	Curbside
07	Other *including* **ABS/PC**	n/a	Direct to recyclers

SOURCE: UNEP and Basel Convention 2020[11]

The three regions selected include North America, Europe, and Asia, which are price setting regions for plastics.

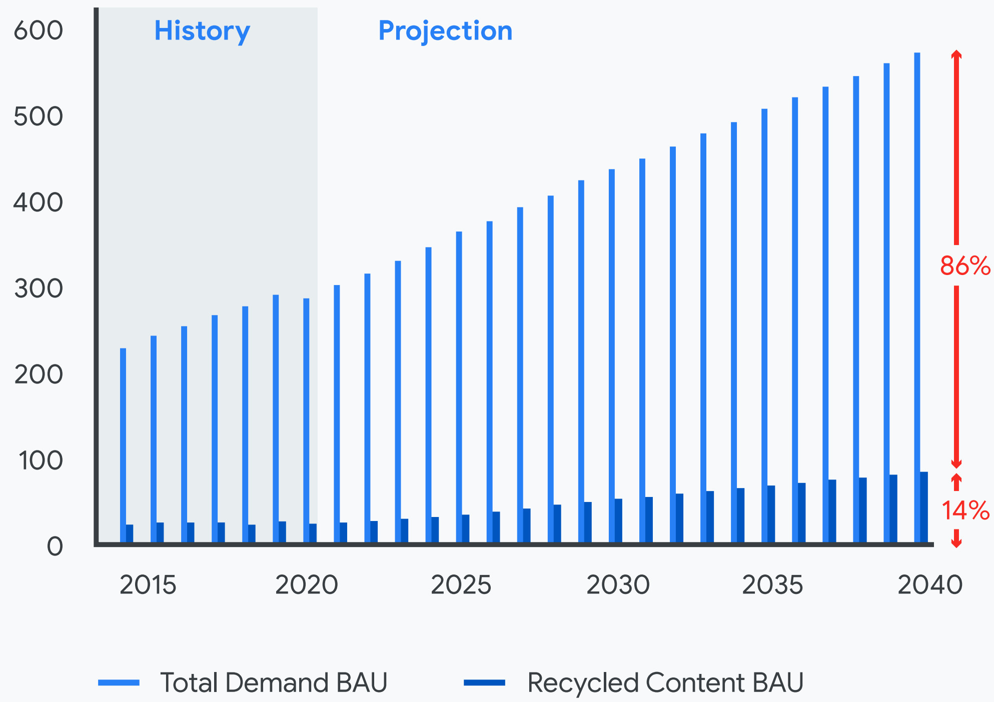
86% of all plastics produced are expected to be landfilled, incinerated, or leaked by 2040 (BAU)

Today, 276 million metric tonnes of plastics are being produced annually and the vast majority of this plastic, 256 million metric tonnes (93%), comes from virgin plastic supply chains made from petroleum products. Only 21 million metric tonnes (7%) are recovered and make their way back into the plastics supply chain as recycled material. Under a business-as-usual scenario (BAU), recycled plastics[12] reentering the economy are projected to more than triple, to 77 million metric tonnes (14%) by 2040, but over the same period, 86% of plastics are projected to be landfilled, incinerated, or leaked into the environment. The growing total volume of plastics compared with the volume of plastics

Figure 2

Global Plastics Demand under Business as Usual

UNIT: million metric tonnes/year



NOTE: Plastics demand presented on an annual basis

NOTE: Analysis based on 6 polymers and 3 regions of interest. Visual for Business as Usual scenario only

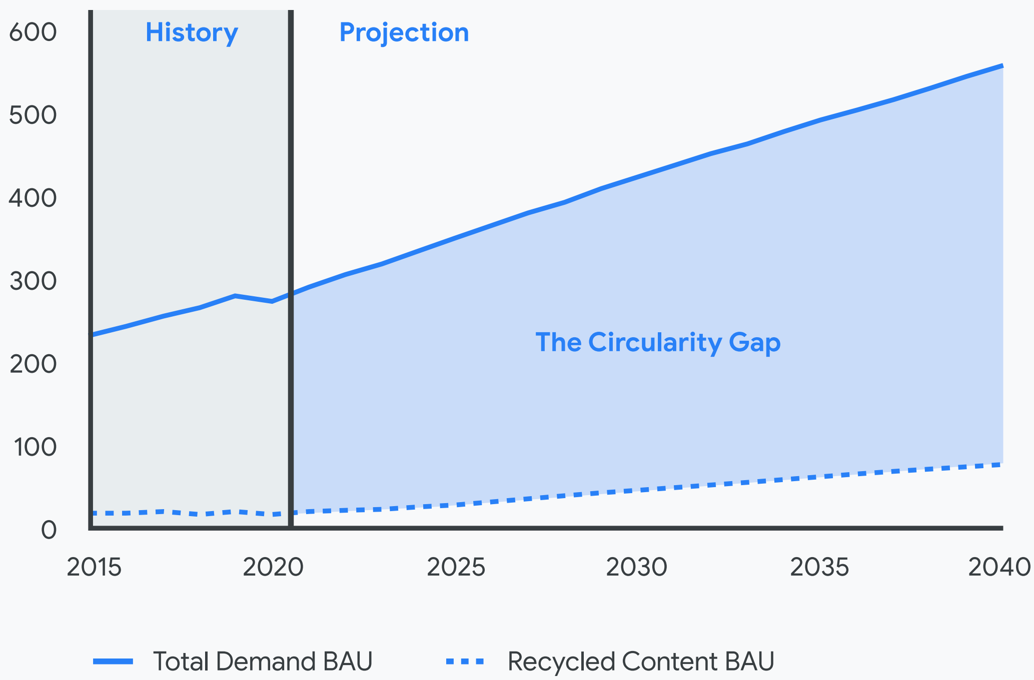
SOURCE: IHS Markit[13], AFARA analysis

coming from circular supply chains is what we call the **plastics circularity gap**.[14] The gap is growing rapidly and by 2040 under a BAU scenario, this would translate to a cumulative ~7.7 billion metric tonnes of plastics left mismanaged (see Figure 3) which is equivalent to the weight of approximately 16 times the mass of the entire human population living on earth today!

Figure 3

The Plastics Circularity Gap under Business as Usual

UNIT: million metric tonnes/year



NOTE: Visual presented on an annual basis; the plastics circularity gap is the cumulative volume of plastics that do not re-enter the plastics supply chain between 2020-2040

NOTE: Analysis based on 6 polymers and 3 regions of interest. Visual for Business as Usual scenario only

SOURCE: IHS Markit,[13] AFARA analysis

Collectively, we can close the plastics circularity gap because consumers, businesses, and governments have choices in how they produce, use, reuse and regulate plastics. However, closing this gap requires multiple strategic interventions.

To understand how to make different choices and take actions that will close or significantly reduce the plastics circularity gap, this study begins with a review of the economic and plastics production landscape today and explores how and why plastics are predominantly produced through virgin supply chains (see Sections 1.2-1.4). Sections 2-4 explore how to change the system and treat plastic waste as a feedstock in the circular economy, while section 5 focuses on actionable insights to dramatically reduce the plastics circularity gap.

1.2 Plastic Production Pathways

3.5% of all crude oil and natural gas liquids in North America are used for virgin plastics production

Virgin Plastic Production

Today, virgin plastics require the extration of new resources and are predominantly produced from petrochemicals derived from one of two pathways:

- Natural gas liquids (NGLs)
- Oil refinery streams

NGLs are obtained from natural gas processing plants. NGLs such as ethane, propane, butane, isobutane, and pentane are used for plastics production. Oil refinery streams are obtained from refining crude oil. Typically, crude oil refining is optimized for production of transportation fuels such as gasoline, diesel, and jet fuel. Therefore, the inexpensive by-product streams containing naphtha and light gas oil are the feedstocks used for plastics production.

There is a 3rd uncommon pathway where plastics are derived from coal using coal-to-olefin processes. Depending on available feedstocks (i.e. natural gas, crude oil, coal), and infrastructure (i.e. NGL fractionation, oil refineries, coal-to-olefin technologies), the plastic production pathways vary. For example, North America predominantly produces plastics from natural gas due to the abundance of shale gas. Asia and Europe's production are based on naphtha (a by-product of oil refinery streams). China is one of the few regions that uses coal to produce plastics. Table 1 summarizes the three production pathways for plastics.

Table 1

Production Pathways for Virgin Plastics

Traditional Feedstocks	Source	Region	Pricing Considerations
Natural Gas	NGL Fractionation	• Plastics manufacturing dominated by NGL fractionation in North America • North American polymers have increasingly used steam cracking of ethane	• Local supply and demand • Transportation limitations • Shale gas production technology/ abundance
Crude Oil	Oil Refineries	• Much of Asia and Europe's production is based on naphtha (via crude oil)	• Global supply and demand • Established oceanic transportation network
Coal	Coal-to-Olefin	• Uncommon pathway for plastics manufacturing • Predominantly in China (multi-step process from syngas to methanol to olefins)	• Inexpensive extraction technologies • Environmental impact issues

SOURCE: AFARA analysis

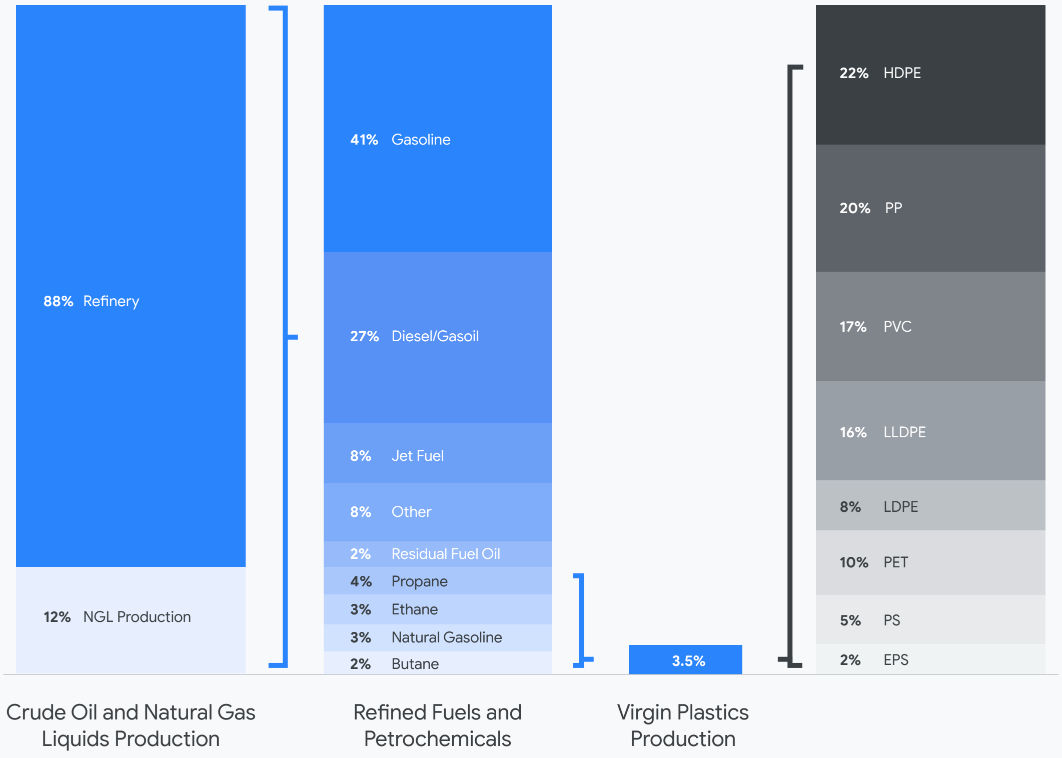
Sidebar 1

Traditional feedstocks for plastic production in North America

In North America, 3.5% of all crude oil and natural gas liquids are used for virgin plastics production. This 3.5% is a co-product of the refining and natural gas processing facilities. These facilities are designed to take a very narrow diet of hydrocarbon inputs and are not optimized to create plastic feedstocks; they are optimized to create fuels. However, these co-products are among the highest margin outputs of the refining and natural gas processing business.

Figure 4

Material Flow for Virgin Plastics Production in North America (2019)



NOTE: Data for breakdown on a volumes basis.

SOURCE: IHS Markit[15], AFARA analysis

Recycled Plastic Production

Today, recycled plastics are predominantly produced from mechanical recycling. Mechanical recycling uses plastic waste as feedstock to produce recycled resins. The process involves a mix of grinding, washing, separating, drying, re-granulating, and compounding without changing the chemical structure of the base polymer. The resulting recycled resins are labeled recycled content; however, the quality is typically lower compared to virgin resins (e.g., reduced clarity and strength).

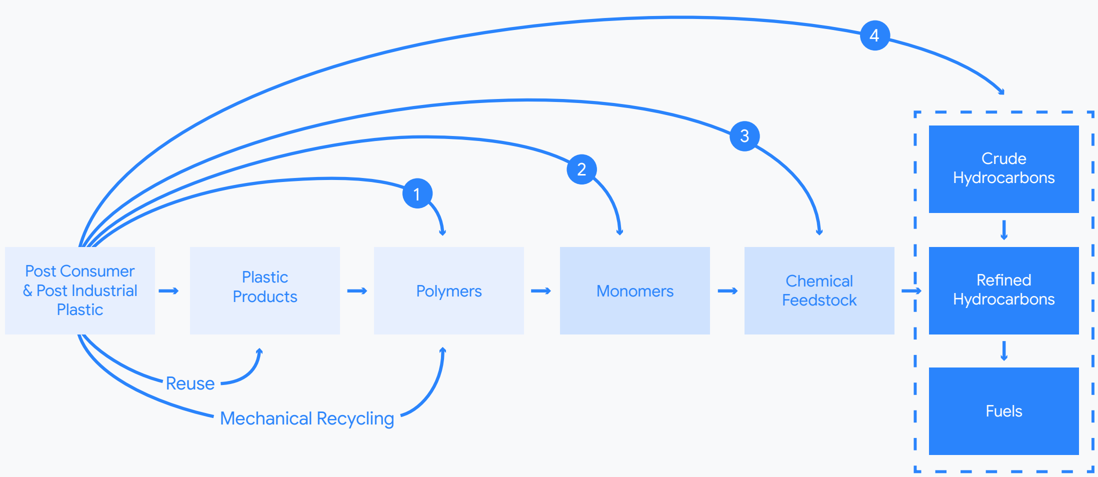
An emerging method to produce recycled plastics is through advanced recycling, also known as chemical recycling. Broadly, there are three types of chemical recycling processes: purification, decomposition, and conversion. These processes often involve breaking molecular bonds and changing the chemical structure of the material. The resulting recycled resins may be labeled recycled content (but are often not yet acknowledged as recycled content) and the quality is equivalent to those of virgin resins.[16] Figure 5 highlights how chemical recycling compares with mechanical recycling.

Purification (Loop 1)

Solvent-based purification extracts additives and dyes from the plastic mixture to ultimately obtain a “purified” plastic, but the purification process does not change the polymer on a molecular level. Solvent-based purification is not always included as a chemical recycling technique because there is no chemical change in the target polymer. Since the base polymer remains the same and the “purified” plastic has desirable physical properties, (e.g. virgin grade clarity and strength), the value of the plastic is maintained, although there is a yield loss with each purification cycle.

Figure 5

Recycled Plastic Production Pathways (Mechanical and Chemical Recycling)



Legend

1. Purification (Recovery of Polymers)
2. Decomposition (recovery of Monomers)
3. Conversion (Recovery of Chemical Feedstocks)
4. Conversion (Recovery of Hydrocarbons)

SOURCE: AFARA analysis

Decomposition (Loop 2)

Monomer recovery involves breaking the molecular bonds of a plastic back to its basic monomer and/or oligomer. Monomer recovery adds optionality since plastics with different properties can be made from the chemically recycled monomers, serving as a link between different value chains (e.g. Polyethylene detergent containers undergo monomer recovery and can enter the films value chain as opposed to the containers value chain). This flexibility within and across value chains allow the plastic to maintain or increase in value with each monomer recovery cycle.

Conversion (Loop 3 and 4)

Recovery of chemical feedstock and hydrocarbon pathways use chemical (i.e. catalytic cracking, hydrogenation) and/or thermal mechanisms (i.e. gasification, pyrolysis). The output products of these processes are often a mix of liquid fuels and petrochemical feedstocks, along with solids such as waxes. This form of chemical recycling is the most challenging to fit in the vision for circular economy as the output products can be, and currently are, used as fuel for combustion and/or a chemical feedstock. Depending on the output product, chemical and hydrocarbon recovery processes may or may not contribute to the vision that “plastics never become waste.”

1.3 Baseline Economics for Production

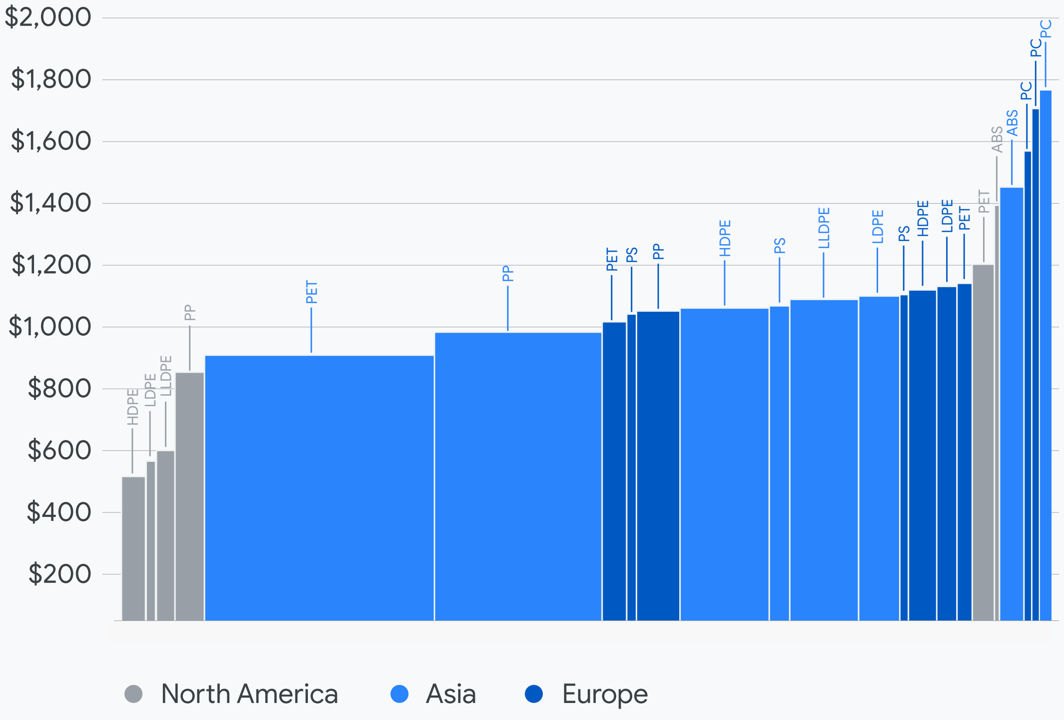
Virgin Plastic Economics

The cost of plastic production varies by polymer and by region. The cash cost of production for virgin plastics for all six polymers and all three regions of interest covered in this study are shown in Figure 6. By volume, PE, PP, and PET make up the bulk of plastics production; PS, ABS, and PC make up a small fraction. Further, North America tends to have a cost advantage due to the low cost of natural gas. The cost of feedstocks, in this case NGLs, is the biggest cost component to manufacturing plastics.

Figure 6

Cash Cost of Virgin Plastic Production by Polymer and Region (2019)

UNIT: USD / metric tonne



NOTE: Values based on non-integrated facilities; Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit[13] AFARA analysis

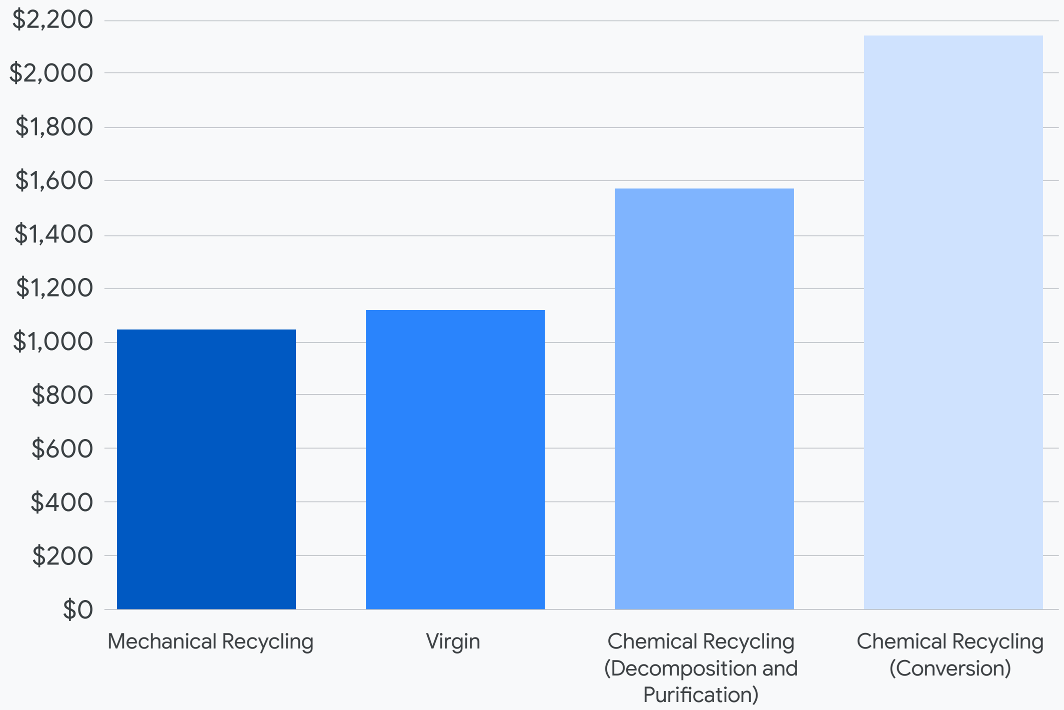
Plastics production from oil and gas (i.e. virgin resins) is economically attractive because:

1. **Feedstock Costs Are Low:** Due to the abundance of shale gas, natural gas liquids are cheap since it is a coproduct of shale gas production. Similarly, naphtha (via crude oil) is typically a co-product of refinery operations
2. **Integration Is High:** Infrastructure today allows for high levels of integration between refiners/upgraders (i.e. producers of ethane) and chemical companies (i.e. producers of ethylene). This allows for co-location benefits, lower transport costs, and synergies in utilities; and
3. **Revenue Is Diversified:** There is a trend for oil companies to expand their business portfolios into petrochemicals in search of more resilient sources of income.

Figure 7

Global Average Cash Cost of Virgin and Recycled Plastic Production (2019)

UNIT: USD / metric tonne



NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit[13], AFARA analysis

Recycled Plastic Economics

The global average cash cost of production for virgin and recycled plastics ranges between approximately $1100 to $2100 per tonne (Figure 7). The global average cash cost for mechanical recycling is slightly lower than virgin plastics, while the global average cash cost for chemical recycling is 1.4-1.9 times higher than virgin plastics. Granularity by region and by polymer are shown in Figures 8 and 9.

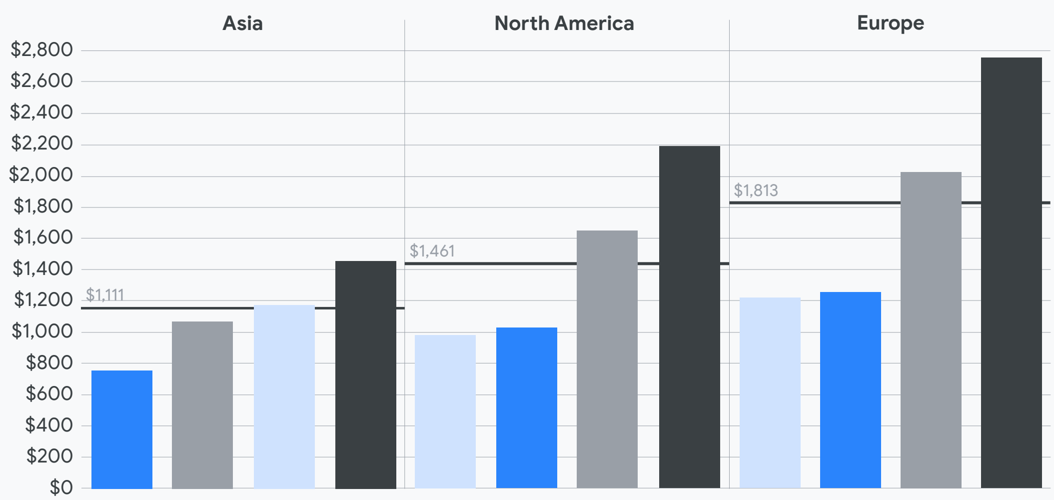
For all production pathways, Europe bears the highest cost of production, averaging $1,813/metric tonne. Asia has the lowest average cost of production averaging $1,111/metric tonne. North America tends to have a cost advantage for virgin plastic production due to the low cost of natural gas (Figure 6).

By polymer, PC has the highest average cost of production with an average of $1,716/metric tonne, followed by HDPE, and ABS. In contrast, PET has the lowest average cost of production with an average of $1,259/metric tonne, followed by LLDPE, and LDPE.

Figure 8

Global Average Cash Cost of Virgin and Recycled Plastic Production by Region (2019)

UNIT: USD / metric tonne



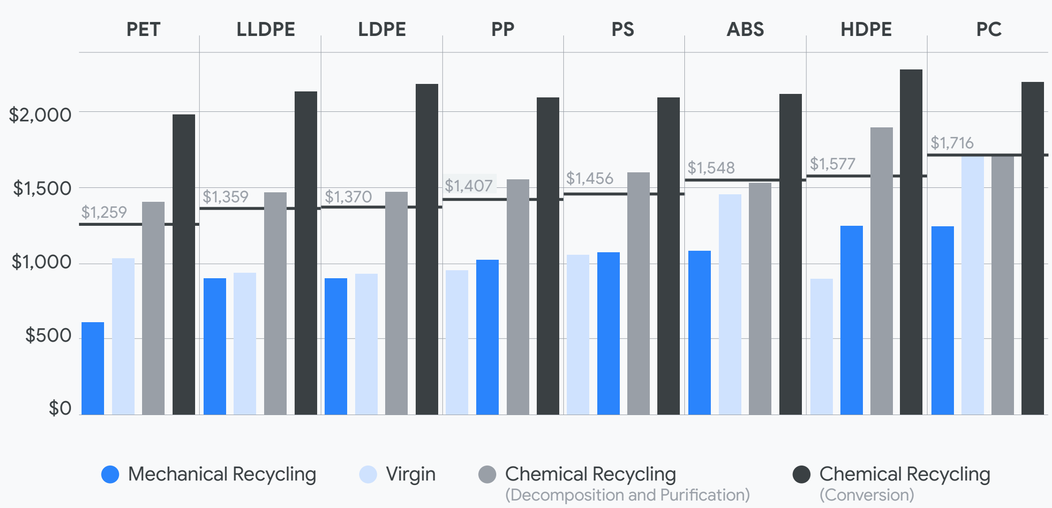
NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit[13] AFARA analysis

Figure 9

Global Average Cash Cost of Virgin and Recycled Plastic Production by Polymer (2019)

UNIT: USD / metric tonne



NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit[13] AFARA analysis

Circular supply chains beyond mechanical and chemical recycling
The circular economy does not aim to end growth, but rather maximize the economic use of products and services created in the economy. The circular economy concept is therefore to enable growth while decoupling growth from the consumption of finite resources and subsequent environmental degradation.

The circular economy requires:

Rethinking by designing out waste and building products and packaging for material efficiency in materials. It also requires reducing resource consumption and implementing new opportunities to reduce plastic demand;

Optimizing the system to keep products and components at their highest value and in use for as long as possible while minimizing material losses. This often includes designing for durability, reuse, and repairability along with designing for recyclability;

Regenerating and preserving natural capital by creating business models that price pollution and externalities and maintain a net positive balance to natural capital; and

Recycling molecules, materials, and products is a critical component of creating circular plastic supply chains and it must work in concert with additional system interventions. [17]

1.4 Headwinds and Tailwinds for Plastics Circularity

Demand from customers, commitments from brands, and early discussions on new policies to support circular supply chains for plastics represent tailwinds (advantages) for plastics circularity. However, the comparatively unfavorable economics for recycled plastics and current infrastructure imbalance represent headwinds (disadvantages). The trends that support and oppose plastics circularity are further explored below:

Unfavorable Economics for Circular Supply Chains

Using virgin resins to manufacture plastics has a tremendous advantage on six of the ten evaluated economic drivers.[18]

Natural gas is an abundant resource in North America and naphtha is a petroleum refining by-product. These petrochemicals do not need extensive upgrading and/or refining before they are able to serve as raw materials for plastics production.

Existing infrastructure for virgin plastic production is highly physically integrated and there are low costs to transport and process feedstocks into petrochemicals and to plastics. The technologies and production pathways are mature and operating on a large scale, leading to economies of scale. In North America today, capacities for ethane-based steam crackers range from 300 – 1,500 thousand tonnes/year and polymer plants range from 100 – 800 thousand tonne/year.[19] Since many of these facilities have been built and commissioned in the 1900's, the cost of capital has been fully depreciated and the bulk of the cost are operating expenses.

Figure 10

Overview of Headwinds and Tailwinds for Plastics Circularity Today

Headwinds:

- Unfavorable economics for plastics made from recycled resins compared to virgin resins
- Infrastructure imbalance because the existing global supply chains are equipped to produce plastics but not as equally well equipped to take it back

Tailwinds:

- Consumer desire for increased recycling and reduced plastic waste
- Commitments from brands for recycling and recycled plastics, many which are backed by short-term targets
- Early discussions and ongoing consideration to enact new policies to support plastics circularity

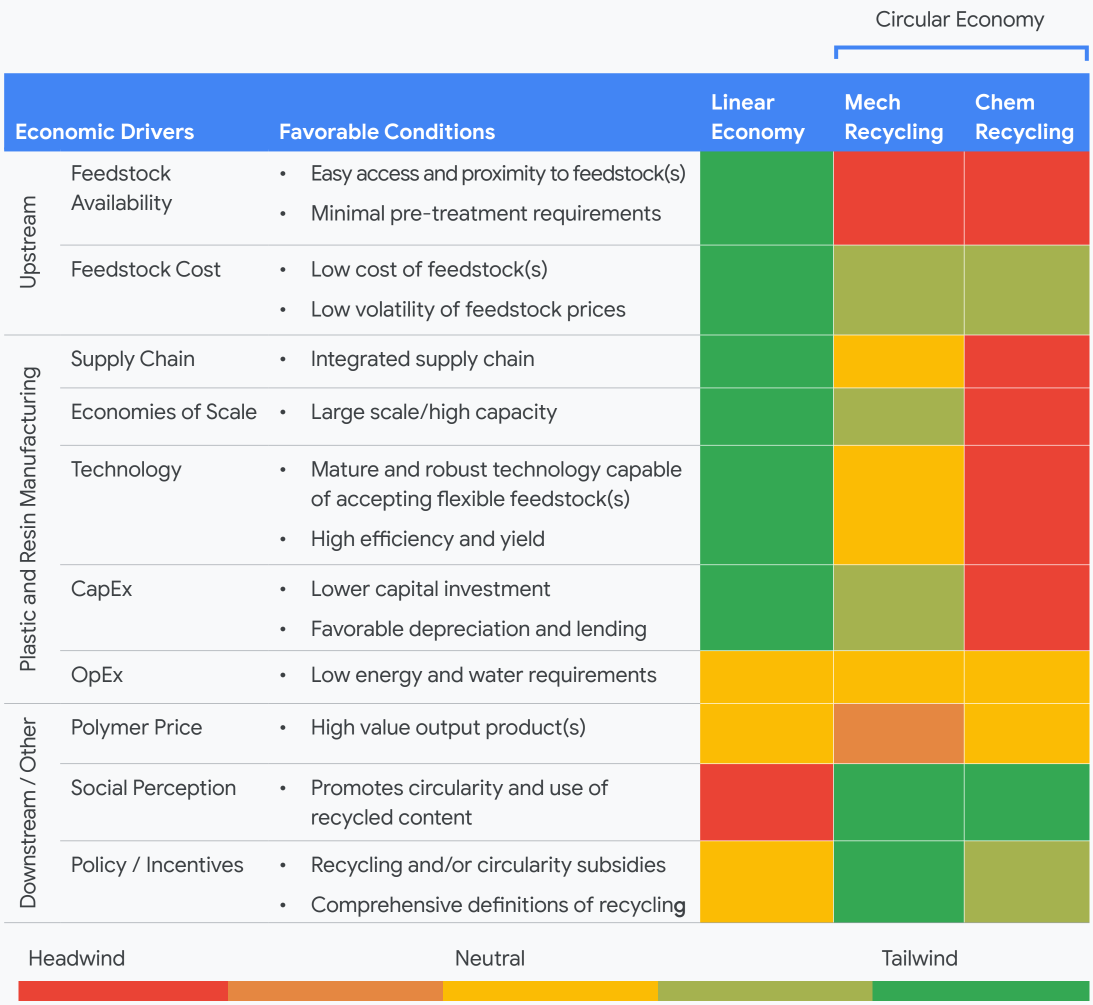
93% of global plastics demand today comes from virgin hydrocarbon value chains

Effect of oil and gas pricing on plastic economics

93% of global plastics demand today comes from virgin hydrocarbon value chains (Figure 2). Since feedstocks are the largest cost for plastics production, hydrocarbon pricing (i.e. oil and gas pricing) is an important factor for plastic economics. Oil and gas pricing is volatile, and the price for oil in the futures market was negative at one point in 2020. Sustained low oil and gas pricing pose a headwind and challenge to circular plastic supply chains. Circular supply chains use plastic bales from waste management streams as feedstocks and are only indirectly affected by oil and gas pricing. Low oil and gas pricing can increase demand for virgin plastics which can decrease demand for recycled plastics and subsequently decrease plastic bale pricing.

Figure 11

Economic Drivers for the Linear and Circular Economy (2019)



SOURCE: AFARA analysis

Using recycled resins to manufacture plastics is gaining traction due to consumer demand for circularity in plastic supply. Social perception for circular supply chains is positive and building momentum leading to demand for resins labelled as recycled content. This is a tailwind for mechanical recycling as policies clearly allow for its output products to be labelled as recycled content. For chemical recycling, the labelling for recycled content is inconsistent. Currently, there is no single, standardized definition for chemical recycling, and a multitude of competing definitions are rapidly evolving and being debated.[20] Conversion technologies are not consistently in scope under the definition of chemical recycling which further poses debates whether its output products can be labelled as recycled content. Some legislative proposals in the US in 2021 seek to exclude chemical recycling technologies from being considered recycling processes, or producing recycled content. At the same time, the Danish Ministry of Environment issued a position supporting chemical recycling technologies under an Executive Order on Waste and the EU Waste Directive framework if those technologies were used to produce chemicals that can be used for new products and not for energy generation.[21] Growth of and investment in chemical recycling may hinge on a global policy climate that accepts the outputs of these technologies as recycled content when incorporated as materials into products.

Another economic advantage in favor of the circular economy is the feedstocks. The circular economy uses plastic bales that are often viewed as waste. Relative to new materials used in virgin plastic production, the cost of raw materials for recycled plastic production is cheap; however, plastic production from circular supply chains is not widespread today because:

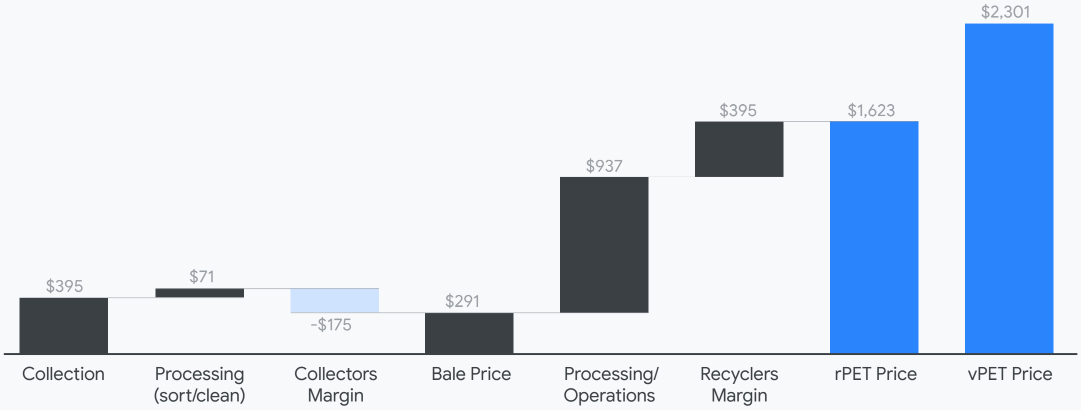
1. The success of mechanical recycling is contingent on clean bales of plastic feedstock from upstream collection/sortation operations.
2. All forms of chemical recycling have unattractive economics on a cash cost of production basis relative to the virgin production pathway (Figure 7).

While the price of recycled PET plastic (i.e. rPET) is lower than virgin PET plastic in North America in 2019, the upstream collection/sortation system (e.g., the material recovery facilities) is operating and funded by the public at a loss through taxpayer dollars (Figure 12).

Figure 12

Breakdown of Upstream and Manufacturing Cost to Produce rPET from Mechanical Recycling (2019)

UNIT: USD / metric tonne



SOURCE: IHS[22], AFARA analysis

Infrastructure Imbalance

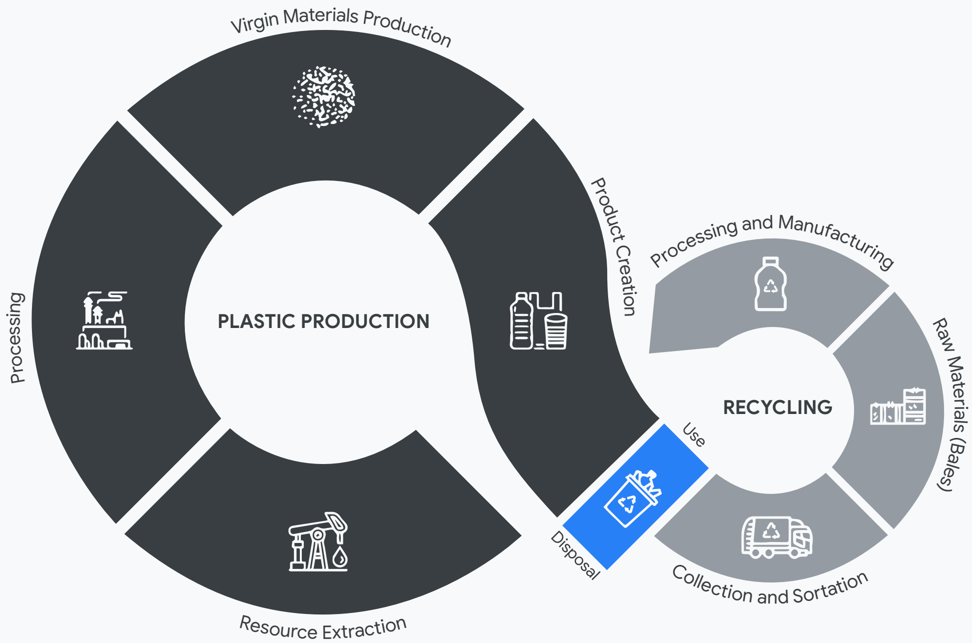
Another headwind to plastics circularity is the infrastructure imbalance. Today, existing global supply chains are equipped to produce plastics but are not as equally well equipped to take it back. In 2019, the total production of plastics was ~300 million metric tonnes (Figure 2) while the recycled resins produced from mechanical and chemical recycling reached 21 million metric tonnes and 1.4 million metric tonnes, respectively. This means the existing supply chain produces 13 times more plastics than the volume of plastics that can re-enter the supply chain.

Consumer Demand

A tailwind for plastics circularity is the growing shift towards conscious consumerism and transparency on the environmental impacts of plastic pollution. In a study on generational attitudes towards conscious consumerism, the results show that Gen Z and Millennials are more likely to be conscious about their purchases.[23] They are "willing to pay a little more to get products made by companies that share [their] values" and "pay more for products that have the least negative impact on the environment". Gen Z and Millennials are the largest living cohorts and will be the next generation of consumers driving the market. This attitude shift creates a tailwind for plastics circularity as brand owners are required to change and adapt if they want to meet consumer and market expectations.

Figure 13

Existing Infrastructure Imbalance



NOTE: Not drawn to scale.

SOURCE: AFARA analysis

Commitments from Brands

In response to consumer demand on plastics circularity, many brand owners have announced sustainability commitments with short-term targets. These commitments include designing new packaging that eliminate or reduce plastics, using recycled content for plastic products, and ensuring packaging is recoverable/recyclable. The Global Commitment 2021 progress report published by The Ellen MacArthur Foundation in collaboration with the UN Environment Programme offers some key insights about sector commitments and progress (Table 2). The commitments and actions by brands are tailwinds driving momentum towards plastics circularity.

Table 2

Sector Progress and Commitments

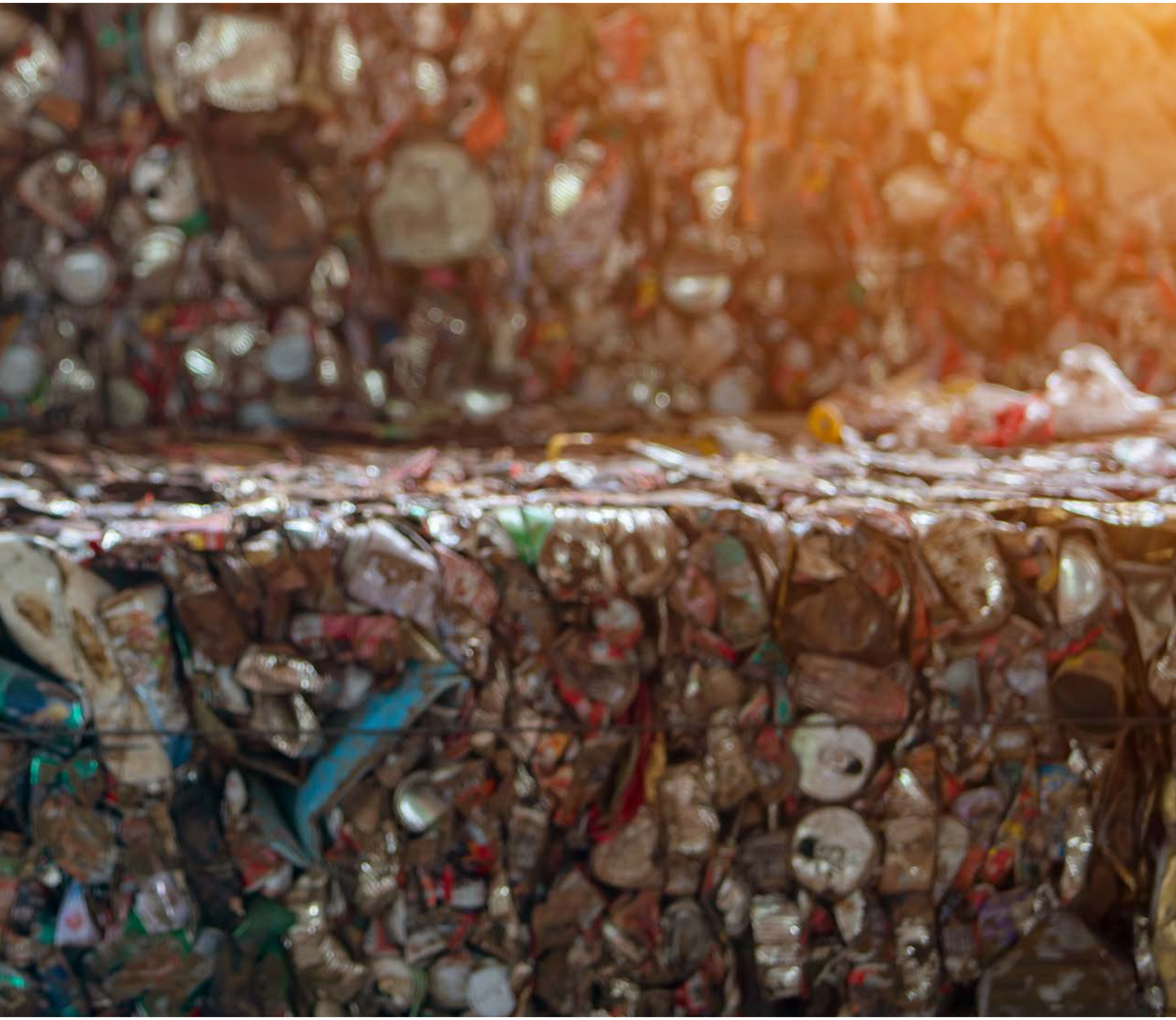
Sector	Progress and Commitments
Beverage	Global Commitment signatories have a commitment to reduce virgin plastic in their packaging by an average of 16% by 2025 while the sector currently has a post-consumer recycled content average of 9.4%.[24]
Cosmetics	Global Commitment signatories are reporting targets to implement reuse models across either a minimum number of retail stores or a minimum number of product lines. Additionally, all signatories have committed to reduce virgin plastic use in packaging by 33% on average by 2025.[25]
Food	80% of food sector Global Commitment signatories have reduced their vigin plastic packaging by 5% on average in 2020, with all signatories committing to further virgin plastic reductions of 21% on average by 2025.[26]
Household and Personal Care	New circular business models are emerging with 82% of household and personal care Global Commitment signatories launching reuse pilots in 2020.[27]
Retail	Retailers are most commonly working to eliminate plastic materials that are hard to recycle (e.g., PVC, PS, and EPS), and 70% of Global Commitment signatories have plans to eliminate or reudce single-use cutlery and straws in their portfolios.[28]

SOURCE: Ellen MacArthur Foundation [29]

Updated and New Policy

Policy leadership on the circular economy is growing as governments and non-government organizations (NGOs) host discussions to collect data on the plastics landscape and enact relevant new policies. In Canada, The Ocean Plastics Charter and related single-use plastic item regulation are under development.[30,31] In the U.S., several states such as New York, California and Oregon are writing legislation to support plastics circularity.[32] For example, a bag waste reduction law took effect in New York on March 1, 2020. In Europe, the European Commission's Circular Economy Action Plan contains a strategy on plastics which include legislative and non-legislative measures.[33] The issue of plastics and the circular economy is becoming top of mind for governments and policy makers, creating a tailwind for plastics circularity.

Section 02
Methodology



2.1 Methodology Overview

Today, plastic supply chains are not set up to be circular. Headwinds for plastics circularity outweigh tailwinds, and unless action is taken, headwinds will dominate through 2040. In recognizing this challenging starting point, this study:

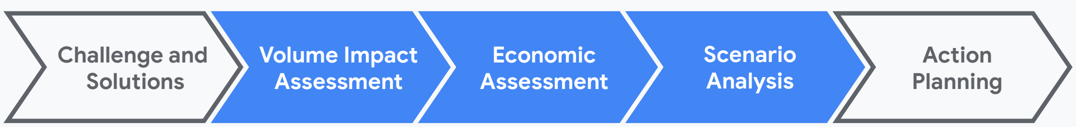
- Examines the suite of interventions that can create irreversible momentum to a future where plastic remains in the economy
- Focuses on actionable insights
- Identifies critical elements to unlock untapped potential and catalyze circular supply chains by emphasizing what is possible, and what is required.

The study starts by identifying the challenges and magnitude of the global plastics problem, followed by proposing a suite of 14 potential interventions. Key elements guiding this study are summarized in Figure 14. An intervention model was built to prioritize interventions and it includes:

- Volume impact assessment
- Economic assessment
- Scenario analysis

Figure 14

Key Elements Guiding this Study



Challenge and Solutions

The challenges were identified by the **plastics circularity diagram**

The magnitude of the problem was defined by the **plastics circularity gap. 14 potential interventions** were mapped against the plastics circularity diagram

Volume Impact Assessment

The **Volume Impact Assessment** determined how much plastic each intervention can address

Economic Assessment

Cash Cost of Production compared the economics between virgin and circular production pathways

Investment Required evaluated the capital investment needed to support the high impact interventions (defined by the volume impact assessment)

Scenario Analysis

Scenario Analysis (Volumes) examined how volumes differ under different versions of the future

Scenario Analysis (Economics) examined how economics differ under different versions of the future

Action Planning

The prioritized interventions combined to create the list of recommended **strategic interventions**

The **action planning matrix** provided an evaluation of the recommended strategic interventions against impact and ease of implementation. This provided clear insight into 'no/low regret' actions and 'moonshots'

Intervention Model (Volume Impact Assessment, Economic Assessment, Scenario Analysis)

NOTE: Further details on the scope of this study can be found in Appendix B.

2.2 Key Elements Guiding the Volume Impact Assessment

In this study, the highest impact interventions are those that can address the highest volumes of plastics. The volume impact assessment is a comprehensive analysis that forecasts the amount of plastic waste that can be addressed by each intervention, year on year. A suite of 14 interventions (Appendix B) were identified and assessed from two perspectives:

- What is the maximum addressable volume an intervention can tackle?
- How quickly can an intervention have an impact on mismanaged plastics and reduce the plastics circularity gap?

The volume impact assessment examined each intervention individually for the six polymers and three regions of interest under three different scenarios of the future. Each intervention has its own unique potential to address plastics volumes. Some interventions are limited to consumer packaged goods (CPG), while other interventions can address all single use plastics but exclude plastics used for food and healthcare applications. By looking at analogous examples of how each intervention has been able to historically create impact (i.e. what is the timeline required to see impact from policies considering time required to draft, propose, announce, and implement?), the volume impact assessment determined the full potential of each intervention.

Although the volume impact assessment can indicate the full potential of each intervention and the timeline required, these interventions need to be holistically reviewed from a systems perspective, including examining what other elements are required to ensure success of an intervention. In this study, the systems review included an economic assessment and scenario analysis (further details can be found in Sections 2.3 and 2.4).

2.3 Key Elements Guiding the Economic Assessment

By definition, a circular economy is an economic system that keeps resources in use for as long as possible, extracting the maximum value from the resource while in use, and maintaining/increasing the value of the resource with each additional use. This means that success for the circular economy is guided by the question—can circular supply chains generate the function or utility of the virgin plastic at a cost that is equal to or lower than the virgin supply chain? Or, in other words, would stakeholders default to the circular supply chain because it provides the same/similar function at a similar/lower cost? This guiding question framed the economic assessment and led to the development of the following:

Baseline supply cost curve: Using 2019 as the baseline to establish the cash cost of producing the six polymers and three regions of interest for the virgin and circular production pathways (see Figure 6 for the 2019 cost curve for virgin plastics).

Projected supply cost curves: Using 2020-2040 for future projections to understand the cash cost of producing the six polymers and three regions of interest through the virgin and circular production pathways. This was evaluated under three different scenarios (see Figures 38, 39, and 40 in Appendix C for the 2040 cost curve for virgin plastics).

Stack ranking interventions by cost of production: Leveraging the difference in the cash cost of production between virgin and circular polymers to identify which interventions would be more economically desirable to pursue. Interventions that allow for plastics demand reduction represented a cost savings (i.e. there is no need to produce the virgin plastics). Interventions that leverage the recycling system examined the cost differential between producing virgin plastics and circular plastics. These cost differentials changed year-on-year between 2020-2040 and were assessed for the six polymers and three regions of interest under three different scenarios.

Investments required: Determining the investments required to support the high impact interventions (defined by plastic volumes addressed).

This cash cost of production model is useful because high impact interventions have historically been defined exclusively by plastic volumes addressed without any consideration for the cost of plastic production. To create irreversible momentum toward plastic circularity, the cost of plastic production for a circular economy must be compared to those of the linear economy. Sustained progress for the circular economy requires recycled plastics to be produced at a cost that is equal to or lower than virgin plastics, allowing stakeholders to default to the circular option.

A limitation to the cash cost of production model is the potential for interventions to be incorrectly perceived as economic. When circular supply chains produce plastic at a lower cost than virgin supply chains, an intervention can be incorrectly perceived as being de-risked and that it requires no supporting investment. Therefore, the economic assessment was paired with insights on the investments required, creating a more holistic view of the economics of circular supply chains. Additionally, we examined the level of supporting infrastructure and investment in technology needed to support circular supply chains. This investment had two components – the first is the required capital expenses (CapEx) to support the intervention (e.g., building mechanical recycling facilities), and the second is the required CapEx to support the system (e.g., building the upstream collection and sortation system, including transfer stations and material recovery facilities).

2.4 Key Elements Guiding the Scenario Analysis

The future is unpredictable which is why future scenarios are a powerful tool in strategy development. Often, planning is done with the unspoken assumption that the future will resemble the past and that change will occur only gradually. However, scenarios are particularly useful in developing strategies and tactics to navigate the kind of extreme events (e.g., global pandemics and extreme weather) that are increasingly having dramatic impacts on the world economy. By demonstrating how and why the future could be different than the past, scenarios help individuals and teams prepare for the range of possibilities the future may hold.

The future of plastics consumption, production and circularity will look different than the past and scenario analysis is a key component to the methodology of this study. The study is based on three scenarios of the future.[34] In each scenario, global mega-trends reshape the volumes and production costs associated with plastic.

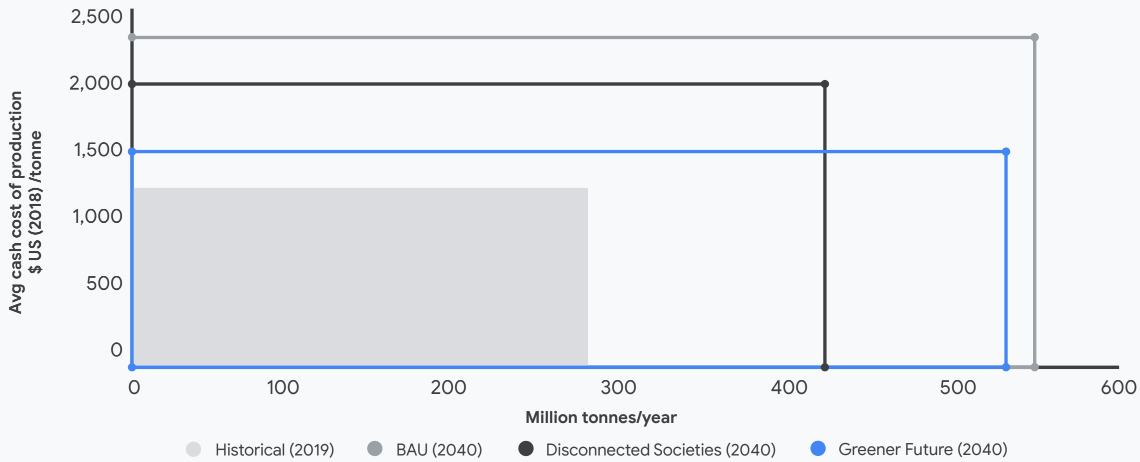
As shown in Figure 15, both the plastics circularity gap and the average cost of production for virgin plastics differ across scenarios.

The Business as Usual (BAU) scenario is a future with the largest plastics circularity gap (548 million metric tonnes in 2040[35]) and the highest average cost of virgin plastics production ($2,293/metric tonne in 2040). In this base case:

- The world endures a difficult and uncertain recovery from the COVID-19 crisis.
- Management of health restrictions and economic revival move at different speeds in different countries, with limited and localized economic impacts from COVID-19 throughout 2021.
- Progress in plastics recycling partially moderates oil demand growth in the petrochemical sector, but does not stop it. Moderate but ongoing economic growth continues to increase demand for plastics.
- After a brief "pause", environmental and climate policies and actions regain momentum in driving change in the global energy mix.
- There is mild improvement in global cooperation associated with actions taken during the global health and economic recovery; however, nationalist policies and underlying mistrust remain.

Figure 15

Plastics Circularity Gap and Average Cost of Production Across Scenarios



NOTE: Plastics circularity gap shown if no additional interventions beyond activities encompassed in the projected scenarios are taken. The average cost of production represents virgin plastics production only.

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

This study also examined other possible futures through two additional scenarios.

The Greener Future Scenario

A combination of strong policy with behavioral and attitudinal changes drives fundamental shifts. A reset in public support for climate change action drives several issues and accelerates efforts to foster a circular economy with more recycling and less single-use plastics. By 2030, 25% of petrochemical products are made from recycled material up from 8% in 2019. Higher taxes on refined products and carbon prices offset low crude oil prices and provide another constraint on oil demand. While the average cost to produce virgin plastics is lower than BAU ($1,493/metric tonne), the plastics circularity gap sees only a modest shift from BAU as global trade and stability support a robust investment environment.

The Disconnected Societies Scenario

Mismanagement of the COVID-19 crisis causes an extended period of disease outbreaks and recurring social lockdowns. Market confidence and the economic recovery are damaged and regional trade dominates resulting in complex systems of bilateral agreements that lack transparency, and strengthen global divides. As a result, political and economic fragmentation of the international community worsens, leading to a chaotic and weak investment environment. As such, the need for plastics is reduced since packaging and products are not in demand compared to the other scenarios, leading to a smaller plastics circularity gap compared to the BAU and the Greener Future scenarios.

The average cost of production for virgin plastics hovers between BAU and the Greener Future scenarios ($1,972/metric tonne) representing local market dynamics where many possible production efficiencies are not realized.

While scenarios are not predictive, the volume impact assessment and cash cost of production analysis was conducted across the three scenarios noted above.

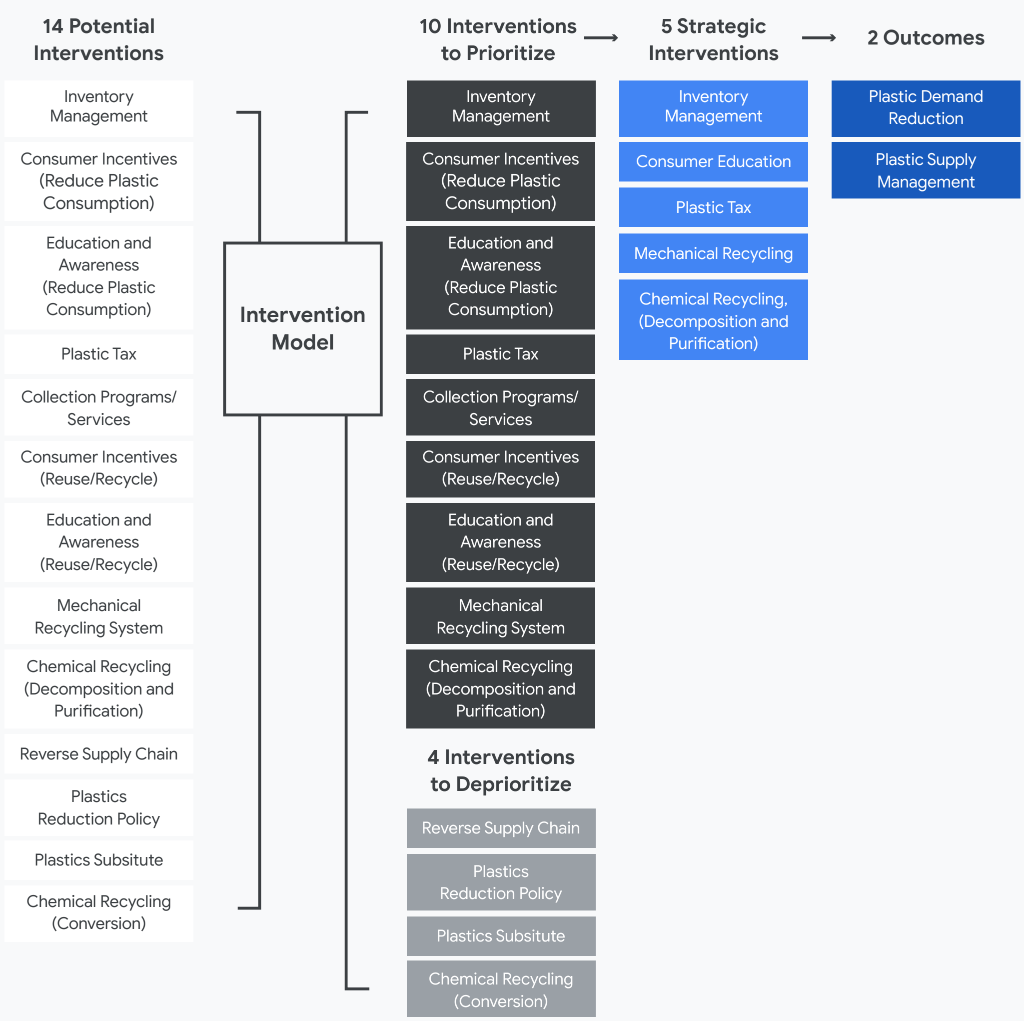
Along with acknowledging growing global uncertainty, this analysis allows stakeholders to plan for multiple possible futures and determine if there are certain strategic interventions that represent low-regret and no-regret early actions across multiple versions of the future.

2.5 Defining Strategic Actions from High Impact Interventions

The intervention model based on the volume impact assessment, economic analysis, and scenario analysis provided insights into the solutions to prioritize and deprioritize. The 10 prioritized interventions (Figure 16) combine to create five strategic interventions and two outcomes (the results of this analysis are in Section 3).

Figure 16

Methodology for Defining Strategic Actions from High Impact Interventions



SOURCE: AFARA analysis

Section 3
Changing the System

3.1 Key Findings (BAU)

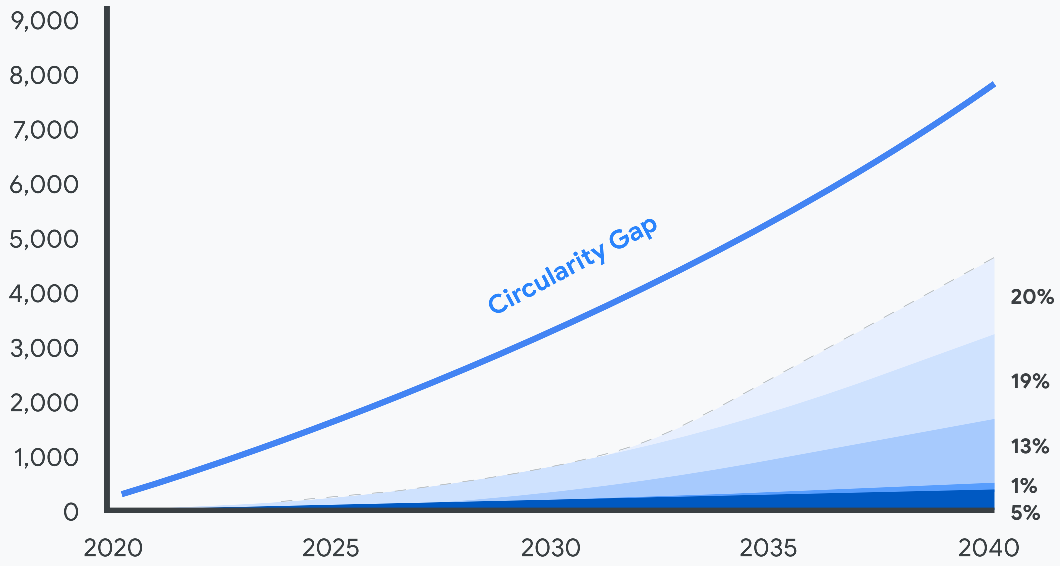
There are five strategic interventions that can be taken to disrupt the landscape today to catalyze circular supply chains for plastics and reduce the plastics circularity gap by 2040. The intervention model shows that with a set of strategic interventions, it is possible to close the plastics circularity gap by 59% under the BAU scenario, addressing a cumulative volume of 4.5 billion metric tonnes by 2040.

The intervention model result shows that chemical recycling (through decomposition and purification pathways) closes the gap by 20% while increased mechanical recycling closes the gap by 19%. Both of these interventions require consumer incentives for recycling, consumer education and awareness, and designing for recyclability to reach the full potential volume. A tax on virgin plastic production is projected to decrease plastic demand in certain packaging and products and close the plastics circularity gap by 13%. Improved inventory management through enhanced sourcing, storing, and selling of products made of plastic or packaged in plastics can close the gap by 5%. Lastly, consumer education and incentives that target plastic reduction in consumption provide 1%.

Figure 17

Global Mismanaged Plastics and Addressable Volumes by Strategic Intervention Under Business as Usual

UNIT: million metric tonnes



20% Chemical Recycling (Decomposition and Purification)
Collection Program/Services
Consumer Incentives (Reuse/Recycle)
Education and Awareness (Reuse/Recycle)
Design for Recyclability

19% Mechanical Recycling System
Collection Programs/Services
Consumer Incentives (Reuse/Recycle)
Education and Awareness (Reuse/Recycle)Design for Recyclability

13% Plastic Tax

1% Consumer Incentives (Reduce Plastic Consumption)
Education and Awareness (Reduce Plastic Consumption)

5% Inventory Management

NOTE: Volumes addressed are presented on a cumulative basis. Volumes addressed individually each year do not exceed the volume of mismanaged plastics in any given year

NOTE: Analysis based on 6 polymers and 3 regions of interest. Visual for Business as Usual scenario only

SOURCE: AFARA analysis

To reach this potential, there are **three key findings** to unpack and assess:

Finding #1 - Infrastructure is Critical
Infrastructure is the key to unlocking tremendous circularity. Underinvestment and under deployment in infrastructure will act as a showstopper on managing plastic volumes. Data and technology will serve as lubricants to accelerate progress.

Finding #2 - Opportunities abound with PE/PP/PET in Asia
There are opportunities to pursue all plastics in all regions of the world. However, PP/PET/PE in Asia represent the largest opportunity.

Finding #3 - A Portfolio Approach is Needed
It is essential to advance multiple solutions in parallel because the solutions that reduce the plastics circularity gap in 2025 will not be the same ones that reduce the gap in 2040. In the short term (2025), improving the mechanical recycling system needs to be the priority. In the long term (2040), chemical recycling will be critical to creating circular supply chains for the remaining mismanaged volumes.

Key findings for Alternative Scenarios

These three key findings are consistent under all three scenarios despite the differences in percentages and volumes of plastics addressed under each scenario.

Under the Greener Future scenario, the plastics circularity gap can be closed by 62%, addressing a cumulative volume of 4.4 billion metric tonnes by 2040. Under the Disconnected Societies scenario, the plastics circularity gap can be closed by 54%, addressing a cumulative volume of 3.7 billion metric tonnes by 2040. Further details by strategic intervention for alternative scenarios can be found in Appendix C.

3.2 Finding #1

Infrastructure is the key to unlocking tremendous circularity for plastics.

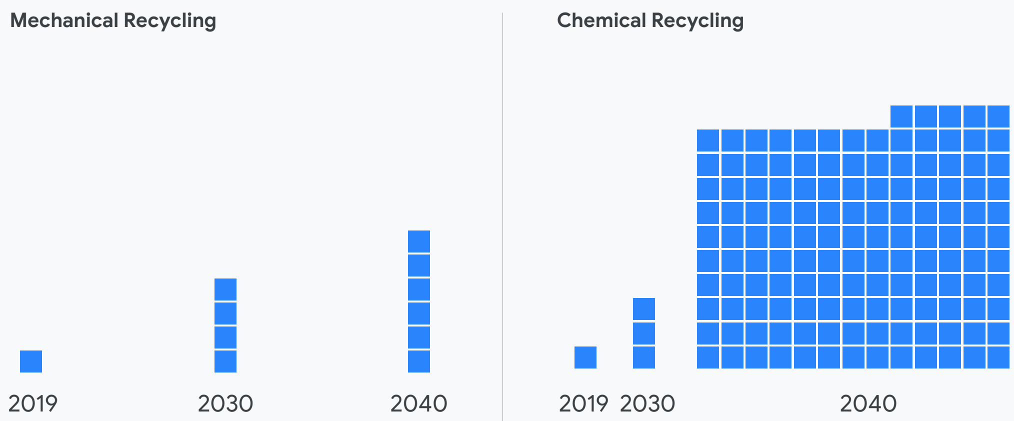
The results of the intervention model are only possible if there is supporting infrastructure to process plastic feedstocks (i.e. bales of sorted, cleaned plastics) and produce recycled resins. To achieve the modeled volumes under BAU, the mechanical recycling system will need to expand its existing capacity 4 times by 2030 and 6 times by 2040. This needs to be complemented by an expansion of the chemical recycling system which require 3 times the existing capacity in 2030 and a dramatic increase of 135 times the existing capacity in 2040 (see Figure 18).[36,37]

The analysis is based on both the mechanical recycling and the chemical recycling systems expanding simultaneously. While chemical recycling has the potential to address the same plastic waste volumes as mechanical recycling (and more), critical enablers are not in place today to tackle plastics waste in the short term. As discussed in Section 3.4, chemical recycling does not address volumes in the short term since technologies are in development and beginning to pilot. Therefore, mechanical recycling needs to be the priority to minimize the plastics circularity gap in the short term. Even when chemical recycling technologies and infrastructure are fully established, it is unlikely that mechanical recycling infrastructure will become obsolete and unnecessary. The volume of plastic is so high that these two systems can work together to minimize the plastics circularity gap. Scaling both mechanical recycling and chemical recycling are complementary solutions.

The expansion of both mechanical and chemical recycling systems is not limited to the infrastructure and equipment required for the recycling process; rather, it requires an expansion across the entire system. This includes increasing equivalent capacity for the upstream collection and sortation of plastics.

Figure 18

Capacity Expansion Requirements for Mechanical and Chemical Recycling Systems (BAU)



Current Capacity: 21 Million Metric tonnes/year
Capacity Required by 2030: 4x
Capacity Required by 2040: 6x

Current Capacity: 1.4 Million Metric tonnes/year*
Capacity Required by 2030: 3x
Capacity Required by 2040: 135x

*1.4 million metric tonne/year represents all types of chemical recycling (i.e. conversion + decomposition + purification)

NOTE: Analysis based on 6 polymers and 3 regions of interest. Visual for Business as Usual scenario only

SOURCE: AFARA analysis

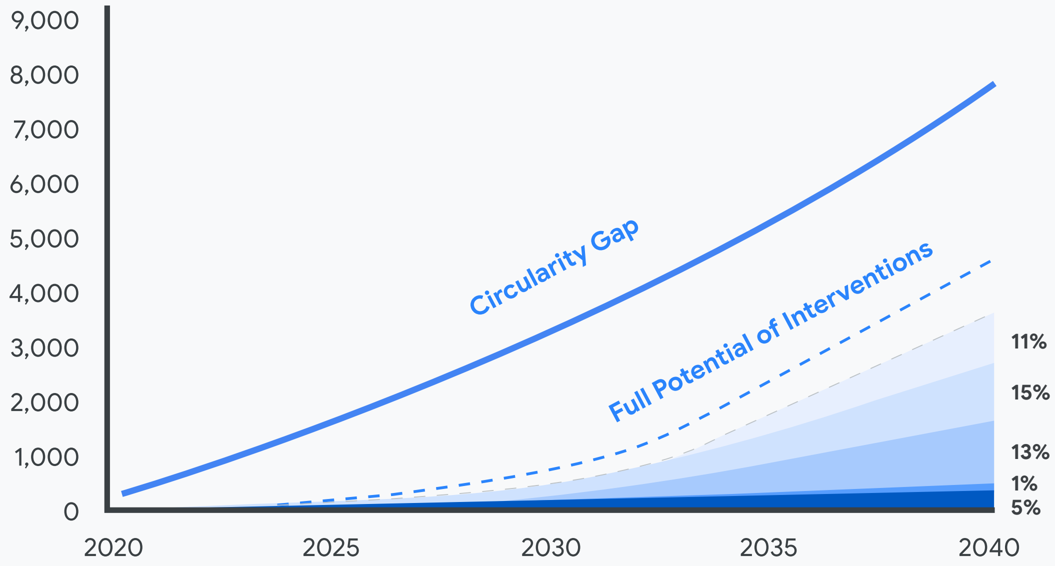
Impact of Infrastructure on the Plastics Circularity Gap

While infrastructure is capital intensive and takes years to build, it is critical to the success of the mechanical and chemical recycling solutions. Building out half the infrastructure required will reduce the ability to bring plastics back into the supply chain from 59% to 45%. Building out a quarter of the infrastructure required will further reduce the ability to bring plastics back into the supply chain from 59% to 35% (see Figures 19 and 20).

Figure 19

Global Mismanaged Plastics and Addressable Volumes by Strategic Interventions under Business as Usual with Capacity Expansion Requirements Reduced to ½

UNIT: million metric tonnes



11% Chemical Recycling (Decomposition and Purification)
Collection Program/Services
Consumer Incentives (Reuse/Recycle)
Education and Awareness (Reuse/Recycle)
Design for Recyclability

15% Mechanical Recycling System
Collection Programs/Services
Consumer Incentives (Reuse/Recycle)
Education and Awareness (Reuse/Recycle)Design for Recyclability

13% Plastic Tax

1% Consumer Incentives (Reduce Plastic Consumption)
Education and Awareness (Reduce Plastic Consumption)

5% Inventory Management

NOTE: Volumes addressed are presented on a cumulative basis. Volumes addressed individually each year do not exceed the volume of mismanaged plastics in any given year

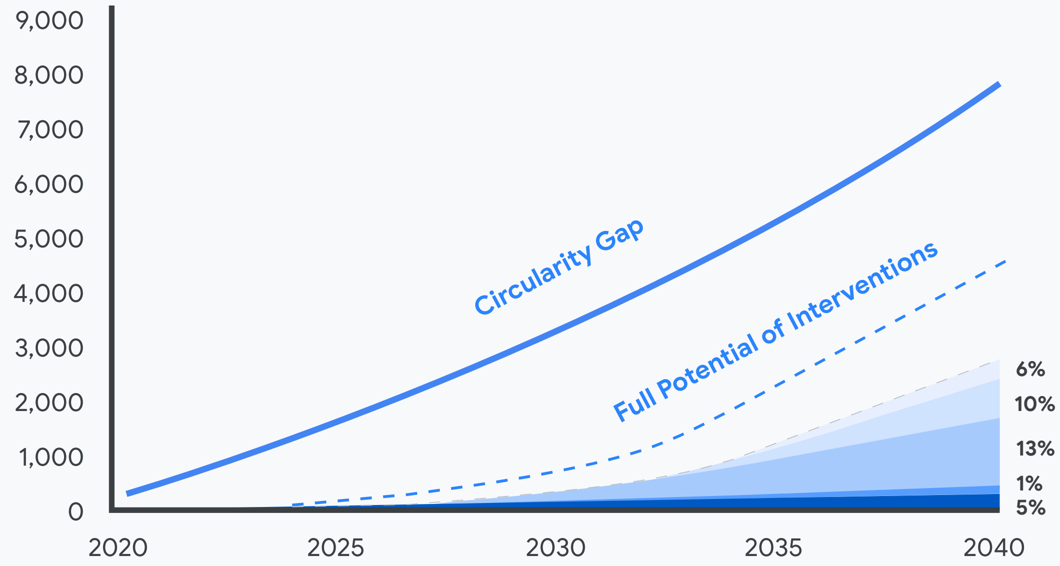
NOTE: Analysis based on 6 polymers and 3 regions of interest. Visual for Business as Usual scenario only

SOURCE: AFARA analysis

Figure 20

Global Mismanaged Plastics and Addressable Volumes by Strategic Interventions under Business as Usual with Capacity Expansion Requirements Reduced to ¼

UNIT: million metric tonnes



6% Chemical Recycling (Decomposition and Purification)
Collection Program/Services
Consumer Incentives (Reuse/Recycle)
Education and Awareness (Reuse/Recycle)
Design for Recyclability

10% Mechanical Recycling System
Collection Programs/Services
Consumer Incentives (Reuse/Recycle)
Education and Awareness (Reuse/Recycle)Design for Recyclability

13% Plastic Tax

1% Consumer Incentives (Reduce Plastic Consumption)
Education and Awareness (Reduce Plastic Consumption)

5% Inventory Management

NOTE: Volumes addressed are presented on a cumulative basis. Volumes addressed individually each year do not exceed the volume of mismanaged plastics in any given year

NOTE: Analysis based on 6 polymers and 3 regions of interest. Visual for Business as Usual scenario only

SOURCE: AFARA analysis

Finding #1 for Alternative Scenarios

Capacity expansion through infrastructure remains critical under all scenarios. Table 3 shows the difference in capacity expansion requirements for Greener Future and Disconnected Societies scenario compared to BAU. Required capacities are reduced for both alternative scenarios.

In a Greener Future scenario, capacities required for the strategic interventions are reduced since the total demand for plastics is expected to decrease while production of recycled content is expected to increase compared to BAU.[38] Under the Disconnected Societies scenario, capacities required for the strategic interventions are reduced since total demand for plastics is expected to decrease compared to BAU. Table 4 and Table 5 show how reducing infrastructure expansion will subsequently reduce the ability to reduce the plastics circularity gap. Across all three scenarios, building out a quarter of the infrastructure required means a lost opportunity to address an additional ~1.7 billion metric tonnes of plastics.

Table 3

Capacity Expansion Requirements for Mechanical and Chemical Recycling Systems by 2040 for All Scenarios

Scenario	Mechanical Recycling	Chemical Recycling
BAU	6x	135x
Greener Future	6x	127x
Disconnected Societies	5x	105x

NOTE: Capacity expansion requirements assumes both mechanical recycling and chemical recycling expand simultaneously

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

Table 4

Plastics Circularity Gap Addressed by Percentage by 2040 and Required Infrastructure Expansion Under All Scenarios

UNIT: percentage of Plastics Circularity Gap addressed

Scenario	All Required Infrastructure	½ of Required Infrastructure	¼ of Required Infrastructure
BAU	59%	45%	35%
Greener Future	62%	47%	36%
Disconnected Societies	54%	41%	31%

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

Table 5

Plastics Circularity Gap Addressed by Volume by 2040 and Required Infrastructure Expansion Under All Scenarios

UNIT: million metric tonnes

Scenario	All Required Infrastructure	½ of Required Infrastructure	¼ of Required Infrastructure
BAU	4,536	3,463	2,675
Greener Future	4,421	3,378	2,611
Disconnected Societies	3,679	2,781	2,096

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

3.3 Finding #2

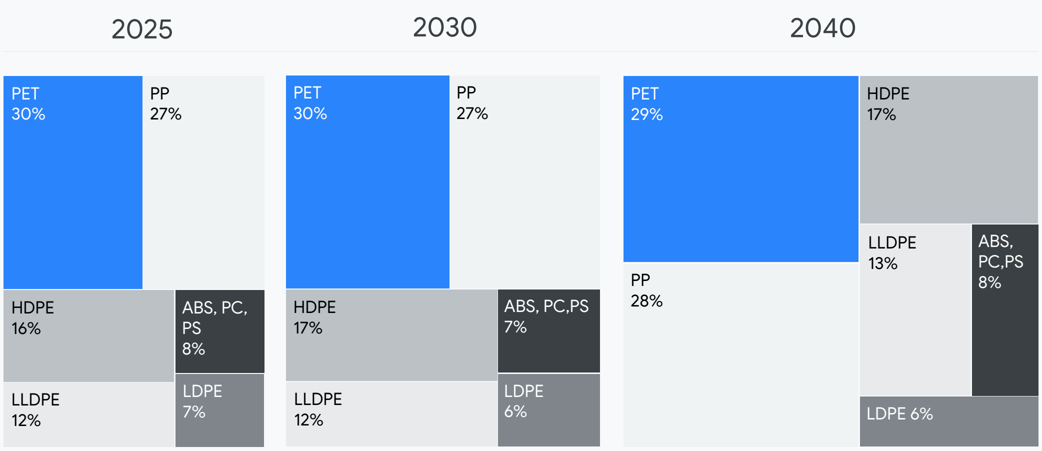
There are opportunities to pursue all plastics and in all regions of the world. However, PE/PP/PET and Asia represent the largest opportunity (BAU).

While there is an opportunity to pursue all plastics in all regions of the world, targeting the plastics and regions with the highest total demand represent the largest opportunities.[39] PET and PP make up ~60% of the polymers of interest in this study, followed by HDPE and LLDPE which make up an additional ~25% (Figure 21). Asia's demand makes up almost 80% of the plastic volumes in this study (Figure 22). These volumes represent global plastics demand on an annual basis.

Figure 21

Global Plastics Demand by Polymer (BAU)

UNIT: Percent of annual plastic volumes



NOTE: Global plastics demand presented on an annual basis. Under BAU, the total plastics demand is 345 million metric tonnes in 2025, 417 million metric tonnes in 2030, and 548 million metric tonnes in 2040.

NOTE: Analysis based on 6 polymers and 3 regions of interest. Visual for Business as Usual scenario only

SOURCE: IHS Markit[13], AFARA analysis

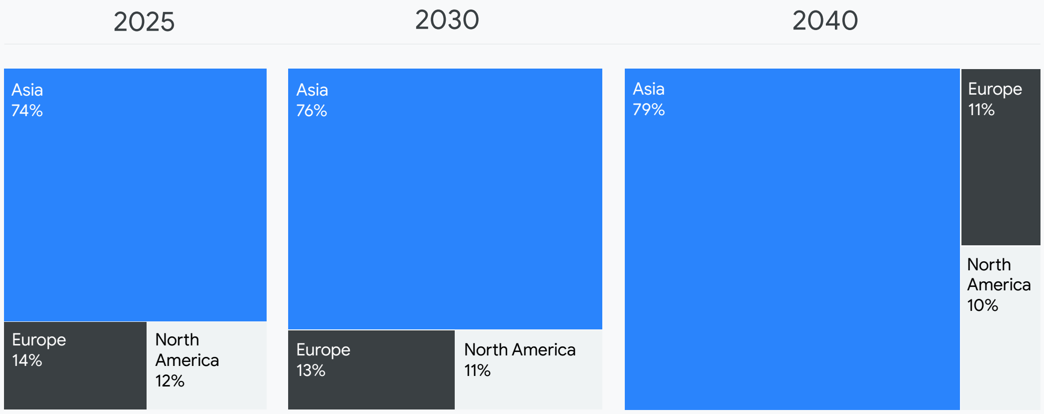
Finding #2 for Alternative Scenarios

PE/PP/PET and Asia represent the largest opportunity across all three scenarios. Table 6 compares the split of plastics demand by polymer in 2040. The split of plastics demand by region for alternative scenarios remains the same as BAU, 79% for Asia, 11% for Europe, and 10% for Asia. It is important to note that while the percentage splits are similar, the total volume of plastics demand differ across scenarios (see Tables 7 and 8).

Figure 22

Global Plastics Demand by Region (BAU)

UNIT: Percent of annual plastic volumes



NOTE: Global plastics demand presented on an annual basis. Under BAU, the total plastics demand is 345 million metric tonnes in 2025, 417 million metric tonnes in 2030, and 548 million metric tonnes in 2040.

NOTE: Analysis based on 6 polymers and 3 regions of interest. Visual for Business as Usual scenario only

SOURCE: IHS Markit[13] AFARA analysis

Table 6

Split of Plastics Demand by Polymer for All Scenarios (2040)

Scenario	PET	PP	HDPE	LLDPE	LDPE	ABS	PS	PC
BAU	29%	28%	17%	13%	6%	4%	2%	1%
Greener Future	26%	29%	17%	13%	6%	5%	2%	2%
Disconnected Societies	29%	27%	16%	13%	7%	4%	3%	2%

NOTE: While the percentage splits are similar across scenarios, the total volume of plastics demand differ across scenarios. In 2040, the total plastics demand is 548 million metric tonnes for BAU, 530 million metric tonnes for Greener Future, 427 million metric tonnes for Disconnected Societies.

NOTE: Listed from largest to smallest percentage split under BAU. Values may not add up to 100% due to rounding.

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit[13] AFARA analysis

Table 7

Split of Plastics Demand by Polymer for All Scenarios (2040)

UNIT: million metric tonnes

Scenario	PET	PP	HDPE	LLDPE	LDPE	ABS	PS	PC
BAU	157	154	94	69	33	21	13	8
Greener Future	140	153	92	67	32	25	11	10
Disconnected Societies	124	117	69	54	28	17	12	7

NOTE: In 2040, total plastics demand is 548 million metric tonnes for BAU, 530 million metric tonnes for Greener Future, 427 million metric tonnes for Disconnected Societies. Values may not add up to total plastics demand due to rounding.

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit,[13] AFARA analysis

Table 8

Split of Plastics Demand by Region for All Scenarios (2040)

UNIT: million metric tonnes

Scenario	Asia	Europe	North America
BAU	435	58	55
Greener Future	419	57	54
Disconnected Societies	337	46	44

NOTE: In 2040, total plastics demand is 548 million metric tonnes for BAU, 530 million metric tonnes for Greener Future, 427 million metric tonnes for Disconnected Societies. Values may not add up to total plastics demand due to rounding.

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit,[13] AFARA analysis

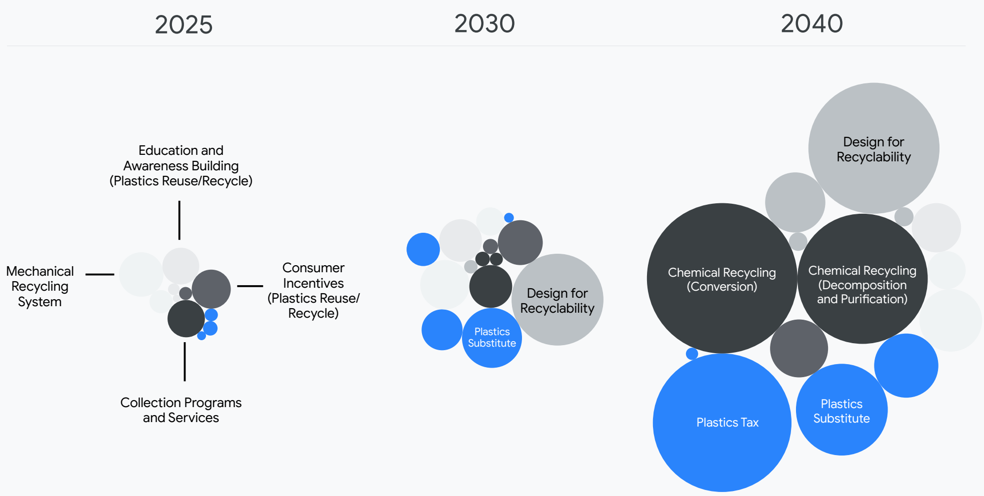
3.4 Finding #3

The solutions that reduce the plastics circularity gap in 2025 will not be the same ones that reduce the gap in 2040 (BAU). A portfolio approach is needed.

To effectively address the plastics circularity gap, interventions need to be prioritized based on their potential to impact volumes. Figure 23 shows the suite of 14 potential interventions evaluated in this study and each one's ability to impact volumes over the next 20 years. Each "bubble" represents addressable volumes given independent deployment of the interventions; therefore, the addressable volumes in each bubble are relative and not additive. The figure shows the interventions that impact volumes and reduce the plastics circularity gap in 2025 will not be the same solutions that impact volumes and reduce the gap in 2040. This is because interventions differ in maturity and readiness to deploy.

Figure 23

Interventions to Address the Plastics Circularity Gap under Business as Usual



NOTE: Size of the bubble represents the relative addressable volumes by intervention individually

NOTE: Analysis based on 6 polymers and 3 regions of interest. Visual for Business as Usual scenario only

SOURCE: AFARA analysis

A intervention's readiness to deploy is contingent on one, or more, of these critical enablers:

Technology maturity
Ensuring technical feasibility and scalability by completing research, development, prototyping, and pilot testing. This requires a deep understanding of the science and engineering, including how a technology can operate at scale.

Policy support
Ensuring policies fairly regulate new technologies/innovation and potentially provide tailwinds for adoption and expansion. Existing policies and subsidies can be unfavorable towards new technologies/innovation. For example, the United States has committed over $204 billion USD towards petrochemical facilities between 2010-2019 which can be a disincentive relative to the circular economy for plastics.[40]

Infrastructure capacity
Ensuring all upstream and downstream infrastructure is built and ready to operate. All supporting infrastructure needs to have sufficient capacity which requires a deep understanding of the throughput of plastic volumes and operational efficiency. This knowledge is critical to optimize material flow between stakeholders (e.g., collectors, sorters, recyclers).

Today, short-term and long-term interventions differ because some critical enablers are missing. Many of the necessary technologies, such as chemical recycling focused on decomposition, exist but are not mature enough to achieve scale. Policies have not been updated to include new recycling technologies, and there is insufficient capacity in today's material recovery and recycling infrastructure. Recognizing the current limitations due to missing critical enablers, the volume impact assessment reveals 10 different interventions are necessary to pursue between now and 2040.

In the short term (2025), the seven intervention areas that will impact volumes and reduce the Plastics Circularity Gap are (Table 9):

1. Collection Programs and Services
2. Consumer Incentives (Recycle/Reuse)
3. Consumer Incentives (Reduction)
4. Education and Awareness (Recycle/Reuse)
5. Education and Awareness (Reduction)
6. Inventory Management
7. Mechanical Recycling

The short-term priority is to improve and expand plastic waste management with the existing enablers that are in place. This includes leveraging the existing mechanical recycling system and making improvements to the upstream collection and sortation operations. Additionally, education and awareness building are required to ensure post-consumer plastics are collected and not leaking out of the system.

In parallel, it is critical to start working on interventions that will reduce the plastics circularity gap in the medium and long term. While these interventions don't impact volumes and create tangible impact until 2030 or 2040, it will take time to develop and scale them up.

The interventions that will impact volumes and contribute to reducing the plastics circularity gap in the medium (2030) and long term (2040) include designing for recyclability, chemical recycling (decomposition and purification), and a tax on the production of virgin plastics (Tables 10 and 11). By 2030, designing for recyclability should be the norm for new products and packaging. By 2040, critical enablers need to be in place to optimize plastics waste management. This includes the adoption of chemical recycling technologies and applying a tax on virgin plastics to encourage use and development of circular supply chains.

Table 9

Top Interventions Reducing the Plastics Circularity Gap in 2025

Interventions	Key Outcomes	Examples
Collection Programs/Services	• Increase accessibility and convenience of collection by providing consumers with new programs/services to increase collection rates	• Adding public bins/receptacles • Emptying bins in a timely manner • Offering pickup of recycling in residential and commercial areas
Consumer Incentives (Plastic Reuse/ Recycle)	• Provide consumers with incentives or disincentives, including monetary/loyalty/ social rewards to shift toward reuse and correct recycling	• Providing a discount when consumers bring their own cup/bag
Consumer Incentives (Reduce Plastic Consumption)	• Provide consumers with incentives/ disincentives, including monetary/loyalty/ social rewards, to encourage a shift in plastic consumption behavior such as eliminating virgin plastics or reducing plastic use	• Setting a fee on plastic bags
Education and Awareness (Plastic Reuse/ Recycle)	• Provide consumers with knowledge to improve plastic management through reuse and recycling correctly • Empower consumers to promote proper plastic management among others	• Sharing positive sustainable impacts • Launching local education and awareness campaigns
Education and Awareness (Reduce Plastic Consumption)	• Provide consumers with knowledge to change plastic consumption behavior by eliminating virgin plastics or reducing plastic use • Empower consumers to promote a change in plastic consumption behavior	• Increasing participation in consumer-led movements
Inventory Management	• Eliminate pre-consumer plastic waste, such as product destructions due to quality issues, product losses during transportation, unsold products due to excess inventory, unsold products due to shelf life expiration, etc.	• Optimizing delivery cycles based on consumer shopping habits
Mechanical Recycling System	• Increase the capacity and quality of the collection network to manage a higher throughput of plastic volumes. • Improve the sortation system to increase the quality and purity of raw materials for recycling (i.e. clean and homogeneous bales)	• Retrofitting/building material recovery facilities (MRFs) and transfer stations • Optimizing optical sensors • Integrating artificial intelligence/ machine learning to recognize waste streams and patterns

NOTE: Interventions listed alphabetically

SOURCE: AFARA analysis

Table 10

Top Interventions Reducing the Plastics Circularity Gap in 2030

Interventions	Key Outcomes	Examples
Design for Recyclability	• Redesign products and packaging to minimize use of plastics • Reduce complexity and barriers to recycling • Design for fit with regional recycling infrastructure (both existing and planned expansions)	• Minimize the number of polymers used in a single package or product • Minimize the amount of inks used • Eliminate small/loose materials (i.e. caps, labels) • Leverage novel additives that improve recyclability

SOURCE: AFARA analysis

Table 11

Top Interventions Reducing the Plastics Circularity Gap in 2040

Interventions	Key Outcomes	Examples
Chemical Recycling (Decomposition and Purification)	• Expand the collection system with a network of infrastructure to increase capacity for managing throughput of plastic volumes • Increase purity of raw materials for recycling (i.e. clean and homogenous bales) by improving the sortation system • Improve and develop polymer-to-polymer recycling technologies • Reduce barrier to entry for chemical recycling by developing clear regulations	• Developing new polyethylene to ethylene monomer technologies • Standardizing the definition of recycled content to include plastics derived from chemically recycled feedstocks
Plastics Tax	• Encourage industry to minimize the use of virgin plastics through pricing signals	• Setting a tax on all virgin plastic production

NOTE: Interventions listed alphabetically

SOURCE: AFARA analysis

Finding #3 for Alternative Scenarios

The top 10 interventions that reduce the plastics circularity gap in 2025, 2030, and 2040 for BAU are the same top interventions that will reduce the gap under the Greener Future and Disconnected Societies scenarios. While these 10 interventions are the same across all three scenarios, the volumes of plastics addressed differ with each one across each scenario.

3.5 Interventions to Prioritize

Analysis from the intervention model shows that there are 10 interventions to prioritize between 2025, 2030, and 2040. These are:

1. Chemical Recycling (Decomposition and Purification)
2. Collection Programs/Services
3. Consumer Incentives (Reuse/Recycle)
4. Consumer Incentives (Reduce Plastic Consumption)
5. Education and Awareness (Reuse/Recycle)
6. Education and Awareness (Reduce Plastic Consumption)
7. Design for Recyclability
8. Inventory Management
9. Mechanical Recycling
10. Plastic Tax

These interventions create the highest impact on plastic volumes across three different scenarios. They either displace the plastic altogether or produce plastic from a circular supply chain at a lower cost of production than the competing virgin plastic.

While all 10 interventions are crucial for reducing the plastics circularity gap, volumes addressed from a single intervention may not always be additive. Some interventions are codependent on others, while some interventions may be parasitic to others. For example, the mechanical recycling intervention is codependent on education and awareness building for consumers to learn how to reuse and recycle plastics.

3.6 Deprioritized Interventions

While there are 14 interventions that have the potential to address the plastics challenge, the analysis from the intervention model shows that there are four that can be deprioritized. These include:

1. Reverse Supply Chain
2. Plastics Reduction Policy
3. Plastics Substitution
4. Chemical Recycling System (Conversion)[41]

For the plastics reduction policy and reverse supply chain interventions, both address plastic volumes that can be tackled through other pathways and neither of the two create additionality. Instead, they create alternative mechanisms for tackling the same feedstocks. A plastics reduction policy is likely only able to address consumer packaged goods and these plastics can equally be addressed through a plastics tax on virgin production. Further, a series of reverse supply chain actions will likely require additional infrastructure for reverse logistics driven by individual brands and manufacturers. Plastics targeted through bespoke reverse supply chains can equally be addressed through mechanical or chemical recycling supply chains driven by collective action that include governments and investors.

On a cash cost of production basis, plastic substitutes are more expensive compared to virgin plastics by 2040 and few of them are viable alternatives in plastic applications. Examples of plastic substitutes include paper, glass, bioplastics, aluminum, jute, nylon, cotton, etc. All of these materials have the ability to replace the utility of plastics, but none of them are universally better in terms of environmental impact when compared to virgin plastics. Each material has a different sustainability footprint when considering carbon emissions, waste, energy use, water use, ozone depletion, toxicity, eutrophication, end of life disposal and other dimensions.

While plastics often fall short on end of life disposal (and its ability to contribute to circularity), it is better in terms of life cycle carbon emissions. In a 2018 study conducted by Denmark's Ministry of Environment and Food on grocery bags, findings showed that paper bags must be used a minimum of 43 times to have the same environmental impact as a single-use plastic bag.[42] While it is possible to dedicate time and energy to develop a new material, the intervention model shows the same volumes can be proactively addressed by designing for recyclability.

Similar to the plastics reduction policy and reverse supply chain, chemical recycling conversion technologies address plastic volumes that can be addressed by other actions. The intervention model indicates that if plastics can be proactively designed for recyclability, then a mix of mechanical recycling and chemical recycling decomposition and purification technologies can address the same plastic volumes. However, there is a risk with strictly pursuing decomposition and purification technologies since there are underlying chemistry and physics challenges and risks surrounding these technologies. It may be important to pursue chemical recycling conversion pathways as a hedge since it is the most technologically mature among chemical recycling technologies.

Table 12

Strategic Interventions for Reducing the Plastics Circularity Gap

Outcomes (2)	Strategic Interventions (5)	Interventions Included (10)
Plastic Demand Reduction	Inventory Management	• Inventory Management
	Consumer Education	• Consumer Incentives (Reduce Plastic Consumption) • Education and Awareness (Reduce Plastic Consumption)
	Plastic Tax	• Plastic Tax
Circular Plastic Supply Chains	Mechanical Recycling	• Collection Programs/Services* • Consumer Incentives (Plastics Reuse/Recycle)* • Education and Awareness (Plastics Reuse/Recycle)* • Design for Recyclability* • Mechanical Recycling System
	Chemical Recycling	• Collection Programs/Services* • Consumer Incentives (Plastics Reuse/Recycle)* • Education and Awareness (Plastics Reuse/Recycle)* • Design for Recyclability* • Chemical Recycling (Decomposition and Purification)
Deprioritized Interventions**		• Reverse Supply Chain • Plastics Reduction Policy • Plastics Substitute • Chemical Recycling System (Conversion)[41]

*These interventions are required for both mechanical and chemical recycling.

**These interventions are deprioritized because they create alternative mechanisms for tackling the same feedstocks as the strategic interventions (i.e. they do not create additionality).

Source: AFARA analysis

Section 4
Economic Impacts of Changing the System

4.1 Economic Impacts of Strategic Interventions

It is possible to create a future where plastics remain in the economy through strategic interventions, but it's critical to assess what the economics and business opportunity look like for these strategic interventions across all three scenarios. Across multiple scenarios, the strategic interventions recommended to increase the circular supply of plastic create an improved cash cost of production compared to virgin polymer production (see Figure 24).

Under BAU, the strategic interventions close the plastics circularity gap by 59% over the 2020-2040 time frame, representing 4.5 billion metric tonnes of plastics addressed. Roughly one-third of the volume (1.5 billion metric tonnes) is achieved through plastic demand reduction interventions such as inventory management, consumer education/incentives, and a plastic production tax. These interventions are deemed to be "no cost" interventions on a polymer production basis since plastics are displaced rather than replaced by polymer production through circular supply chains. The other two-thirds of the volume to close the gap (3.0 billion metric tonnes) come from interventions that produce plastics through circular supply chains. On average over the 2020-2040 timeframe, these circular supply chains create plastic polymers at $1,122/metric tonne, which is a lower cost of production compared to the virgin supply chain at $1,694/metric tonne.[43]

When expanding the analysis to all three scenarios, the plastics circularity gap can be closed 18-21% economically through demand reduction interventions and 37-42% by supplying plastics through circular supply chains. Further, the cost of producing plastics through circular supply chains is 28-34% lower compared to the cost of producing plastics through virgin supply chains when averaged across 2020-2040 in all three scenarios.

Global Cost of Polymer Production by Production Pathway

Broadly, circular production pathways show an improvement in cost while the virgin production pathway is expected to climb in cost from 2020-2040. Further granularity on the cost of polymer production for all three scenarios can be found in Figure 25.

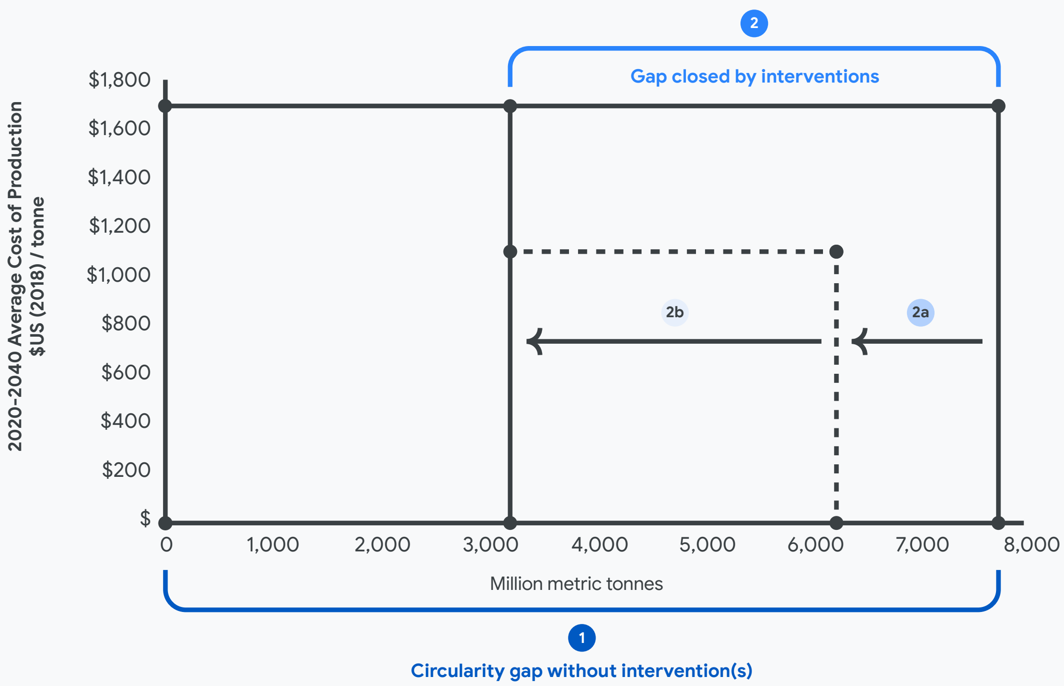
The average cost improvement for chemical recycling (conversion) under all three scenarios is 39% from $2,137/metric tonne to $1,309/metric tonne while the average cost improvement for chemical recycling (decomposition and purification) under all three scenarios is 36% from $1,580/metric tonne to $1,010/metric tonne. The cost of production from mechanical recycling is expected to be similar in both 2019 and 2040 at $1,078/metric tonne. Mechanical recycling and chemical recycling (decomposition/purification), achieve cost parity by 2040. The parity is based on scaling up capacity and expansion of infrastructure which reduces the costs of both forms of recycling.

By 2040 across the three scenarios, the virgin cost of production is expected to rise by 71%, from $1,120/metric tonne in 2019 to $1,919/metric tonne in 2040.

Figure 24

Economic Impacts of Reducing the Plastics Circularity Gap for All Scenarios

(1 out of 3)



BAU

1 — Plastics Circularity Gap without intervention: 7.7 billion metric tonnes

2a — Plastics Circularity Gap addressed by demand reduction: 1.5 billion metric tonnes

2 — Plastics Circularity Gap addressed with intervention: 4.5 billion metric tonnes (59% of total)

2b — Plastics Circularity Gap addressed by circular supply chains: 3.0 billion metric tonnes

NOTE: The x-axis represents the plastics circularity gap as projected under the future scenarios.

NOTE: This visual is in reference to Figure 15 which previously showed the projected plastics circularity gap if no additional solutions beyond activities encompassed in the projected scenarios are taken

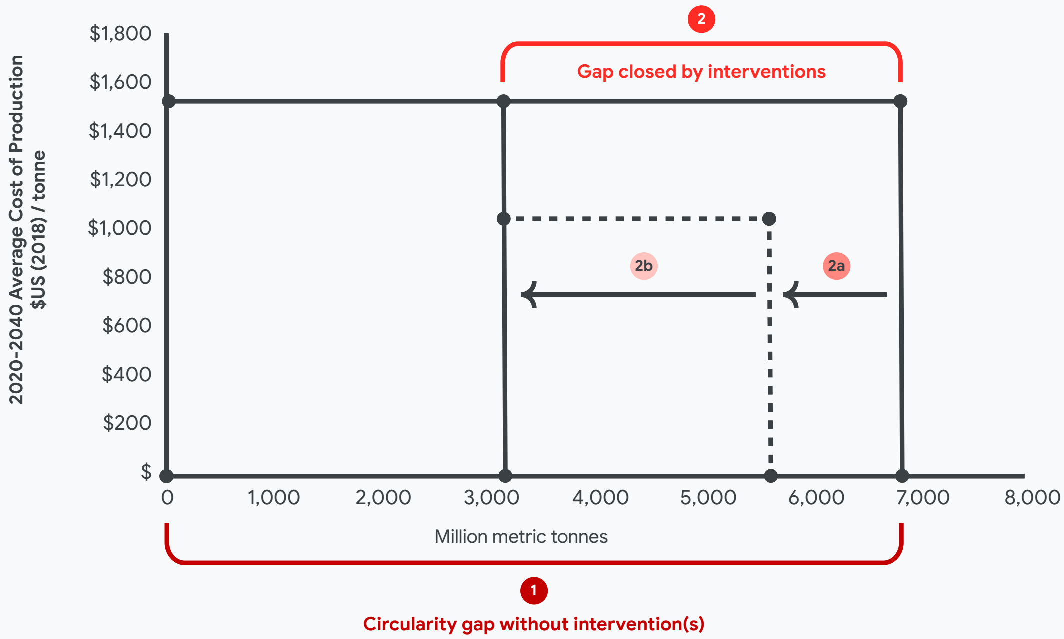
NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

Figure 24

Economic Impacts of Reducing the Plastics Circularity Gap for All Scenarios

(2 out of 3)



Disconnected Societies

1 Plastics Circularity Gap without intervention: 6.8 billion metric tonnes

2a Plastics Circularity Gap addressed by demand reduction: 1.2 billion metric tonnes

2 Plastics Circularity Gap addressed with intervention: 3.7 billion metric tonnes (54% of total)

2b Plastics Circularity Gap addressed by circular supply chains: 2.5 billion metric tonnes

NOTE: The x-axis represents the plastics circularity gap as projected under the future scenarios.

NOTE: This visual is in reference to Figure 15 which previously showed the projected plastics circularity gap if no additional solutions beyond activities encompassed in the projected scenarios are taken

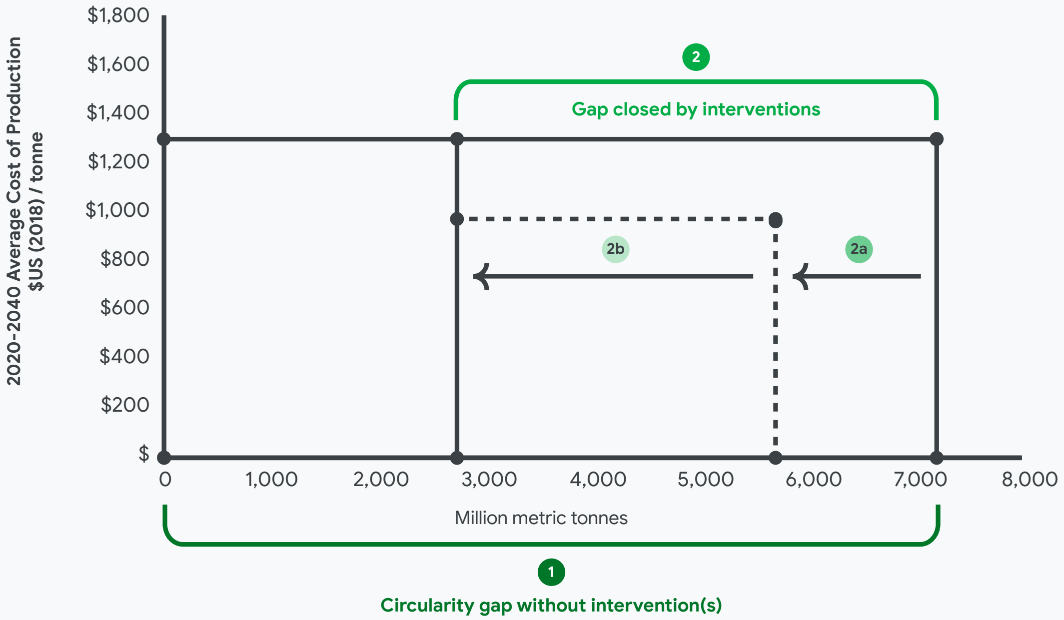
NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

Figure 24

Economic Impacts of Reducing the Plastics Circularity Gap for All Scenarios

(3 out of 3)



Greener Future

- **1** Plastics Circularity Gap without intervention: 7.2 billion metric tonnes
- **2a** Plastics Circularity Gap addressed by demand reduction: 1.5 billion metric tonnes
- **2** Plastics Circularity Gap addressed with intervention: 4.4 billion metric tonnes (62% of total)
- **2b** Plastics Circularity Gap addressed by circular supply chains: 3.0 billion metric tonnes

NOTE: The x-axis represents the plastics circularity gap as projected under the future scenarios.

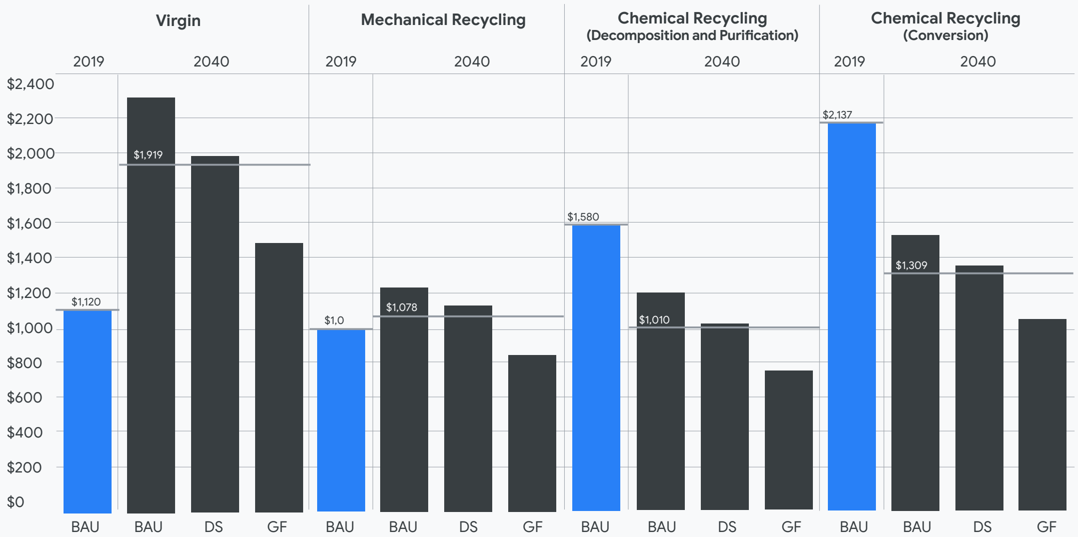
NOTE: This visual is in reference to Figure 15 which previously showed the projected plastics circularity gap if no additional solutions beyond activities encompassed in the projected scenarios are taken

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

Figure 25

Global Average Cash Cost of Virgin and Recycled Plastic Production (2019 and 2040)



NOTE: Cash cost improvements are derived from increases in facility capacity for mechanical and chemical recycling from 2020-2040. This increase in capacity is based on the volumes impact assessment.

NOTE: This visual is in reference to Figure 7 which previously showed the global average cash cost for 2019 only

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

Global Cost of Polymer Production by Region

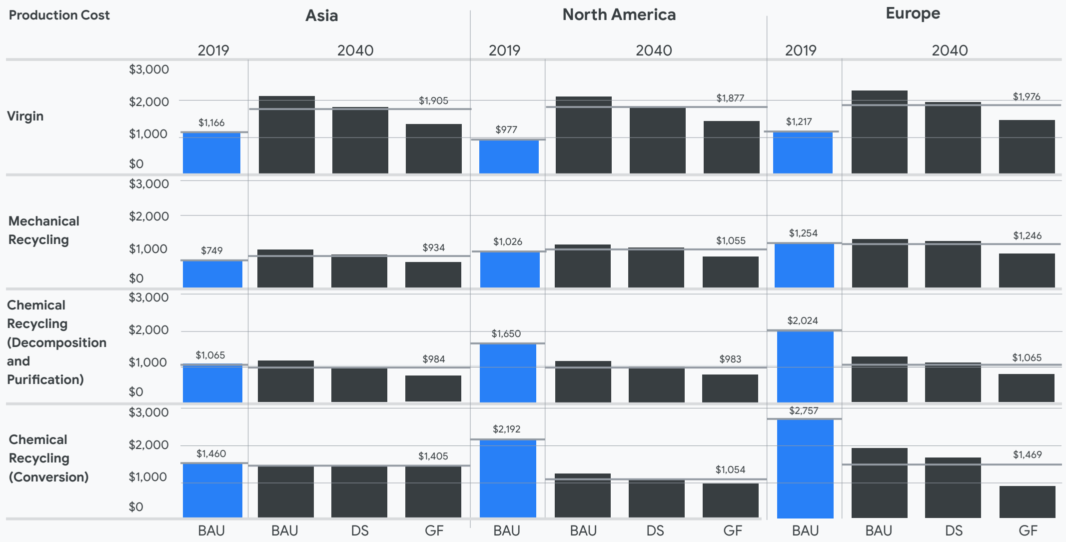
The spread for cost of production between regions is the largest for chemical recycling (conversion) ranging from an average of $1,054/metric tonne in North America to an average of $1,469/metric tonne in Europe across the three scenarios. Other production pathways including chemical recycling (decomposition and purification), mechanical recycling, and virgin plastics do not show high variance across regions in 2040. Further granularity on the cost of polymer production by production pathway and by region for all three scenarios can be found in Figure 26.

Global Cost of Polymer Production by Polymer

There are no distinct cost trends between polymers produced under the same production pathway in 2040. The biggest differentiation on cost of polymer production is based on the production pathway as previously discussed in this section. Further granularity on the cost of polymer production by production pathway and by polymer for all three scenarios can be found in Figure 27.

Figure 26

Average Cash Cost of Virgin and Recycled Plastic Production by Region (2019 and 2040)



NOTE: Cash cost improvements are derived from increases in facility capacity for mechanical and chemical recycling from 2020-2040. This increase in capacity is based on the volumes impact assessment.

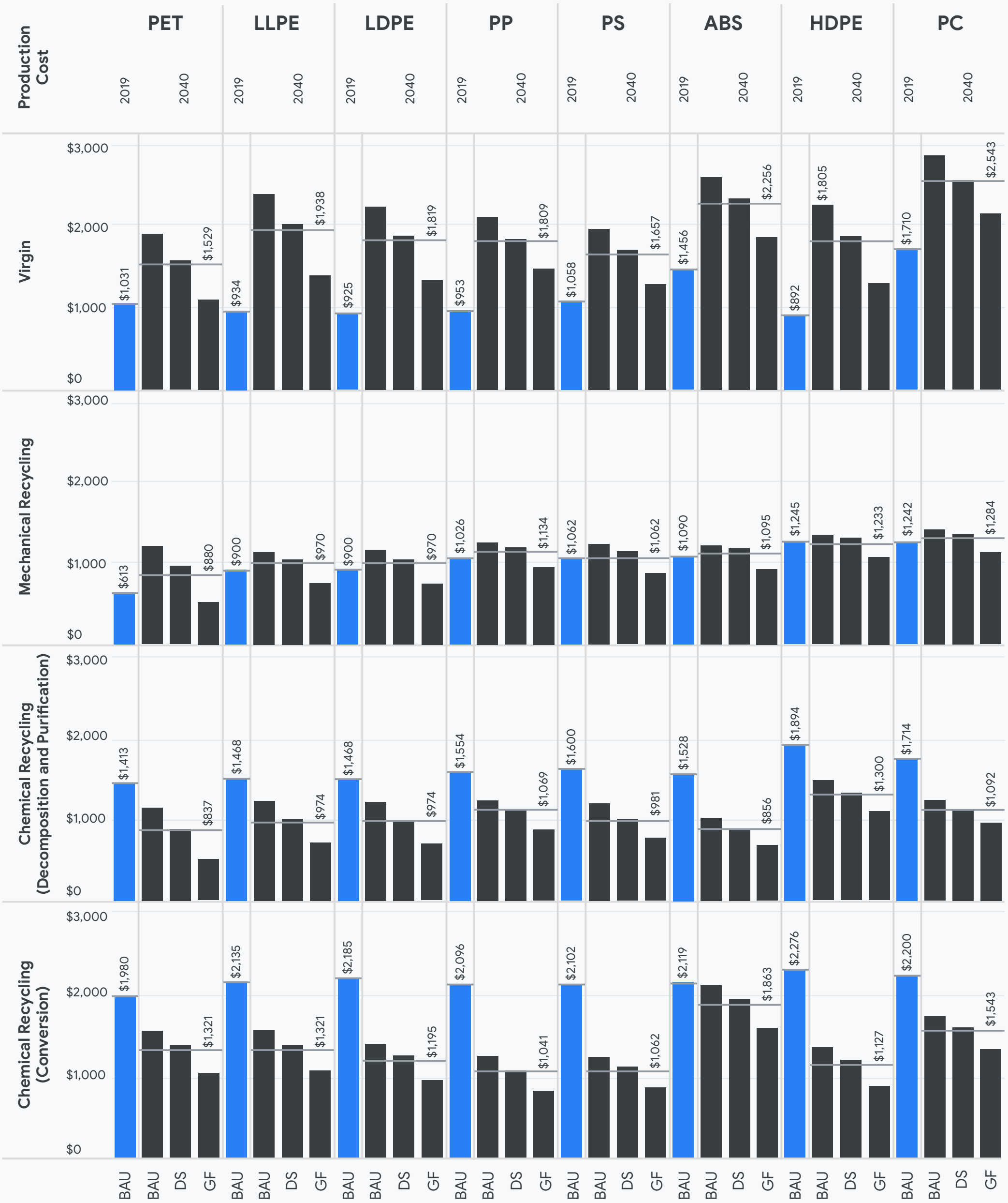
NOTE: This visual is in reference to Figure 8 which previously showed the global average cash cost for 2019 only

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

Figure 27

Global Average Cash Cost of Virgin and Recycled Plastic Production by Polymer (2019 and 2040)



NOTE: Cash cost improvements are derived from increases in facility capacity for mechanical and chemical recycling from 2020-2040. This increase in capacity is based on the volumes impact assessment.

NOTE: This visual is in reference to Figure 9 which previously showed the global average cash cost for 2019 only

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

4.2 Investments Required

Significantly reducing the plastics circularity gap is possible under different scenarios with investment. In each scenario assessed in this study, the strategic interventions both reduce the need for certain plastics and create value chains where it often costs less to create plastics through circular supply chains than through the virgin supply chains; however, a major redirection of capital investment is needed to achieve these outcomes (Table 13).

Between 2020-2040, roughly $426-544 billion USD in net present value (NPV) must be redirected from linear supply chains to circular supply chains. This range is based on discounting the value of the investment in the circular economy at a rate of 6% annually. Put another way, $634-995 billion USD of capital must be mobilized over the next 20 years to reduce the plastics circularity gap under the three scenarios (see Figure 28).

Table 13

Total Global Investment Needed by Scenario

UNIT: billion USD

Scenario	NPV* of Investment Needed
BAU	$544
Greener Future	$517
Disconnected Societies	$426

* Net present value (NPV) based on based on a 6% annual discount rate

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

To put $634-995 billion USD of investment into context, spending on transportation and water infrastructure in the United States was $441 billion in 2017, the most recent year on record according to the Congressional Budget Office.[44] Therefore, global investment required between 2020-2040 is:

- 1.4-2.3 times the value of a single year's infrastructure spent in the United States
- Similar to the GDP of Netherlands, $914 billion USD (2018 nominal)[44]
- Equivalent to 3.0-4.6% the GDP of the United States in 2019[45]

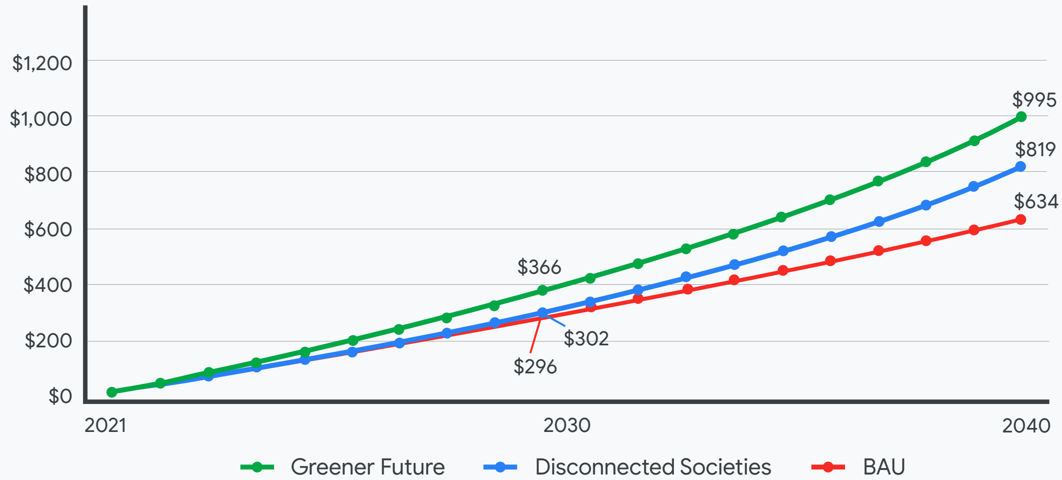
This investment figure is global in nature and includes investment in technologies and infrastructure. The global shift in capital expenditure may represent a challenge since some technologies are less financially, technologically, and commercially viable than the technologies used in the virgin production systems today. For example, many forms of chemical recycling will require nearly a decade of sustained investment before significant volumes of chemically recycled plastics can be expected (Figure 28).

Such a shift in capital investment may not happen naturally and sustained investment in technology and infrastructure needs to be coupled with sustained efforts on policy, regulations, education and product design. To catalyze change toward such an integrated approach, collaboration and coordination across sectors, regions, businesses, consumers, and multiple levels of government is needed. Collaboration is critical to unlock investment of this scale because organizations that may be willing to act, need counter parties in order to act. For example, a consumer goods company depends on the availability of recycled plastic to increase recycled content in their products and packaging, recyclers depend on design for recyclability standards to be enacted along with supporting infrastructure to increase quantity and quality of feedstock, and investors depend on access to affordable capital.

Figure 28

2020-2040 Cumulative Cash Investment by Scenario

UNIT: billion USD



NOTE: NPV based on a 6% annual discount rate. The cumulative cash investment required is 634 billion USD under BAU, 995 billion USD under Greener Future, and 819 billion USD under Disconnected Societies.

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: AFARA analysis

Section 5
Action Planning and Implementation

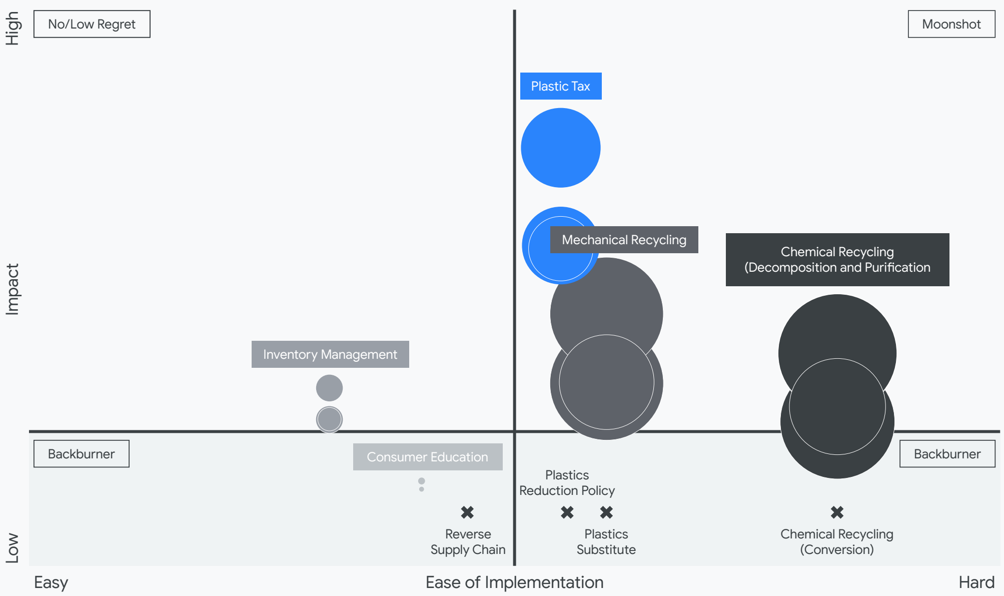
5.1 Ease of Implementing Strategic Interventions

The strategic interventions identified in this study can close the plastics circularity gap 54-62% by 2040 and requires $426-544 billion USD in NPV of global investments over this time period. The next critical step is to identify how to turn this data into actionable insights.

The combination of interventions that work in unison to become the five strategic interventions referenced in Table 12 were further assessed to understand relative impact and the ease of implementation for all three scenarios. Mapping these axes demonstrate which interventions are no/low-regret actions compared to those that are more difficult and are “moonshots” (Figure 29). Further details for all strategic interventions are provided in following sections.

Figure 29

Relative Impact of Strategic Interventions and Ease of Implementation Under All Scenarios



NOTE: Size of the bubble represents volume of plastics addressed. Impact and ease of implementation are relative for all strategic interventions. Since the five strategic interventions were high graded using the intervention model, the quadrant lines were determined based on average impact including the deprioritized interventions.

NOTE: Analysis based on 6 polymers and 3 regions of interest

Source: AFARA analysis

Sidebar 2

Ease of implementation was evaluated from six lenses

1. **Multiple Parties:** Do the set of interventions require multiple stakeholder groups to succeed? Stakeholder groups can broadly be broken down into consumers, industry, and governments. Interventions requiring fewer parties are easier to implement.
2. **Technology Risk:** Do the set of interventions have technical limitations to overcome in order to succeed? For example, decomposition technologies in chemical recycling from polyethylene to ethylene are still under research and development today, so success will require significant scientific advancement. Interventions with low/no technical risks are easier to implement.
3. **CapEx Required:** Do the set of interventions require heavy investment in hard technology and/or physical assets to succeed? This includes investment towards infrastructure. Interventions with low/no CapEx are easier to implement.
4. **Policy Change:** Do the set of interventions require a policy change to succeed? For example, better standardized definitions for chemical recycling are required before chemical recycling can be widely adopted. Interventions with little/no policy changes required are easier to implement.
5. **Threat to Incumbents:** Do the set of interventions pose a threat to incumbent industries and market players? For example, a tax on virgin plastic production will likely provoke petrochemical companies to re-evaluate their business case and strategies. Interventions that do not pose a threat to incumbents are easier to implement.
6. **Codependency:** Are the set of interventions codependent of one another? For example, mechanical recycling can only reach its full potential when plastic products and packaging are proactively designed for recyclability. Interventions that are not codependent on other interventions are easier to implement.

Plastic Demand Reduction: Inventory Management

Inventory management is the easiest intervention to implement. It requires action by industry only, has limited technological risk, does not require extensive CapEx investment, does not require new policy, is not a threat to incumbents, and is not codependent on other interventions. There is no cost of polymer production with this intervention since inventory management focuses on reducing and eliminating plastic waste. However, compared to other strategic interventions, the volume of plastics addressed is low. Under the three scenarios, it has the potential to address 300-358 million metric tonnes of plastics, and it is a no/low-regret action (Figure 29).

Plastic Demand Reduction: Consumer Education

Consumer education is relatively easy to implement. This intervention includes both consumer incentives, and education and awareness building. It has no technological risk, does not require CapEx investment, does not require new policy, and is not codependent on other interventions. Action can start with industry and government; however, success of this intervention will require consumers to be receptive to take action. Further, this intervention may pose a slight threat to incumbent industries who are dedicated to selling plastic products and packaging. There is no cost of polymer production with this intervention since this strategic intervention focuses on eliminating plastics. Relative to other strategic interventions, consumer education has the lowest impact by volume. Under the three scenarios, it has the potential to address 79-94 million metric tonnes of plastics. Therefore, consumer education for plastics reduction should be a lower priority since relative volumes are small for this intervention compared to other interventions.

Plastic Demand Reduction: Plastic Tax

Imposing a plastics tax has a potential for high impact to support circular supply chains for plastics because it serves to disincentivize use of virgin petroleum feedstocks and catalyze investment in recycled plastics production. However, it is difficult to implement. While taxing virgin production has no technological risk and does not require heavy investment, implementing a plastics tax requires multiple stakeholder groups to implement (e.g., both industry and government). Further, it requires new policy with commensurate auditing and may pose a significant threat to the profit and losses for companies in the virgin plastics supply chain. A plastics tax has a high impact because there is no cost of polymer production associated with this intervention. Under the three scenarios, it has the potential to address 832-1,039 million metric tonnes of plastics.

Circular Plastic Supply Chains: Mechanical Recycling

Mechanical recycling is a relatively challenging intervention to implement. While there is little technological risk since mechanical recycling equipment and processes are well understood, new policy is not required, and there is little threat to incumbents, mechanical recycling requires heavy investment due to the infrastructure needs and requires a high level of coordination among stakeholders to succeed. Mechanical recycling is also codependent on other interventions such as consumer education on how to recycle plastics, as well as designing products and packaging for recyclability.

Today, one limitation to mechanical recycling comes from multilayer plastic packaging and products. Mechanical recycling can unlock additional volumes if product design proactively adapts to meet the conditions of mechanical recycling infrastructure. While implementing additional mechanical recycling capacity will be challenging, it has the potential to address 1.2-1.5 billion metric tonnes of plastics under the three scenarios.

Circular Plastic Supply Chains: Chemical Recycling

Chemical recycling is the most difficult intervention to implement, but impact is the highest among all interventions. This intervention requires action by multiple parties, has high technological risk, requires heavy investment, requires new policy, and is highly codependent on other interventions. Success for chemical recycling is codependent on designing for recyclability and, if implemented poorly, poses a threat to some mechanical recycling activities. However, if executed well, chemical recycling activities should not be parasitic to mechanical recycling. Coordination between the two interventions will be important to ensure plastics are recycled at the best suited facilities. Today, decomposition and purification technologies are not mature and require further research, testing, and development. Of the polymers studied, decomposition technology is only available for PET and PS at the pilot and early commercial scale today. There are also regulatory uncertainties regarding chemical recycling processes and, where defined, chemical recycling processes are often regulated under a waste-to-energy regulatory framework. Under the three scenarios, chemical recycling has the potential to address 1.2-1.6 billion metric tonnes of plastics.

Sidebar 3

Investing in all forms of chemical recycling

Based strictly on the methodology used in this study, chemical recycling conversion technologies were not identified as a strategic intervention. There are multiple reasons why conversion technologies are not recommended including cost of production, emissions, and many conversion technologies target fuels as their primary output. Conversion technologies have an interim step of creating naphtha and then the monomers required to make plastics. As a result of the technology used (i.e. pyrolysis/gasification) combined with this additional process step, conversion technologies often have a higher greenhouse gas emissions profile compared to decomposition and purification pathways. However, there is a case for revisiting this conclusion and even investing in the conversion pathways because the recommended decomposition and purification pathways and technologies are highly dependent on high quality feedstock and require extensive investment in infrastructure. Conversion technologies, on the other hand, are often more flexible in their feedstock requirements and can process feedstock that may not be appropriate for the mechanical recycling or for decomposition and purification technologies. Therefore, conversion can act as a hedge if infrastructure development is slow, undersized, or if fundamental physics or chemistry problems remain.

5.2 The Unaddressed Volumes (Remaining Plastics Circularity Gap)

While this study shows that there is an opportunity to address 3.7 billion- 4.5 billion metric tonnes (54%-62%) of the plastics circularity gap by 2040 with strategic interventions, there will still be 2.7 billion-3.2 billion metric tonnes (38%-46%) that is unaddressed and remains as mismanaged plastics.

Part of these volumes include durable plastic goods, while the remaining portion remain mismanaged single-use plastics. In this study, volumes addressed individually each year do not exceed the volume of mismanaged plastics in any given year. All plastics that do not re-enter the plastics supply chain in any given year are landfilled, incinerated, or leaked into the environment. Although there is no opportunity to recover plastics that have been incinerated, future efforts could explore strategic interventions that capture plastics that are landfilled or in the environment. Examples may include mining landfills with robotics for plastics that can be fed into the chemical recycling system as feedstock, or leveraging floating devices and the ocean's currents to collect plastics from the ocean.

Accelerating a Circular Economy for Plastics

This research study identifies a pathway to creating irreversible momentum toward circular supply chains for plastics by implementing economic and strategic low-risk and no-risk interventions. Each point of intervention needs attention and investment starting today to close the plastics circularity gap by 2040. Under BAU, one-third of the volume to reduce the plastics circularity gap (1.5 billion metric tonnes) is achieved through plastic use and demand reductions while the other two-thirds of the volume (3.0 billion metric tonnes) produces plastics through circular supply chains. It is possible to create plastics through circular supply chains with a lower cash cost of production compared to virgin plastic supply chains, but it requires investment starting today of approximately $25 billion in NPV per year globally.

While the type of systemic shift needed goes far beyond Google, we believe that business will lead the change toward a circular economy, as the primary designers, builders, and users of materials. Looking ahead, there is an important opportunity to determine how to quickly and effectively mobilize the vast amounts of capital needed to invest in the requisite infrastructure, technologies, and integrated supply chains around the world. Governments can send the signals that circularity is needed and in the public benefit and enact enabling policies. Businesses can continue to improve product and packaging design, integrate recycled materials into products and packaging and support the innovation and engagement needed to further enable a circular economy for plastics. And each of us, every day, can keep the circular economy turning by choosing circular products and services for our own lives and playing our part to keep resources in use longer.

Glossary

Cash Cost: processing cost for a polymer that includes the cost of raw materials, utilities, and others such as labor, maintenance, and quality control. Cash cost excludes sales and distribution expenses, depreciation, return on investment, and income taxes.

Chemical Recycling: an emerging method to produce recycled plastics, also known as advanced recycling. There are three types of chemical recycling processes: purification, decomposition, and conversion. These processes often involve breaking molecular bonds and changing the chemical structure of the material, resulting in a quality that is equivalent to those of virgin plastics.

Circular Economy: an economic system that keeps resources in use for as long as possible, extracting the maximum value from the resources while in use, and maintaining/increasing the value of the resources with each additional use.

Recycled Plastics: plastics produced through the mechanical or chemical recycling of plastic waste, also known as recycled content. Recycled plastics allow for a reduction in plastic waste that would otherwise end up in a landfill or being leaked into the environment.

Conversion: chemical recycling process that breaks down polymers to produce a chemical feedstock for materials and/or fuels for combustion.

Cracking: chemical process that breaks down larger hydrocarbon chains into smaller ones. Cracking processes include thermal cracking, catalytic cracking, and steam cracking. Steam cracking is commonly used to break down naphtha and ethane into ethylene, a typical feedstock for virgin plastics.

Decomposition: chemical recycling process that breaks the molecular bonds in polymers to obtain building blocks (monomers or oligomers) that have virgin-material properties.

Feedstock: raw materials for an industrial process. Feedstocks for plastics may be virgin materials obtained from extraction or plastic waste streams.

Gasification: one type of chemical recycling (conversion) process. Gasification is a thermal process using a partial amount of air.

Hydrogenation: chemical process that breaks the hydrocarbon bonds and creates higher-value compounds, used in chemical recycling to transform plastics into petrochemical feedstocks.

Irreversible Momentum: socio-economic movement that once in motion can not be reversed. Irreversible momentum in this study is driven by the success of the circular supply chain in supplying plastics at a cost that is equal to or lower than the plastics supplied by the linear supply chain.

Mechanical Recycling: the traditional method to produce recycled plastics. The process involves a mix of grinding, washing, separating, drying, re-granulating, and compounding plastic waste without changing the chemical structure of the material. The resulting recycled plastics are labelled recycled content; however, the quality is typically lower compared to virgin plastics (e.g., reduced clarity or strength).

Monomer: basic chemical structure that constitutes the building blocks of polymers/plastics. They are typically reacted in the presence of catalysts to create polymer chains of multiple repeating monomers.

Moonshot: a challenging and innovative project, idea, or process. This term is akin to the challenging idea of taking a man to the moon as presented by President John F. Kennedy in his speech to Congress in May 1961.

Natural Gas Liquids (NGLs): components of natural gas that are separated as liquids at processing plants, include ethane, liquefied petroleum gases (propane and butanes), pentanes, and small fractions of higher carbon number hydrocarbons. NGLs are used as raw materials to produce virgin plastics.

Oligomer: a polymer that is made up of a few monomers. In chemical recycling processes, polymers are typically broken down into monomers or oligomers.

Polymer: material where chemical structure consists of long chains of repeating units (monomers). The six polymers of interest of this study are:

> **Acrylonitrile-butadiene-styrene (ABS):** classified under Plastic #7 or Other under the ASTM Resin Identification Coding system. It is a polymer commonly used in household piping, musical instruments, automotive components, electronic housings, golf club heads, 3D-printer raw material, and Lego bricks.
>
> **Polycarbonate (PC):** classified under Plastic #7 or Other under the ASTM Resin Identification Coding system. It is a polymer commonly used in applications where transparency is desired, such as lenses in eyewear, automotive components, clear protective barriers at sports arenas, household appliances, medical surgical instruments, and electronic housings.
>
> **Polyester terephthalate (PET):** Plastic #1 under the ASTM Resin Identification Coding system. It is the most commonly recycled polymer and is used in plastic bottles, food packaging, containers for cosmetics and personal care products, and clothing fibers.
>
> **Polyethylene (HDPE and LDPE/LLDPE):** Plastic #2 and #4 respectively under the ASTM Resin Identification Coding system. It is a polymer commonly used in milk jugs, flexible piping, foldable chairs, toys, cable insulations, bags, covers, and pond liners.
>
> **Polypropylene (PP):** Plastic #5 under the ASTM Resin Identification Coding system. It is a polymer commonly used in flexible and rigid packaging, plastic utensils, tote bags, rugs, mats, and medical supplies.
>
> **Polystyrene (PS):** Plastic #6 under the ASTM Resin Identification Coding system. It is a polymer commonly used in disposable plastic cutlery and dinnerware, appliances, electronics, and automobile parts.

Post Consumer Recycled (PCR): refers to materials such as paper and plastic that are collected for recycling and become materials to produce new products.

Purification: chemical recycling process that removes additives and dyes to obtain a virgin-like polymer. This process does not change the molecular structure of the polymer.

Pyrolysis: one type of chemical recycling (conversion) process. Pyrolysis is a thermal process in the absence of air.

Resins: plastic resins are the polymers used to manufacture plastic products. Virgin resins come from the processing of raw materials such as natural gas or crude oil. Recycled resins are the output of mechanical or chemical recycling processes.

Supply Chain: series of processes required to produce and distribute a product. A linear supply chain requires continuous extraction and production of raw materials to manufacture new products. A circular supply chain allows the product to re-enter the system as a feedstock for the production of new products, creating a closed loop.

Virgin Plastics: plastics produced from raw petrochemical materials through the linear supply chain. Virgin plastics require extraction of new resources/materials such as natural gas or crude oil.

References

[1] Mathy Stanislaus, "A Virtuous Circle," The Environmental Forum, September/October 2016.

[2] *Estimating the Date of Earth Overshoot Day 2021*. Global Footprint Network, 29 July 2021, https://www.overshootday.org/content/uploads/2021/07/Earth-Overshoot-Day-2021-Nowcast-Report.pdf

[3] *The State of Plastics: World Environment Day Outlook 2018*. UNEP, 2018, https://wedocs.unep.org/bitstream/handle/20.500.11822/25513/state plastics_WED.pdf?sequence=1&isAllowed=y

[4] Geyer et al. "Production, use, and fate of all plastics ever made" Science Advances. 19 Jul 2017, https://advances.sciencemag.org/content/3/7/e1700782.full

[5] *No Plastic In Nature: Assessing Plastic Ingestion from Nature to People*. World Wildlife Fund, 2019, https://wwwwwfse.cdn.triggerfish.cloud/uploads/2019/06/dalberg-advocacy-analysis_for-web.pdf

[6] *The New Plastics Economy: Catalyzing Action*. Ellen MacArthur Foundation, 2017, https://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-rethinking-the-future-of-plastics-catalysing-action

[7] Dorceta Taylor, "Toxic Communities: Environmental Racism, Industrial Pollution, and Residential Mobility." 2014

[8] *The Role of Safe Chemistry and Healthy Materials in Unlocking the Circular Economy*. Google, 2018, https://www.gstatic.com/gumdrop/sustainability/role-of-safechemistry-healthymaterials-circulareconomy.pdf

[9] Closed Loop Partners, "Accelerating Circular Supply Chains for Plastics: A landscape of transformational technologies that stop plastic waste, keep materials in play and grow markets." 2019 https://www.closedlooppartners.com/wp-content/uploads/2021/01/CLP_Circular_Supply_Chains_for_Plastics_Updated.pdf

[10] "Virgin" is used to describe newly mined/produced resources before they enter a recycling stream to be converted into secondary products. Alternative terms were considered for the plastics use-case (e.g., new, prime, petroleum-derived, fossil-feedstocks), but none are as easily recognized, understood, or succinct. Additionally, use of the term 'virgin' is harmonized with use by international governments and, in some cases, federal and state laws.

[11] United Nations Environment Program and Basel Convention, "Baseline Report on Plastic Waste," Plastic Waste Partnership working group, Beau Vallon, Seychelles, 2-5 March 2020.

[12] Recycled plastics are defined as plastics produced from a circular production pathway, such as mechanical or chemical recycling. This is contrasted by virgin plastics that are produced from a virgin production pathway, also known as the linear economy.

[13] IHS Markit, “The IHS Markit View of the Energy Future for Rivalry, Autonomy, and Discord (2020–2050),” 2020.

[14] Values do not add up to 100% due to rounding.

[15] IHS Markit, “Data and Analysis for Polymer Flow in North America,” 2019.

[16] Policies regarding chemical recycling are not standardized and the output products from these novel technologies are sometimes deemed recycled content, but often are not yet recognized by governments as producing recycled content.

[17] Environment and Climate Change Canada (ECCC), “Circular North America: Accelerating the Transition to a Thriving and Resilient Low-carbon Economy,” 2020.

[18] Definitions for the economic drivers can be found in Appendix A.

[19] TechnipFMC, “Ethylene Production,” Nature, vol. 225, pp. 1019–1022, 2017.

[20] Current definitions of chemical recycling by various organizations can be found in Appendix A.

[21] Ministry of Environment of Denmark, 2021. “The Minister of the Environment’s answer to question no. 782 (MOF general part) asked on 2 February 2021 at the request of the chairman René Christensen (DF) on behalf of the committee.” https://www.ft.dk/samling/20201/almdel/mof/spm/782/svar/1752141/2343993.pdf

[22] IHS Markit, “Impact of Plastics Recycling on the Future of Energy Transition,” Chem. Res. Anal., pp. 1–7, 2020.

[23] A. Grimmelt, M. Magni, and A. Rodriguez, “McKinsey 2020 Global Consumer Sentiment Survey: A Tale of Two Segments,” no. February, 2020.

[24] Ellen MacArthur Foundation, “The Global Commitment 2021 Progress Report” Beverage Sector Insights report, 2021.

[25] Ellen MacArthur Foundation, “The Global Commitment 2021 Progress Report” Cosmetics Sector Insights report, 2021.

[26] Ellen MacArthur Foundation, “The Global Commitment 2021 Progress Report” Food Sector Insights report, 2021.

[27] Ellen MacArthur Foundation, “The Global Commitment 2021 Progress Report” Household and Personal Care Sector Insights report, 2021.

[28] Ellen MacArthur Foundation, “The Global Commitment 2021 Progress Report” Retail Sector Insights report, 2021.

[29] Ellen MacArthur Foundation, “The Global Commitment 2021 Progress Report” 2021.

[30] Canada-wide Action Plan on Zero Waste Plastics (in collaboration with the Canadian Council of Ministers of the Environment)

[31] Government of Canada, “Ocean Plastics Charter,” 2020. https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/international-commitments/ocean-plastics-charter.html (accessed Nov. 25, 2020).

[32] E. A. Crunden, “Increasingly Popular Single-Use Bans Pose Hurdle for Plastics Industry,” Waste Dive, 2019. https://www.wastedive.com/news/plastics-bans-taxes-straws-circular-economy-panel/565669/ (accessed Nov. 25, 2020).

[33] European Commission, “EU Circular Economy Action Plan,” 2020. https://ec.europa.eu/environment/circular-economy/ (accessed Nov. 25, 2020).

[34] Scenarios in this study are based on IHS Markit’s Energy and Climate Scenarios[13]. The scenarios evaluate three plausible future pathways for primary energy. This study leverages these inputs to determine how plastic supply chains may be affected.

[35] On a cumulative basis over the 20 years, the Plastics Circularity Gap is ~7.7 billion metric tonnes.

[36] Existing capacity based on 2019 where capacity for mechanical recycling is 21 million metric tonnes/year.

[37] Existing capacity based on 2019 where capacity for chemical recycling is 1.4 million metric tonnes/year. This includes all types of chemical recycling (i.e. conversion + decomposition + purification).

[38] Refers to the production of recycled content related to activities encompassed in the projected scenarios, not strategic interventions identified in this study.

[39] Assumes plastic demand is an indicator for the amount of plastic waste generated in a region.

[40] Congressional Budget Office, “Public Spending on Transportation and Water Infrastructure, 1956 to 2017,” 2018.

[41] Conversion technologies may be treated as a hedge for decomposition and purification technologies.

[42] The Danish Environmental Protection Agency, Ministry of Environment and Food of Denmark. “Life Cycle Assessment of grocery carrier bags” February 2018. Retrieved from https://www2.mst.dk/udgiv/publications/2018/02/978-87-93614-73-4.pdf

[43] It is important to recognize that polymer production from circular supply chains can be lower than the virgin supply chain; however, these interventions require investment both in technology and in infrastructure in order to scale circular supply chain capacity. Further details can be found in Section 4.2.

[44] World Bank, “Netherlands,” 2020. https://data.worldbank.org/country/netherlands (accessed Nov. 26, 2020).

[45] World Bank, “United States,” 2020. https://data.worldbank.org/country/united-states

(accessed Nov. 26, 2020).

[46] American Chemistry Council, "What is Chemical Recycling?," 2019. https://plastics.americanchemistry.com/what-is-chemical-recycling/ (accessed Nov. 20, 2019).

[47] Ellen MacArthur Foundation, "Enabling a circular economy for chemicals with the mass balance approach," 2019. Accessed: Nov. 21, 2019. [Online]. Available: https://www.ellenmacarthurfoundation.org/assets/downloads/Mass-Balance-White-Paper.pdf.

[48] ISO, "Guidelines for the recovery and recycling of plastics waste," ISO, 2008. https://www.iso.org/standard/45089.html (accessed Nov. 21, 2019).

[49] Stina, "The Economics of Recycling," Recycling Market Development Platform, 2020. https://www.circularityinaction.com/#showcircularecon (accessed Nov. 28, 2020).

[50] Each model differs based on different total demand of plastics (data provided from IHS[13]).

[51] The volumes calculated in the volume impact assessment only demonstrate the addressable volumes by solution/intervention if leveraged individually. The combination of solution/intervention that address the plastics circularity gap is based on AFARA's analysis.

[52] Each category is inclusive of the category above; therefore, the categories are not additive and 'ALL SU' is the largest category.

[53] Factors were validated by a 3rd party with expertise in plastics, recycling and the circular economy.

[54] S-curves are expressed as a percentage that changes year on year. S-curves are applied directly to the MTV to forecast the plastic volumes addressed year on year.

[55] OECD, "Environment Database - Municipal Waste, Generation and Treatment," 2020. https://stats.oecd.org/Index.aspx?DataSetCode=MUNW# (accessed Dec. 01, 2020).

[56] E. Kirschbaum, "Germany to close all 84 of its coal-fired power plants, will rely primarily on renewable energy," Los Angeles Times, 2019. https://www.latimes.com/world/europe/la-fg-germany-coal-power-20190126-story.html (accessed Dec. 01, 2020).

[57] Closed Loop Partners, "Accelerating Circular Supply Chains For Plastics," pp. 1–90, 2019, [Online]. Available: http://www.closedlooppartners.com/wp-content/uploads/2019/04/CLP_Circular_Supply_Chains_for_Plastics.pdf.

[58] The Pew Charitable Trust and SystemIQ, "Breaking the Plastic Wave: A Comprehensive Assessment of Pathways Towards Stopping Ocean Plastic Pollution," p. 152, 2020.

Appendix

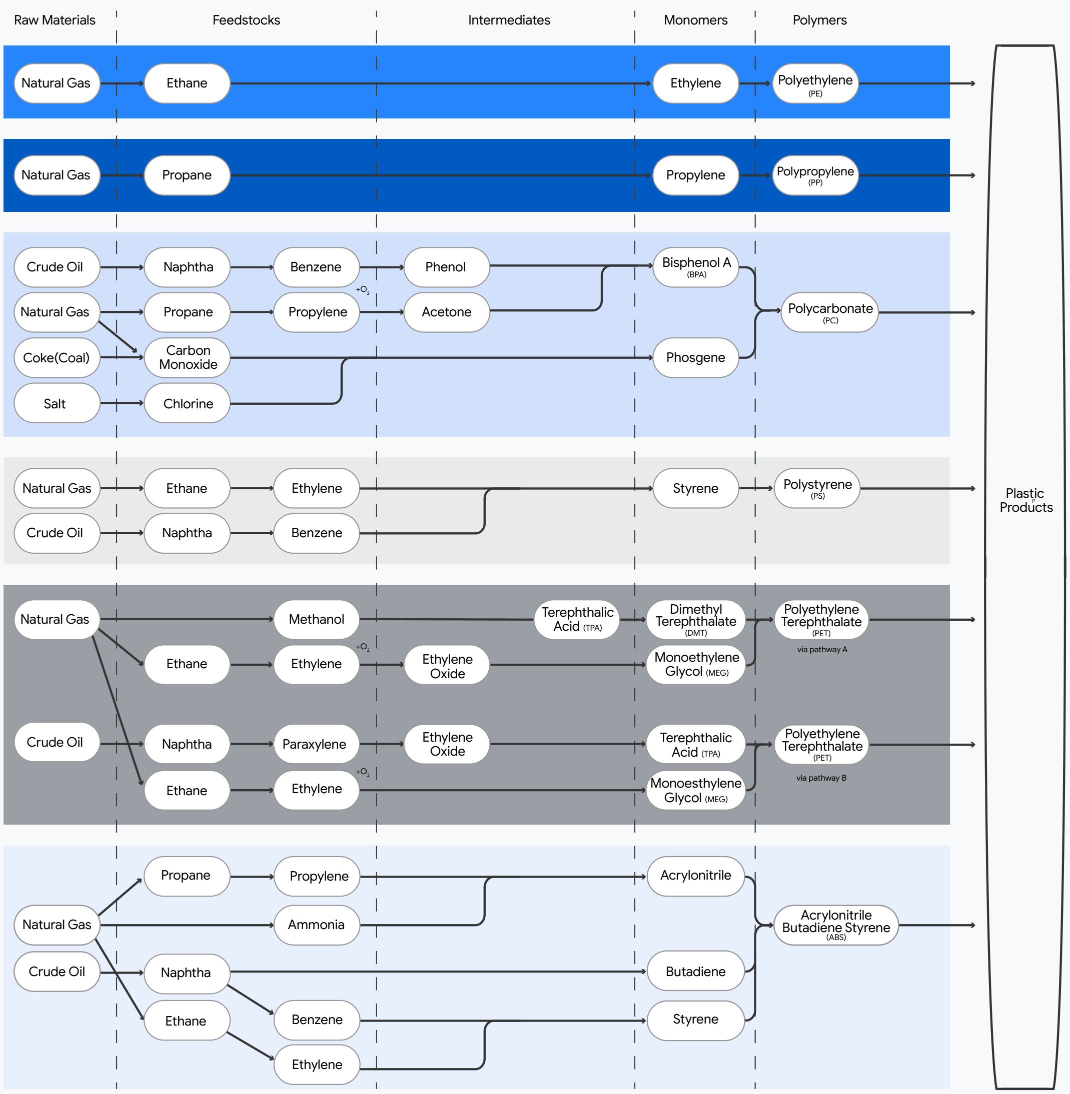
Appendix

A Plastics Landscape Today

1. Typical Virgin Production Pathway

Figure 31

Typical Virgin Production Pathway for Six Polymers of Interest



SOURCE: AFARA analysis

2. Definitions of Economic Drivers

Table 15

Definitions of Economic Drivers

	Economic Drivers	Definitions
Upstream	Feedstock Availability	Ability to secure feedstock(s) to the quality required for manufacturing plastic resins. Includes source location, transportation needs, and pretreatment. For the circular economy, feedstocks are secured through recycling which includes collecting, sorting, and cleaning
	Feedstock Cost	Unit cost (USD/tonne) of feedstock(s) required. May be spot or contract pricing
Plastic and Resin Manufacturing	Supply Chain	Ability to leverage shared infrastructure and colocation benefits to minimize transportation of intermediate commodities between feedstock(s) and output product(s)
	Economies of Scale	Capacity of equipment and infrastructure to leverage economies of scale
	Technology	Assessment of technology maturity, sophistication, robustness, stability, and usability
	CapEx	Capital expenditure to build new infrastructure or integrate new technologies
	OpEx	Operational expenditure for day-to-day operations. Affected by labor cost and utilities (i.e. energy and water requirement)
Downstream/ Other	Polymer Price	Unit cost (USD/tonne) of output product(s)
	Social Perception	Current narrative related to activity or output product(s), both positive and negative
	Policy/Incentives	Support from governments to promote and incentivize circular economy over linear economy

SOURCE: AFARA analysis

3. Definitions of Chemical Recycling

Table 16

Current Definitions of Chemical Recycling by Organization

Organization	ACC*	CLP	CRE*	EMF†,‡	ISO	PE	PRE	SPC
Last Updated	2019	2019	2019	2019	2018§	2019	2019	2019
Geographical Adoption	North America	North America	Europe	Global	Global	Europe	Europe	North America
Direct Use of Term 'Chemical Recycling'	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Alternate Terms for Chemical Recycling (if applicable)	Advanced Recycling and Recovery, Transformational Technologies	Transformational Technologies	n/a	Feedstock Recycling	Feedstock Recycling	Feedstock Recycling	Feedstock Recycling	n/a
Inclusions								
Recovery of polymers	Purification	Purification	Included	Excluded‖	Unclear	Excluded	Unclear	Purification
Recovery of monomers	Decomposition, depolymerization	Decomposition	Included	Cracking, gasification, depolymerization	Cracking, gasification, depolymerization	Depolymerization	Pyrolysis, gasification, chemical depolymerization, catalytic cracking and reforming, hydrogenation	Decomposition
Recovery of chemical feedstock	Conversion	Conversion	Included	Cracking, gasification, depolymerization	Cracking, gasification, depolymerization	Gasification, pyrolysis	Pyrolysis, gasification, chemical depolymerization, catalytic cracking and reforming, hydrogenation	Conversion
Recovery of fuels	Conversion	Conversion	Included	Excluded	Excluded	Gasification, pyrolysis	Excluded	Conversion

* ACC and CRE are in a cross-Atlantic alliance[46]

† EMF's definition of chemical recycling directly references ISO 15270:2008[47]

‡ This white paper was published in collaboration with BASF, Eastman, Michelin, Schneider Electric, Solvay, Tarkett, UL, and UPM Raflatac[47]

§ ISO's standard was last updated in 2008; however, ISO has expressed that this standard has been reviewed in 2018 and maintains the 2008 version as current[48]

‖ EMF excludes recovery of polymers in its definition of chemical recycling since it is included under "open-loop mechanical recycling"[47]

SOURCE: AFARA analysis

Appendix

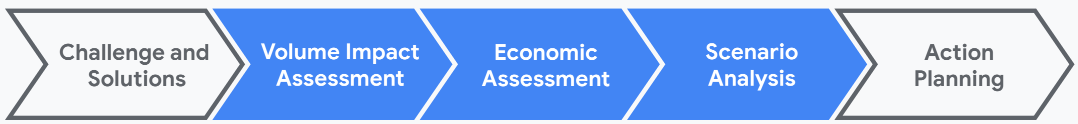
B

Methodology for the Study

1. Methodology Overview

Figure 32

Key Elements Guiding this Study



Challenge and Solutions

The challenges were identified by the **plastics circularity diagram**

The magnitude of the problem was defined by the **plastics circularity gap 14 potential interventions** were mapped against the plastics circularity diagram

Volume Impact Assessment

The **Volume Impact Assessment** determined how much plastic each intervention can address

Economic Assessment

Cash Cost of Production compared the economics between virgin and circular production pathways

Investment Required evaluated the capital investment needed to support the high impact interventions (defined by the volume impact assessment)

Scenario Analysis

Scenario Analysis (Volumes) examined how volumes differ under different versions of the future

Scenario Analysis (Economics) examined how economics differ under different versions of the future

Action Planning

The prioritized solutions combined to create the list of recommended **strategic interventions**

The **action planning matrix** provided an evaluation of the recommended strategic interventions against impact and ease of implementation. This provided clear insight into 'no/low regret' actions and 'moonshots'

Intervention Model

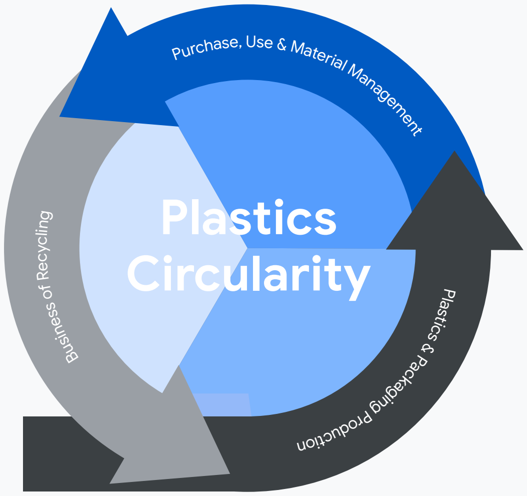
NOTE: This is Figure 14 in the report.

2. Plastics Circularity Diagram

The starting point of this study is identifying the challenges with plastics circularity today and understanding the magnitude of this problem. Referencing the Recycling Market Development Platform developed by Stina, the plastics circularity diagram show that the three big challenges for circular supply chains are found in ‘Plastics and Packaging Production’, ‘Purchase, Use and Material Management’ and the ‘Business of Recycling’ (see Figure 33).

Figure 33

Plastics Circularity Diagram



	Challenges
■ (dark grey)	Plastics and Packaging Production
■ (blue)	Purchase, Use, and Material Management
■ (light grey)	Business of Recycling

SOURCE: Stina[44]

3. Plastics Circularity Gap

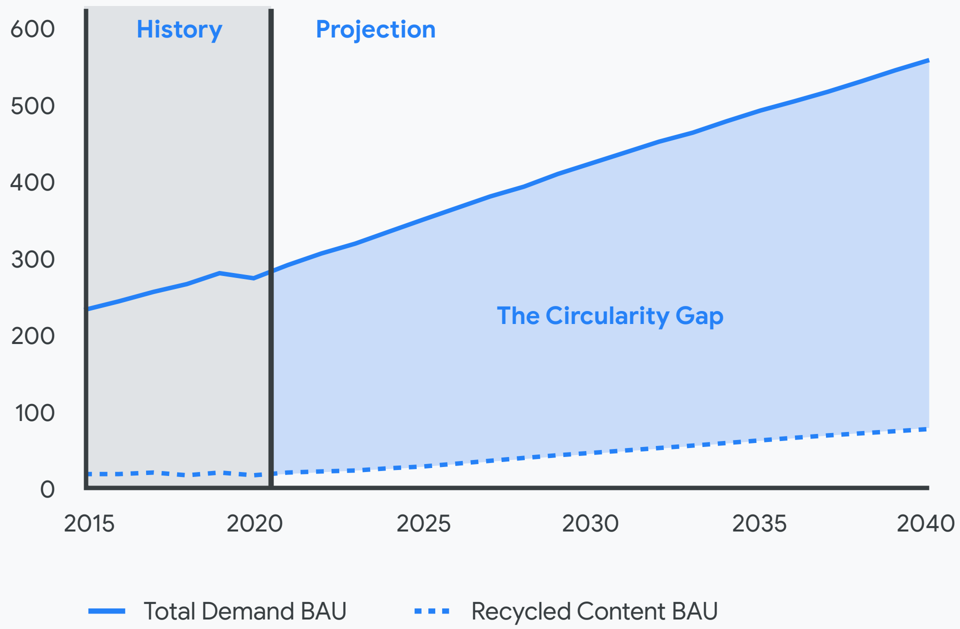
The magnitude of these challenges is expressed by the term plastics circularity gap. The plastics circularity gap represents all mismanaged plastics that are either landfilled, incinerated, or leaked into the environment. Specifically, the gap is defined by the amount of plastics that do not make it back into the plastics supply chain to produce recycled polymers.

Consequently, the plastics circularity gap is the difference between total plastics demand (i.e. top line) and the amount of post-consumer recycled plastics (i.e. bottom line). Between 2020-2040, the plastics circularity gap is between 86-92% annually. By 2040, this translates to a cumulative ~7.7 billion metric tonnes of plastics left mismanaged under the Business as Usual scenario.

Figure 34

The Plastics Circularity Gap under Business as Usual

UNIT: million metric tonnes/year



NOTE: This is Figure 3 in the report

NOTE: Visual presented on an annual basis; the plastics circularity gap is the cumulative volume of plastics that do not re-enter the plastics supply chain between 2020-2040

NOTE: Analysis based on 6 polymers and 3 regions of interest. Visual for Business as Usual scenario only

SOURCE: IHS Markit[13]; AFARA analysis

4. Potential Interventions

A suite of 14 potential interventions were identified to tackle the three challenges presented in the plastics circularity diagram. Each are summarized in Figure 35 and further elaborated with key outcomes and examples in Table 17. A successful intervention requires all key outcomes to be achieved.

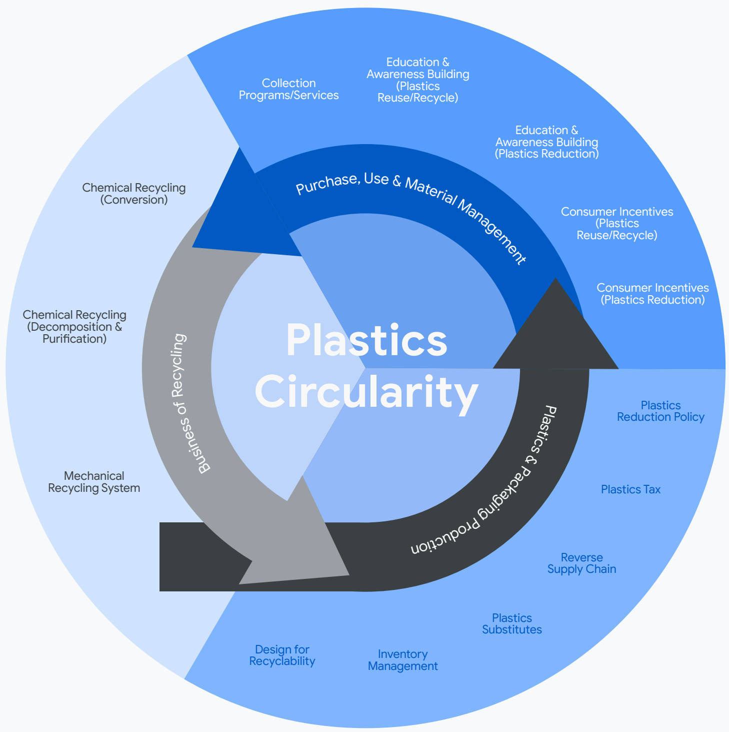
To tackle challenges found in 'Plastics and Packaging Production', interventions include designing products for recyclability, using inventory management, substituting plastics with new materials, developing reverse supply chains, implementing plastics tax, and implementing a plastics reduction policy.

To tackle challenges found in 'Purchase, Use and Material Management', interventions include creating consumer incentives to reduce plastics consumption and to reuse/recycle plastics properly, leveraging education and awareness building to reduce plastics consumption and to reuse/recycle plastics properly, and expanding collection programs and services for consumers.

To tackle challenges found in the 'Business of Recycling', interventions include developing and scaling chemical recycling of all types (i.e. conversion, decomposition, and purification), and improving the mechanical recycling system.

Figure 35

Potential Interventions Against the Plastics Circularity Diagram



	Interventions
	Design for Recyclability
	Inventory Management
	Plastic Substitution
	Reverse Supply Chain
	Plastics Tax
	Plastics Reduction Policy
	Collection Programs/Services
	Education & Awareness Building (Plastics Reuse/Recycle)
	Education & Awareness Building (Plastics Reduction)
	Consumer Incentives (Plastics Reuse/Recycle)
	Consumer Incentives (Plastics Reduction)
	Chemical Recycling System (Conversion)
	Chemical Recycling System (Decomposition & Purification)
	Mechanical Recycling System

SOURCE: Stina[49], AFARA analysis

Table 17

Key Outcomes and Examples of Interventions

Interventions	Key Outcomes	Examples
Plastics and Packaging Production		
1. Design for Recyclability	• Redesign products and packaging to minimize use of plastics • Reduce complexity and barriers to recycling • Design for fit with regional recycling infrastructure (both existing and planned expansions)	• Minimize the number of polymers used in a single package or product • Minimize the amount of inks used • Eliminating small/loose materials (i.e. caps, labels) • Leveraging novel additives that improve recyclability
2. Inventory Management	• Eliminate pre-consumer plastic waste, such as product destructions due to quality issues, product losses during transportation, unsold products due to excess inventory, unsold products due to shelf life expiration, etc.	• Optimizing delivery cycles based on consumer shopping habits
3. Plastics Substitution	• Substitute plastics with a novel material that has better environmental impacts and an improved end of life than virgin plastics	• Substituting plastics with edible packaging
4. Reverse Supply Chain	• Provide consumers with a convenient collection program for end-of-life plastics directly back to the manufacturer to encourage plastics reuse	• Offering pick of up recycling with product delivery
5. Plastics Tax	• Encourage industry to minimize the use of virgin plastics through pricing signals	• Setting a tax on all virgin plastic production
6. Plastics Reduction Policy	• Enforce industry to minimize the use of plastics through regulations and bans • Provide industry with resources to adapt to changes	• Setting a standard for minimum recycled content • Mandating mono-material products • Banning certain plastic types • Providing directories for recycled content suppliers
7. Consumer Incentives (Plastic Reuse/Recycle)	• Provide consumers with incentives or disincentives, including monetary/loyalty/social rewards to shift toward reuse and correct recycling	• Providing a discount when consumers bring their own cup/bag

Table 17 (Cont.)

Interventions	Key Outcomes	Examples
Purchase, Use, and Material Management		
8. Consumer Incentives (Reduce Plastic Consumption)	• Provide consumers with incentives/ disincentives, including monetary/ loyalty/social rewards to encourage a shift in plastic consumption behavior such as eliminating virgin plastics or reducing plastic use.	• Setting a fee on plastic bags
9. Education and Awareness Building (Plastic Reuse/Recycle)	• Provide consumers with knowledge to improve plastic management through reuse and recycling correctly • Empower consumers to promote proper plastic management among others	• Sharing positive sustainable impacts • Launching local education and awareness campaigns
10. Education and Awareness Building (Reduce Plastic Consumption)	• Provide consumers with knowledge to change plastic consumption behavior by eliminating virgin plastics or reducing plastic use. • Empower consumers to promote a change in plastic consumption behavior	• Increasing participation in consumer-led movements
11. Collection Programs/ Services	• Increase accessibility and convenience of collection by providing consumers with new programs/services to increase collection rates	• Adding public bins/receptacles • Emptying bins in a timely manner • Offering pickup of recycling in residential and commercial areas
12. Chemical Recycling (Conversion)	• Expand the collection system with a network of infrastructure to increase capacity for managing throughput of plastic volumes • Improve polymer to petrochemical technologies (i.e. pyrolysis/ gasification) • Optimize supply chain and logistics for polymer production (using output from conversion technologies) • Reduce barrier to entry for chemical recycling by developing clear regulations	• Lowering energy requirements • Improving yield • Improving output quality • Defining what chemical recycling entails and differentiating the process from incineration

Table 17 (Cont.)

Interventions	Key Outcomes	Examples
Business of Recycling		
13. Chemical Recycling (Decomposition and Purification)	• Expand the collection system with a network of infrastructure to increase capacity for managing throughput of plastic volumes • Increase purity of raw materials for recycling (i.e. clean and homogenous bales) by Improving the sortation system • Improve and develop polymer-to-polymer recycling technologies • Reduce barrier to entry for chemical recycling by developing clear regulations	• Develop new polyethylene to ethylene monomer technologies • Expand the definition of recycled content to include chemically recycled materials
14. Mechanical Recycling System	• Increase the capacity and quality of the collection network to manage a higher throughput of plastic volumes • Improve the sortation system to increasethe quality and purity of raw materials for recycling (i.e. clean and homogeneous bales)	• Retrofitting and building new material recovery facilities (MRFs) and transfer stations • Optimizing optical sensors • Integrating artificial intelligence/ machine learning to recognize waste streams and patterns

NOTE: Solutions listed in relation to the Plastics Circularity Diagram

SOURCE: AFARA analysis

5. Volume Impact Assessment

The volume impact assessment is a comprehensive analysis that forecasts the amount of plastic waste that can be addressed by solutions, year on year. The volume impact assessment is built based on plastic volumes (metric tonnes) with granularity by polymer, by region, and by intervention. Three different volume impact assessments were built to represent the three different scenarios.[50]

Each intervention is first assessed for its maximum total volume (MTV) which is a measure of the amount of plastic waste (by volume) that can be practically addressed. Each intervention is then assessed for speed using s-curves to understand how quickly it can affect plastic waste volumes. Finally, the MTV and s-curves are collectively assessed and matched to historic and projected volumes of plastic demand. The volume impact assessment is then able to create a forecast of the plastic volumes addressed by each intervention, year on year.[51]

5.1. Maximum Total Volume (MTV)

MTV is a measure of the amount of plastic waste (by volume) that can be practically addressed by each intervention. The MTV does not take time into consideration the time required to implement an intervention. In this study, MTV is determined as follows:

Maximum Total Volume (MTV) =
Total Demand (TD) x Category Assignment (CA) x Application Factor (AF)

Where:
- MTV is expressed in metric tonnes; calculated for each solution/intervention by polymer, by region, by year
- TD is expressed in metric tonnes; based on IHS data provided by polymer, by region, by year
- CA is assigned for each solution/intervention by polymer, and is not differentiated by region nor year
- AF is assigned for each solution/intervention by polymer, and is not differentiated by region nor year

The Category Assignment (CA) is determined by identifying the category of plastics an intervention can address. For this study, an intervention can address one of three categories below:[52]
- **CPG**: Consumer packaged goods only
- **SU W/O CPG+**: All single use applications (i.e. consumer packaged goods and single use industrial applications) but does not include consumer packaged goods that follow stricter regulations due to food and health safety
- **ALL SU**: All single use applications including consumer packaged goods that follow stricter regulations due to food and health safety

The CA dictates which plastic applications are included in the analysis. Depending on the CA, the application is either fully included (100%), partially included (50%), or fully excluded (0%). The applications covered in this study include:
- Agriculture
- Automotive and Transportation
- Building, Construction, and Infrastructure
- Consumer Good and Appliances
- Food and Beverages
- Healthcare, Hygiene and Medical
- Home and Personal Care
- Industrial Applications
- Packaging (secondary/tertiary)

These applications further dictate the volumes of plastics to include in the analysis and reflect the split of total demand. The application split differs by polymer and changes year on year. For this analysis, the application split uses an average of 2020-2040 values since changes year on year are less than 1%. Further, the application split differs by region. As an example, the application split for ABS and HDPE in North America is shown in Table 18.

The Application Factor (AF) is a factor assigned to further adjust the category assignment based on the possibility of each intervention. Factors use proxies based on the plastics industry today and analogous consumer facing industries (i.e. percentage of plastics banned in Canada, inventory loss rate in the fashion industry, etc.).[53] Factors differ by intervention and polymer. As an example, factors for two different interventions are shown for ABS and HDPE in Table 19.

Table 18

Split of Applications for ABS and HDPE in North America

Application	ABS	HDPE
Agriculture	-	7%
Automotive and Transportation	20%	7%
Building, Construction, and Infrastructure	19%	18%
Consumer Good and Appliances	53%	16%
Food and Beverages	-	16%
Healthcare, Hygiene and Medical	-	5%
Home and Personal Care	-	7%
Industrial Applications	-	18%
Other	8%	-
Packaging (secondary/tertiary)	-	6%

NOTE: The split of application differs by region and takes an average of 2020-2040 values.

SOURCE: IHS Markit[13]

Table 19

Sample Application Factors for ABS and HDPE by Intervention

Intervention	Application Factor	ABS	HDPE
Inventory Management	Inventory loss rate	0.25	0.40
Chemical Recycling System (Conversion)	Recycling factor	1.00	1.00

NOTE: The application factor differs by solution/intervention and polymer, but is not differentiated by region nor year.

SOURCE: AFARA analysis

Example:

MTV Calculation

Intervention	Inventory Management
Polymer	ABS
Region	North America
Year	2021
Scenario	Business as Usual

- The category assignment (CA) is CPG
- This CA implies the inclusion of "Consumer Goods and Appliances," "Home and Personal Care," "Packaging (secondary/tertiary)"
- Based on the North American context, this is respectively 53%, 0%, and 0% of the total ABS demand
- Under the BAU scenario in 2021, the total demand for ABS plastics is 664,000 metric tonnes
- The application factor (AF) for this intervention is 0.25

MTV = 664,000 metric tonnes x 53% x 0.25 = 87,989 metric tonnes

This calcluation shows the maximum theoretical addessable volume of the Inventory Management intervention in North America for ABS in 2021 under Business as Usual is 87,980 metric tonnes. The corresponding s-curve is then applied to this value to identify the volume of plastics addressed in 2021.

5.2. S-Curves

The s-curves measure how quickly an intervention can affect plastic waste volumes and are a function of time.[54] S-curves are governed by the following equation:

$$y = \frac{1}{1 + e^{-c(x-x_0)}} + y_0$$

Where:

y = market penetration (%)
x = time (year)
c, x_0, y_0 = constants customized to an intervention based on the curve selection criteria and matched to the landscape today

In this study, each intervention can be categorized by one of nine trajectories. S-curves are selected based on the scoring obtained from the curve selection criteria tables (See Tables 20, 21, and 22). There are three different curve selection criteria tables depending on the nature of the intervention. Each table determines whether the intervention is categorized by a base case, a fast case, or a slow case. The starting point in the curve differs by region.

The three categories are:

Improvement
Interventions characterized by stepwise operational changes and improvements. These interventions are able to impact plastic waste volumes immediately (i.e. no lag time), but at a steady linear pace. The curve selection criteria for improvement interventions are found in Table 20.

Policy
Interventions characterized by policy changes or updates. These interventions may or may not exist today and are highly dependent on region. These interventions have a medium lag time due to the time required to draft, propose, and announce policies. Once policies are implemented, there is a gradual impact on plastic volumes. The curve selection criteria for policy interventions are found in Table 21.

Innovation
Interventions characterized by innovation and new development. These interventions may not exist today or are extremely novel. These interventions have a long lag time due to the required research, development, testing, piloting, and scaling; however, they have a potential for exponential growth and high volumes once scaled. The curve selection criteria for innovation solutions are found in Table 22.

The s-curves were developed using existing analogous interventions. The improvement curve follows the OECD countries' historical recycling rates;[55] the policy curve follows Germany's coal-phase out implementation plan (i.e. number of plants to be closed by year);[56] and the innovation curve follows the recent trajectory and scale of chemical recycling projects from concept to growth stage.[57] Each of these three curves were accelerated and decelerated by 25% of the time required to create the fast and slow case respectively.

Table 20

Curve Selection Criteria for Improvement Interventions

Selection Criteria	Scoring
Does this intervention require investment in hard tech and/or physical assets?	
Yes, it requires a high level of investment	1
No, it requires a low/little level of investment	3
How many stakeholder groups* are required for this intervention to succeed?	
3 groups	1
2 groups	2
1 group	3

NOTE: Max score is six

* The three stakeholder groups for consideration are consumers, industry members, and governments

SOURCE: AFARA analysis

All improvement interventions were scored out of six. Interventions that fall under improvement include:

- Collection Programs/Services
- Consumer Incentives (Plastics Reuse/Recycle)
- Consumer Incentives (Reduce Plastic Consumption)
- Education and Awareness Building (Reduce Plastic Consumption)
- Education and Awareness Building (Plastics Reuse/Recycle)
- Inventory Management
- Reverse Supply Chain
- Mechanical Recycling System

If the score falls between:

5-6: The intervention is assigned a fast case. It likely requires a low level of investment due to the ability to leverage existing tools, technologies, infrastructure, and logistics networks, and requires very few stakeholders (typically industry members only).

4: The intervention is assigned a base case.

2-3: The intervention is assigned a slow case. It likely requires a high level of investment for physical assets such as infrastructure and requires many stakeholders.

Table 21

Curve Selection Criteria for Policy Interventions

Selection Criteria	Scoring
Is this intervention a first of its kind?	
Yes, this is being introduced for the first time	1
No, a reference case exists	3
Does this intervention lack political durability?	
Yes, it is non-durable and likely to change based on political party in power	1
No, it is durable and unlikely to change based on political party in power	3
How many stakeholder groups* are required for this intervention to succeed?	
3 groups	1
2 groups	2
1 group	3

NOTE: Max score is six

* The three stakeholder groups for consideration are consumers, industry members, and governments

SOURCE: AFARA analysis

All policy interventions were scored out of nine. Those that fall under policy include:

- Plastics Reduction Policy
- Plastics Tax

If the score falls between:

8-9: The intervention is assigned a fast case. It is likely able to replicate or take inspiration from a reference case, is durable regardless of the political party in power, and requires very few stakeholders.

5-7: The intervention is assigned a base case.

3-4: The intervention is assigned a slow case. It is likely going to take time to develop and refine since it is being introduced for the first time, is non-durable depending on the political party in power and requires many stakeholders.

Table 22

Curve Selection Criteria for Innovation Interventions

Selection Criteria	Scoring
Does this innovation disrupt incumbents?	
Yes, it disrupts incumbents	1
No, it creates a new/novel market	3
Does this innovation disrupt existing supply chains?	
Yes, it disrupts existing supply chain	1
No, it integrates easily into existing supply chain	3
How many stakeholder groups* are required for this innovation to succeed?	
3 groups	1
2 groups	2
1 group	3

NOTE: Max score is six

* The three stakeholder groups for consideration are consumers, industry members, and governments

SOURCE: AFARA analysis

All innovation interventions were scored out of nine. Those that fall under innovation include:

- Chemical Recycling System (Conversion)
- Chemical Recycling System (Decomposition and Purification)
- Design for Recyclability
- Plastic Substitute

If the score falls between:

8-9: The intervention is assigned a fast case. It likely creates a new/novel market without disrupting incumbents, integrates easily into the infrastructure and logistic network of existing supply chains, and requires very few stakeholders (typically industry members only).

5-7: The intervention is assigned a base case.

3-4: The intervention is assigned a slow case. It likely disrupts incumbents and creates competition on the market, requires new infrastructure and logistic network separate from existing supply chains, and requires many stakeholders.

Example:

Curve Selection (Innovation)

Intervention	Chemical Recycling (Conversion)
Region	North America

- Chemical recycling (conversion) does not disrupt incumbents. Incumbents, in this case, are mechanical recyclers. Chemical recycling (conversion) would target plastic feedstocks that are currently not processed by mechanical recycling. The score is three.
- Chemical recycling (conversion) does not easily integrate into existing supply chains. It requires new infrastructure and expansion of the collection system. The score is one.
- Successful chemical recycling (conversion) requires industry members to develop and deploy the technology, as well as governments to update policies to better define what chemical recycling entails so it is not incorrectly regulated as incineration. The score is two.

Score = 3 + 1 + 2 = 6

This score means that Chemical Recycling (conversion) in North America will follow the base case of the innovation trajectory.

Determining Impact Over Time

The MTV and s-curves are collectively assessed and matched to historic and projected volumes of plastic demand. The volume impact assessment is then able to create a forecast of the plastic volumes addressed, year on year. In this study, the volume impact is calculated by:

Volume Impact by Intervention = MTV x S-Curve

Where:

MTV is expressed in metric tonnes; calculated for each solution/intervention by polymer, by region, by year
S-curve is expressed as a percentage year on year; determined from scoring on curve selection criteria

The volumes calculated through the volume impact assessment only demonstrate the addressable volumes by intervention if leveraged individually. The combination of interventions that reduce the plastics circularity gap, labeled as the five strategic interventions, are proposed after the economic assessment based on AFARA's analysis.

Example:

Volume Impact Calculation

Intervention	Inventory Management
Polymer	ABS
Region	North America
Year	2021 and 2040
Scenario	Business as Usual

- The MTV (calculated previously is 87,980 metric tonnes in 2021 and 127,995 metric tonnes in 2040.
- Based on the scoring for this intervention in North America, the s-curve is an improvement intervention following a fast trajectory.
- By matching historic volumes to represent the landscape today, the s-curve is 28% in 2021 and 42% in 2040.

Volume Impact (2021) = 87,980 metric tonnes x 28% = 24,635 metric tonnes
Volume Impact (2040) = 127,995 metric tonnes x 42% = 53,760 metric tonnes

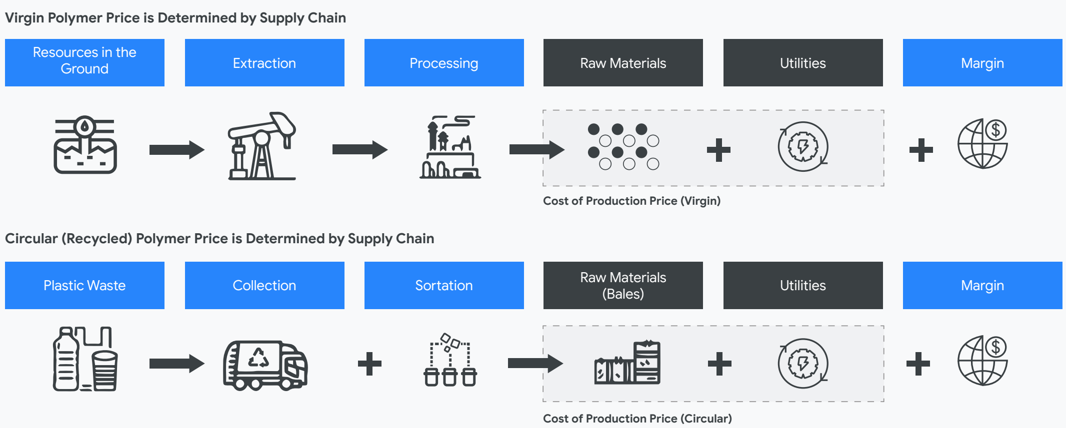
The volume impact of inventory management in North America for ABS is 24,635 metric tonnes in 2021 and 53,760 metric tonnes in 2040.

6. Economic Assessment

The economic assessment analyzes the difference in cash cost of production between virgin and recycled polymers to identify which interventions are more economically desirable to pursue. Those that allow for plastics demand reduction represent a cost savings (i.e. there is no need to produce the virgin plastics). Interventions that leverage the recycling system examine the cost differential between producing virgin plastics and recycled plastics. These cost differentials vary between 2020-2040 and are assessed for the six polymers and three regions of interest under three different scenarios.

Figure 36:

Boundaries of the Economic Assessment



6.1. Cash Cost of Production

The boundaries for the economic assessment for both virgin polymer and recycled polymer production are shown in Figure 36. In this study, the economics show the cash cost of polymer production. Each scenario assessed four production pathways: virgin, mechanical recycling, chemical recycling (conversion), and chemical recycling (decomposition and purification). Therefore, a total of 12 economic models were built to represent the three different scenarios.

Example:

Cash Cost Calculation

Intervention	Mechanical Recycling System
Polymer	HDPE
Region	North America
Year	2021
Scenario	Business as Usual

Facility Capacity (metric tonne/year)	10,000
Cash Cost Component ($/metric tonne)	
Raw Materials	$533
Utilities	$52
Other	$467
Total	$1,052

The cash cost of mechanical recycling in North America for HDPE is $1,052 /metric tonne in 2021.

7. Investment Required

The investment in this study includes investment in technologies and infrastructure. For technologies and infrastructure, the investment is differentiated by mechanical recycling and chemical recycling and it represents the cost of the total number of plants required every year to achieve the volumes estimated by the intervention model. The annual number of plants vary by scenario. To achieve the mechanical recycling volumes, 207 - 259 new plants of 20,000 metric tonnes are required every year over the next 20 years. To achieve the chemical recycling volumes, 243 - 313 new plants of 30,000 metric tonnes are required every year over the next 20 years. For the collection and sortation infrastructure, a factor of $24 per metric tonne is used for the annual recycling volumes estimated by the intervention model.[57] A discount rate of 6% is used to calculate the NPV of the investment.

8. Scenario Analysis

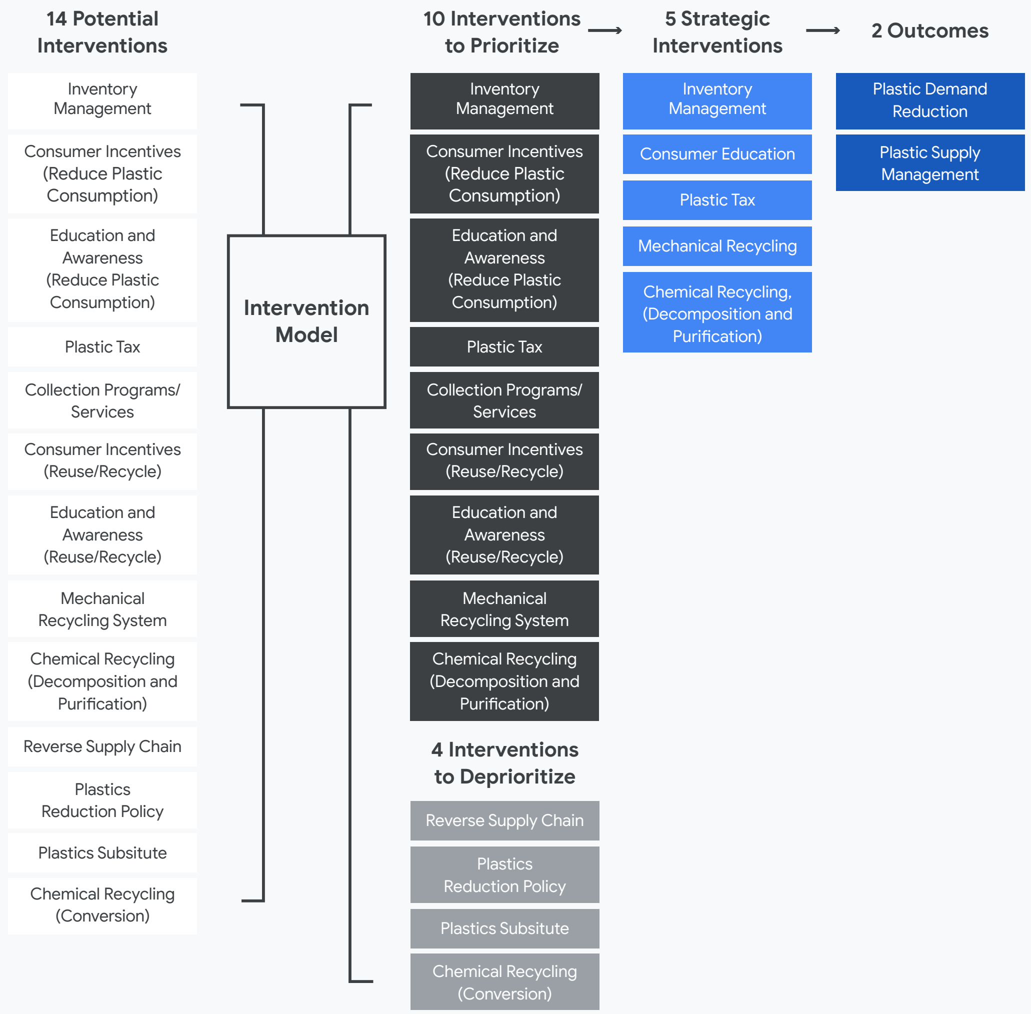
Scenarios in this study are based on IHS Markit's Energy and Climate Scenarios.[13] The scenarios evaluate three plausible future pathways for primary energy. This study leverages these inputs to determine how plastic supply chains may be affected. The volume impact assessment differs based on different total demand of plastics under each scenario. The economic assessment differs based on different pricing of raw materials, utilities, and other under each scenario.

9. Strategic Interventions

The intervention model based on the volume impact assessment, economic analysis, and scenario analysis provided insights into the interventions to prioritize and deprioritize. The 10 prioritized interventions combine to create five strategic interventions and two outcomes (see Figure 37).

Figure 37

Methodology for Defining Strategic Actions from High Impact Interventions



NOTE: This is Figure 16 in the report

SOURCE: AFARA analysis

10. Action Planning Matrix

Prioritization was determined based on mapping strategic interventions against impact and ease of implementation. Impact is defined by volume of plastics addressed and the average cost differential for polymer production between 2020-2040. Sample calculation for cost differential for polymer production can be found below for year 2021 and 2040. For the action planning matrix, an average cost of production between 2020-2040 was used. Ease of implementation was evaluated from 6 lens (multiple parties, technology risk, CapEx required, policy change, threat to incumbents, and codependency) which are further detailed out in the report.

Example:

Cost Differential Calculation

Intervention	Mechanical Recycling System
Polymer	HDPE
Region	North America
Year	2021 and 2040
Scenario	Business as Usual

	2021		2040	
	Circular Supply Chain	Linear Supply Chain	Circular Supply Chain	Linear Supply Chain
Facility Capacity (metric tonne/year)	10,000	650,000	30,000	650,000
Cash Cost Component ($/metric tonne)				
Raw Materials	$533	$414	$982	$1,889
Utilities	$52	$25	$82	$41
Other	$467	$38	$198	$65
Total Cash Cost	$1,052	$477	$1,262	$1,995
Differential	$575		$(733)	

The difference in the cash cost of production between recycled and virgin HDPE in North America is $575 /metric tonne in 2021 and $(733) in 2040. This means that by 2040 recycled HDPE produced through mechanical recycling is more economically desirable to pursue than virgin HDPE.

Appendix

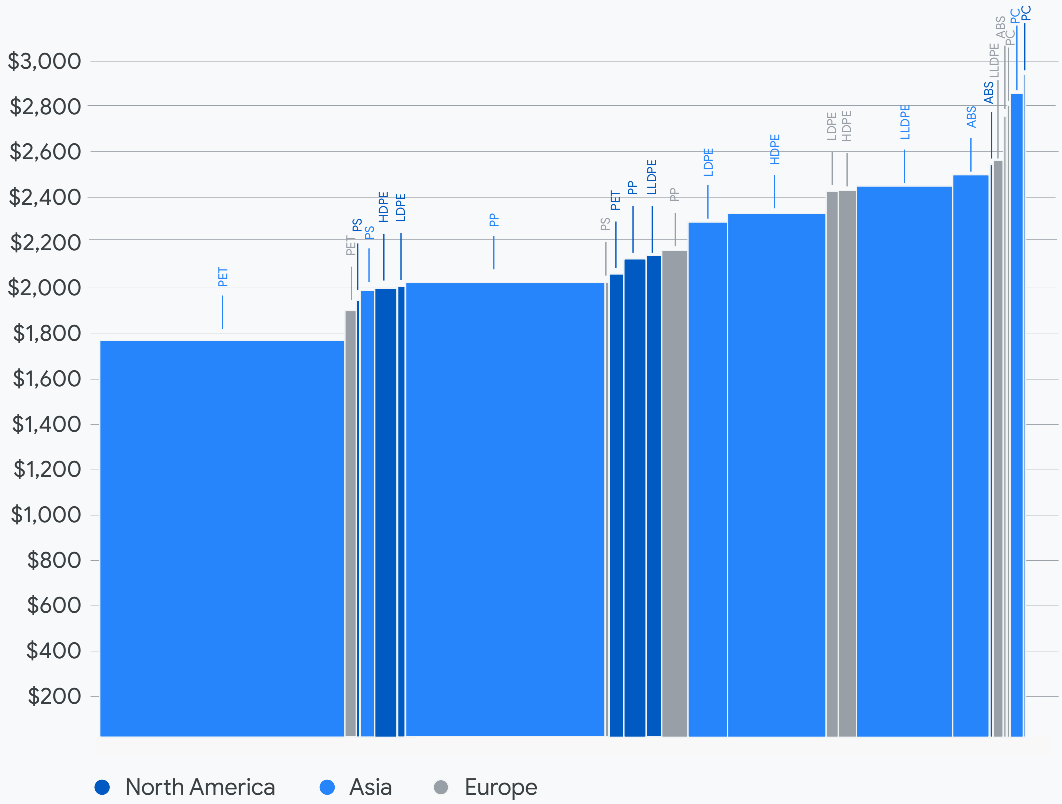
C Key Findings

1. Projected Supply Cost Curves

Figure 38

Cash Cost of Virgin Plastic Production by Polymer and Region under BAU (2040)

UNIT: USD/metric tonne



NOTE: Values based on non-integrated facilities. In 2040, the total plastics demand is 548 million metric tonnes under BAU and the average cost of virgin production is $2,293/metric tonne.

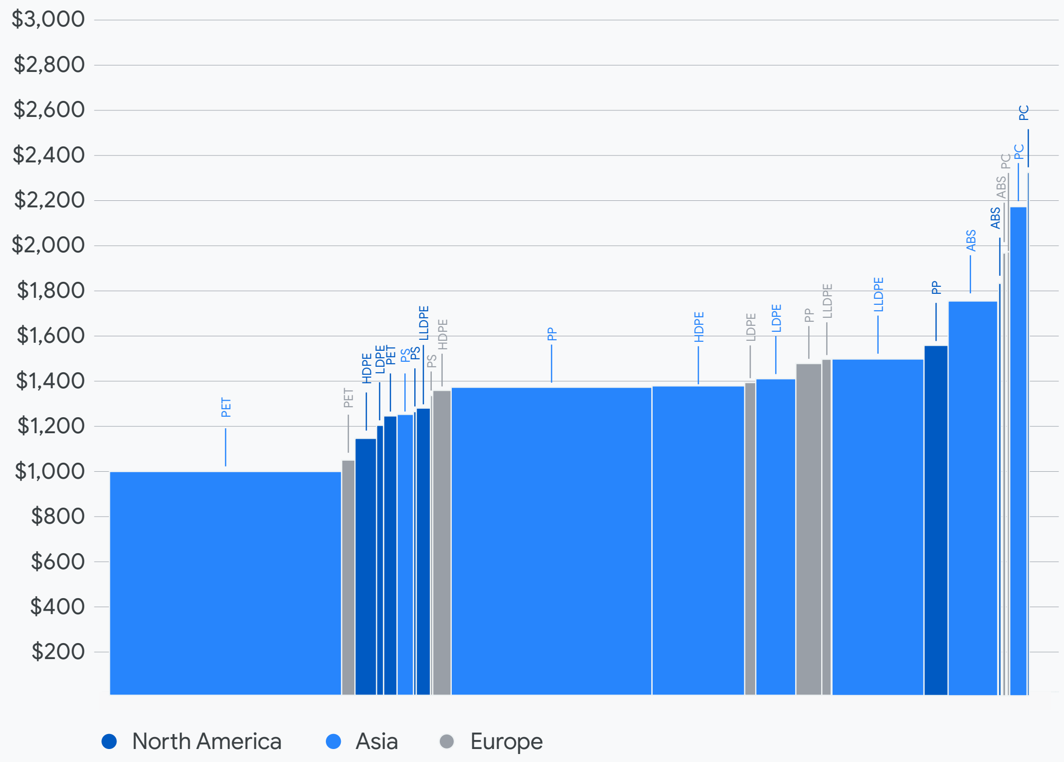
NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit[13] AFARA analysis

Figure 39

Cash Cost of Virgin Plastic Production by Polymer and Region under Greener Future (2040)

UNIT: USD/metric tonne



NOTE: Values based on non-integrated facilities. In 2040, the total plastics demand is 530 million metric tonnes under Greener Future and the average cost of virgin production is $1,493/metric tonne.

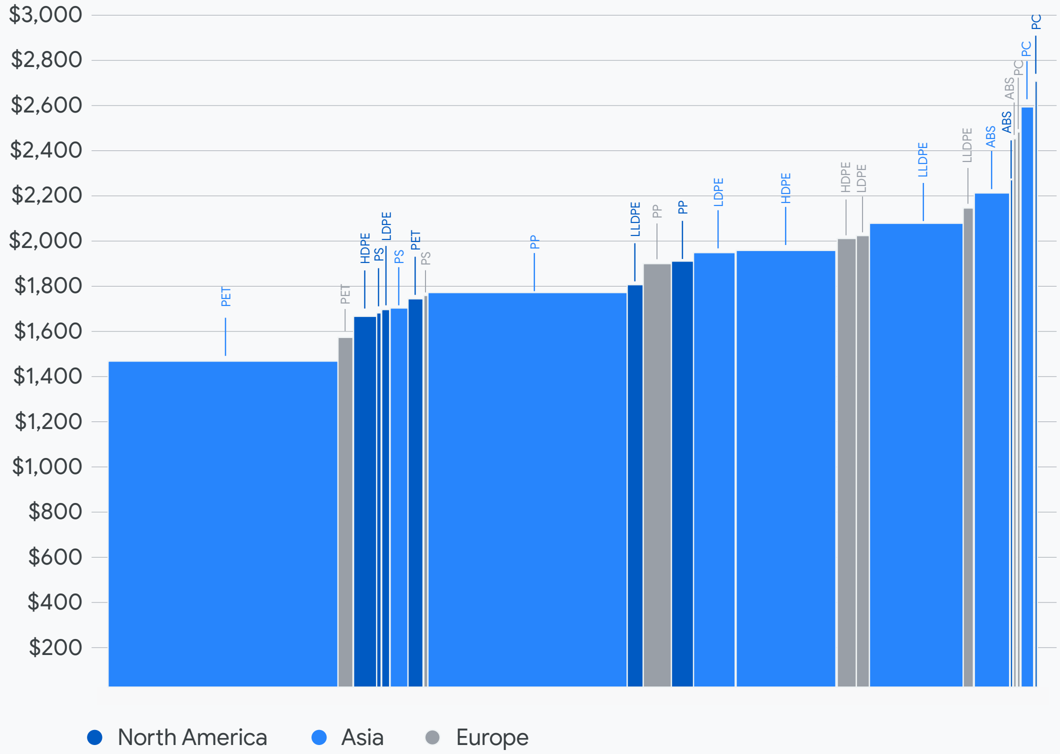
NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit[13], AFARA analysis

Figure 40

Cash Cost of Virgin Plastic Production by Polymer and Region under Disconnected Societies (2040)

UNIT: USD/metric tonne



NOTE: Values based on non-integrated facilities. In 2040, the total plastics demand is 427 million metric tonnes under Disconnected Societies and the average cost of virgin production is $1,972/metric tonne.

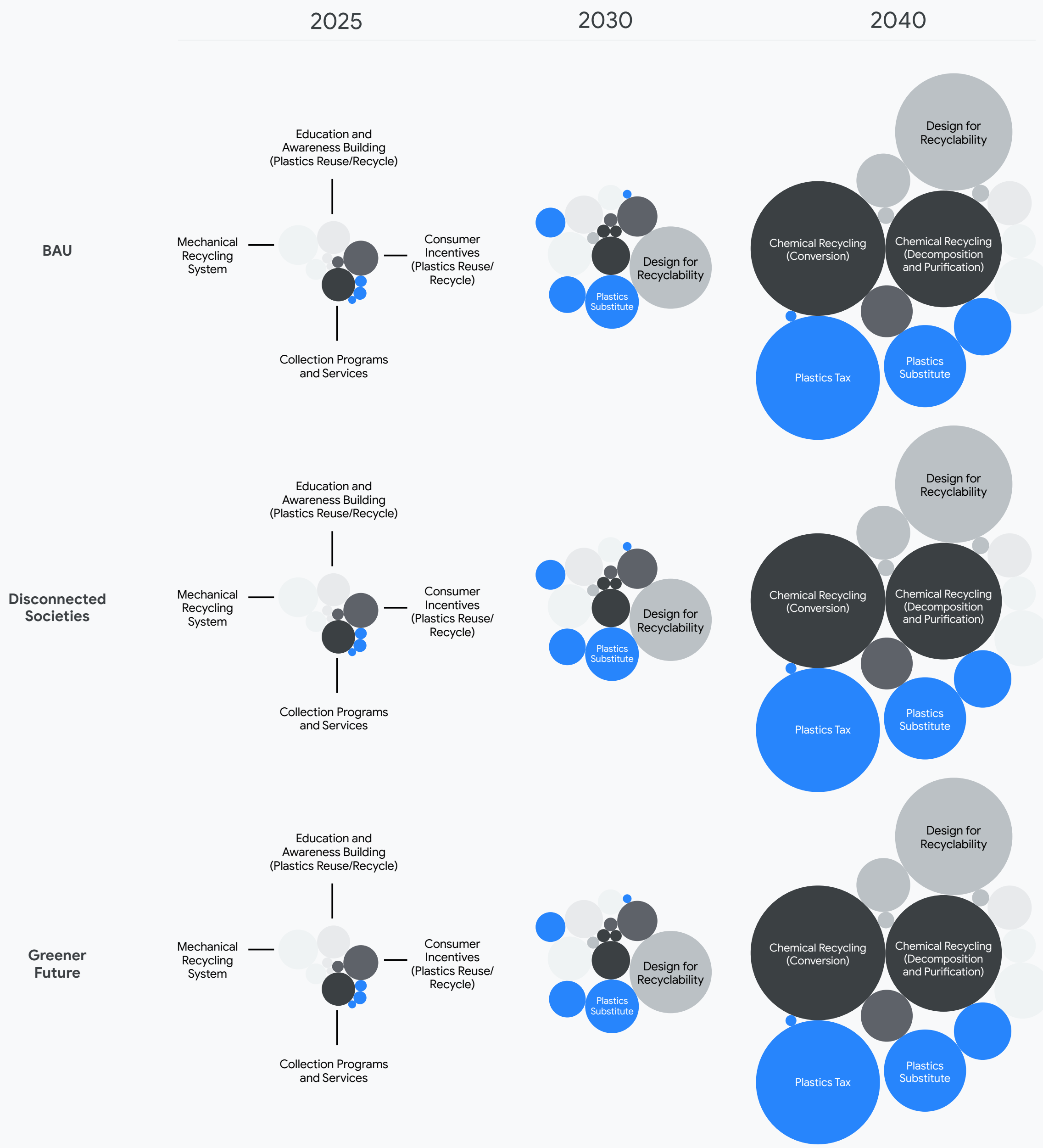
NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit[13], AFARA analysis

2. Addressable Volumes by Intervention

Figure 41

Relative Addressable Volumes by Intervention over Time for All Scenarios



NOTE: Size of the bubble represents the relative addressable volumes by intervention individually

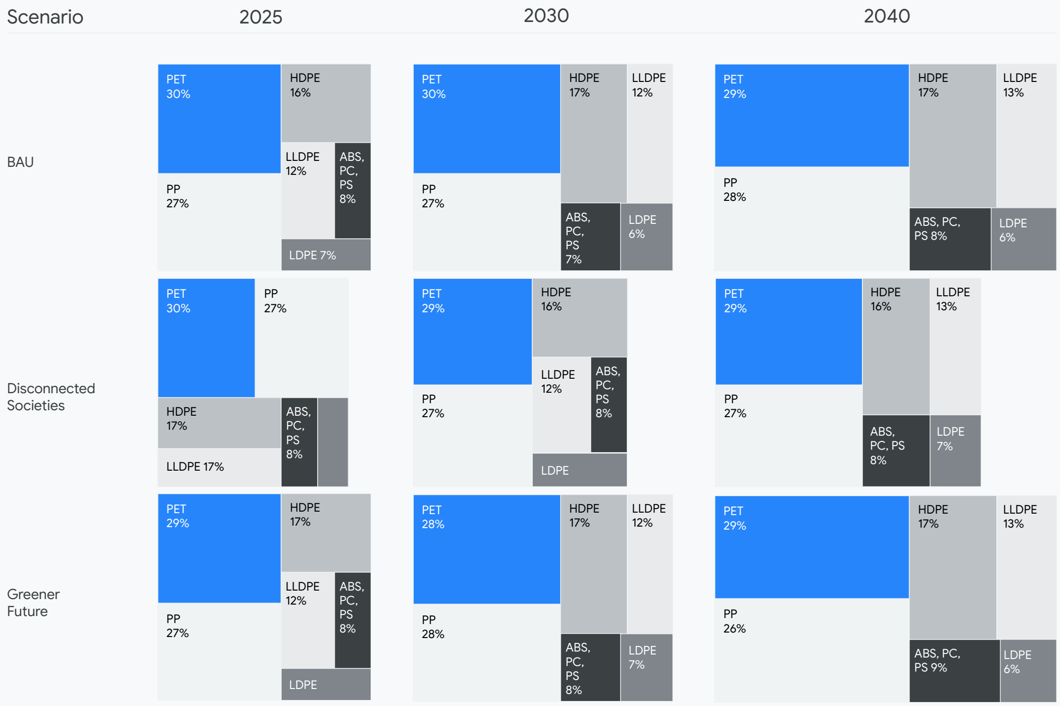
NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit[13]; AFARA analysis

3. Plastics Demand by Polymer

Figure 42

Global Plastics Demand by Polymer for All Scenarios



NOTE: Global plastics demand presented on an annual basis. In 2040, the total plastics demand is 548 million metric tonnes under BAU, 530 million metric tonnes under Greener Future, and 427 million metric tonnes under Disconnected Societies.

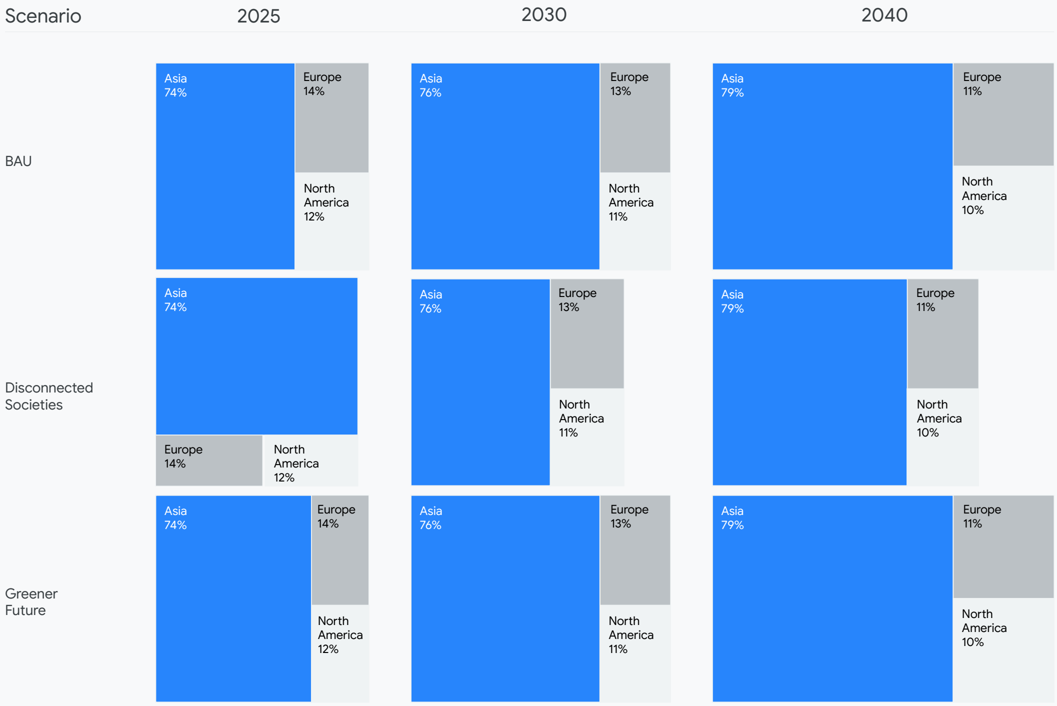
NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit[13]; AFARA analysis

4. Plastics Demand by Region

Figure 43

Global Plastics Demand by Region for All Scenarios



NOTE: Global plastics demand presented on an annual basis. In 2040, the total plastics demand is 548 million metric tonnes under BAU, 530 million metric tonnes under Greener Future, and 427 million metric tonnes under Disconnected Societies.

NOTE: Analysis based on 6 polymers and 3 regions of interest

SOURCE: IHS Markit[13], AFARA analysis

Appendix

D List of Tools/Technologies

The five strategic interventions include key outcomes that need to be achieved; however, there is no prescriptive method on how this can be accomplished. There are various tools/technologies that can be deployed to achieve the key outcomes. Some tools/technologies can address multiple interventions and challenges for plastics circularity at the same time. Table 23 captures the list of tools/technologies evaluated in this study. Table 24 captures a list of companies and organizations that are working on tools/technologies that support the recommended strategic interventions in this study.

Table 23

List of Tools/Technologies and Possible Challenges Addressed

Tools/Technologies	Plastics and Packaging Production	Purchase, Use and Material Management	Business of Recycling
Advanced Optical Sensors			✓
Advocacy for Policy Updates	✓	✓	✓
AI and Advanced Sortation Technologies			✓
AI and Predictive Analytics on Inventory Management	✓		
Apps for Consumer Incentives		✓	
Bottle Bills			✓
Chemical Recycling Technologies (Decomposition/Purification)			✓
Chemical Recycling Technologies (Conversion)			✓
Community Outreach Materials (Direct Mail, Banners, Info Card)		✓	
Competition and Challenges for New Designs	✓		
Consumer Facing Directory of Recycled Products or Brands		✓	
Directory of Recycled Content Suppliers	✓		
Documentaries and Reports		✓	
Drones			✓
Education Platforms for Recycling		✓	

Table 23 (Cont.)

Tools/Technologies	Plastics and Packaging Production	Purchase, Use and Material Management	Business of Recycling
Facilities Mapping (Collection Sites)		✓	
Government Mandated Fees	✓	✓	
Government Regulation and Bans	✓	✓	
Government Taxes and Subsidies	✓		✓
Horizontal and Vertical Integrations	✓		✓
Loyalty and Reward Platforms		✓	
Machine Learning and Predictive Analytics on Plastic Streams			✓
Manufacturing Standards	✓		
Material Compatibility Database	✓		
Material Composition/Streams Database			✓
Material Innovation to Design for Recyclability	✓		
Material Tracking Hardware and Software			✓
Monetary Credits		✓	
New/Retrofitted Infrastructure (Collection Centers, Transfer Stations, MRFs)		✓	✓
New/Updated Policy	✓	✓	✓
Real Time Analytics		✓	✓
Regional How to Recycle Data Bank		✓	
Routing/Facility Optimization for Plastic Streams			✓
Satellite Imagery			✓
Smart Collection Bins		✓	
Subsidies to Compete with Virgin Plastics	✓		
Sustainable Product Discounts		✓	
Technology Advancement and Data Sharing Platform			✓

SOURCE: AFARA analysis

Table 24

List of Companies and Organizations Working on Tools/Technologies Relevant to Recommended Strategic Interventions

Tools/Technologies	Companies/ Organization	Region	Notes
Advocacy for Policy Updates	Environmental Defense Fund (edf.org)	US	Environmental advocacy to end plastic pollution
	Break Free from Plastic	Global	Movement to reduce plastic
AI and Advanced Sortation Technologies	AMP Robotics (AMP Cortex)	US	AI for sorting, picking, and placing material
	Zen Robotics	Europe	AI for sorting, picking, and placing material
	Umincorp	Europe	AI/sort at facility; magnetic density separation technique for sorting mixed plastics
	Clean Robotic (Trashbot)	US	Trash can with built in sortation
	Cambridge Consultants (Smart Bin)	Europe	Trash can with built in sortation using image recognition and rewards customers
	Garbi	US	Trash can with image recognition and builds grocery list for customers based on what's thrown away
	Peruza	Europe	AI based package deposit refund machine
	Machinex (SamurAI)	Canada	AI for sorting, picking, and placing material
	Sadako and Bulk Handling Systems (Max-AI)	Europe/US	AI for identifying complex objects in waste streams
	SAP (Plastics Cloud)	Europe	Machine learning and forecasting plastic trends (purchasing and recycling)
Alliances and Industry Collaboration	WEF Global Battery Alliance	Global	Alliance to take action related to batteries
	WEF Global Plastic Action Partnership	Asia	Partnership to collectively avert plastic pollution from source to sea
	EMF CE 100 Network	Global	Network of industry members committed to circular economy
	Alliance to End Plastic Waste	Global	Convenes stakeholders to invest and scale solutions to manage plastic waste and end of life solutions
	Platform for Accelerating the Circular Economy	Global	Public-private collaboration mechanism and project accelerator for the circular economy
	NSW Circular Economy Innovation Network	Australia	Network of government, industry, research organizations & communities established by NSW government
	Circular Economy for Flexible Packaging (CEFLEX)	Europe	Convenes stakeholers to take action
Apps for Consumer Incentives	Rubicon Technologies	US	Data collection by app users; on-demand trash pick up

Table 24 (Cont.)

Tools/Technologies	Companies/ Organization	Region	Notes
	Starlight Software Solutions	US	Data collection by app users; integrated apps - live inventory, ordering/payment, centralized dispatch, etc.
	Agilyx	US	PS decomposition and conversion
	Ambercycle	US	PET decomposition
	APK “Newcycling”	Europe	PE, PS, PP, and multilayer purification
	Biocellection	US	PE purification
	Cadel Deinking	Europe	PE/PP purification
	Carbios	Europe	PET decomposition
	CreaCycle GmbH	Europe	PE, PS, and multilayer purification
	Enerkem	Canada	Conversion
	Garbo (ChemPET Project)	Europe	PET decomposition
	Geo-Tech Polymers	US	PE, PS, and PP purification
	Gr3n	Europe	PET decomposition
	GreenMantra Technologies	Canada	PS decomposition and conversion
	IFP Energy Nouvelles	Europe	PET decomposition
	Illinois Sustainable Technology Center (ISTC)	US	e-Waste (i.e. PC/PA mixtures) purification
Chemical Recycling Technology	Ioniqa	Europe	PET decomposition
	Jeplan	Asia	PET decomposition
	Karlsruhe Institute of Technology	Europe	PE, PP decomposition
	Loop Industries	Canada	PET decomposition
	Next Generation	Europe	PET purification
	New Hope Energy	US	Conversion
	Next Generation Group	Europe	PET purification
	Nexus Fuels	US	Conversion
	perPETual	Asia	PET decomposition
	Plastic Energy	Europe	Conversion
	PolyCycl	Asia	Conversion
	Polystyvert	Canada	PS purification
	PureCycle Technologies	US	PP purification
	Pyrowave	Canada	PS decomposition
	Reclaimed EcoEnergy (REE)	US	Purification

Table 24 (Cont.)

Tools/Technologies	Companies/ Organization	Region	Notes
	Recycling Technologies	Europe	Conversion
	ReNEW ELP	Europe	Conversion
	Renewlogy	US	Conversion
	Resinate Materials Group	US	PET decomposition
	Resynergi	US	Conversion
	SABIC Innovative Plastics	US	PET decomposition
	TRASH2CASH	Europe	PET decomposition
	Tyton BioSciences	US	PET decomposition
	University of Massachusetts-Lowell	US	Multilayer packaging decomposition
	University of Ulsan	Asia	e-Waste purification
Collection Programs/ Services	Dow Chemical Company (Hefty Energy Bags)	US	Curbside collection from residential communities
Competition and Challenges for New Designs	SAP Leonardo (2018 Plastics Challenge)	Europe	Design competition to use innovative technology to eliminate single-use plastic waste
	MITSolve (2019 Rethink Plastics)	Global	Design competition
Directories (Sustainable Brands/Recycled Content Suppliers)	EPA (CPG Product Supplier Directory)	US	Recycled content/suppliers database
	CalRecycle (Recycled-Content Product Manufacturers Directory)	US	Recycled content/suppliers database
	Buy Recycled (RecycleMorePlastic.org)	Canada/US	Sustainable product database
	WRAP Recycled Content Database	Europe	Recycled content/suppliers database
	PlasticsMarkets	Canada/US	Recycled content/suppliers database
	SPOT (UL)	Global	Sustainable product database
Education Platforms for Recycling	Recycle Mate	Other	Consumer app with image recognition and information on correct disposal method
	Keep America Beautiful (KAB)	US	Programs, initiatives, education, grants, etc to end littering, improve recycling, and beautify communities
	Applying Systems Thinking to Recycing (ASTRX)	US	Consumer guides

Table 24 (Cont.)

Tools/Technologies	Companies/ Organization	Region	Notes
Government Taxes and Subsidies	European Union (Plastic Tax)	Europe	As of January 1, 2021; tax calculated according to the weight of nonrecycled plastic products at a rate of €800/ton
Investment Funds	Closed Loop Partners	US	Provides equity and project finance to scale products, services and infrastructure for the circular economy
	Circulate Capital	Asia	Financing innovation, companies, and infrastructure that prevent the flow of plastic waste into the world's ocean
	Circularity Capital	Europe	Private equity firm investing in European growth stage businesses in the circular economy
	Breakthrough Energy Ventures	Global	Investment aiming to accelerate innovation in sustainable energy and in other technologies to reduce greenhouse gas emissions
Breakthrough Energy Ventures	The Ocean Cleanup (Interceptor)	Europe	Collect from oceans/bodies of water; targeting the Great Pacific Garbage Patch and lakes
	The Great Bubble Barrier (The Bubble Barrier)	Europe	Using bubbles to redirect ocean plastics and prevent from entering oceans
Loyalty and Reward Platforms	SAP Leonardo Plastics Challenge prototype	Europe	Chip in cup payment tracking/loyalty program for customers
	Reward for Change	Europe	Tracks products purchased by customers, loyalty and reward program for environmentally friendly products
Machine Learning and Predictive Analytics on Plastic Streams	AMP Robotics (AMP Neuron)	US	Recognize characteristics of objects within a mixed material stream
	Greyparrot	Europe	Measures waste streams using AI-powered computer vision software for sortation
Manufacturing Standards	International Organization for Standardization	Global	Technical committee (ISO/TC 323) since Jul 2019 to develop requirements/ frameworks etc. to support UN SDGs
Material Composition/ Streams Database	SAP (Plastics Cloud)	Global	Stores data on plastics supply chain
Material Innovation to Design for Recyclability	Youth Contact Association (Leash the Lid)	Other	Keeps lid on bottles
	Connora Technologies	US	Epoxy resin that allows thermosets to be recycled (currently cannot due to bonds)
Real Time Analytics	Topolytics	Europe	Waste flows tracking

Table 24 (Cont.)

Tools/Technologies	Companies/ Organization	Region	Notes
	TemperPack	US	Material consumption tracking
	Universiti Tun Hussein Onn Malaysia (Smart Recycle Bin)	Asia	Wifi operated notification when bin is full
	Starlight Software Solutions	US	Material profiling and LEED reporting
	Trimble - InsightHQ	US	Cloud based platform for fleet analysis
	Trimble - Stratus	US	Material movement/calculate volumes
	Trimble - VisionLink	US	Cloud-based dashboard with querying tools for airspace consumption (i.e. tracks compaction efforts)
	CLAIM (FerryBox)	Europe	Live image of environmental conditions
Satellite Imagery	NASA - Earth Observing System	US	Satellite imaging

SOURCE: AFARA analysis