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Climate Knowledge Initiative

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Rethinking Plastics

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Industry Overview

Key Messages
Industry Overview

Landscape: Plastic production and demand are rising

- ~450 million metric tons of plastics were produced in 2025, with China and the U.S. accounting for half of that — 32% and 14%, respectively
- Plastics demand could exceed ~100 billion metric tons by 2060 if current investment and policy trends continue
- The current plastics system generates ~2 Gt of CO_2e, with limited progress in reuse and energy capture. Plastic production and related emissions are expected to double, or even triple, until 2060

Problem: Plastics generate negative climate impacts across the value chain

- While this deck focuses on climate, plastics also have health, social, and economic impacts
- Emissions are present across the full plastics value chain, from fossil-based feedstocks and energy-intensive production to high-volume industrial uses and end-of-life treatment
- Weak incentives and regulation further reinforce the problem; policy does not incentivize consumption reduction, plastic alternatives, recycling, or waste management

Solutions: Tackling plastics' impact requires coordinated action across five levers

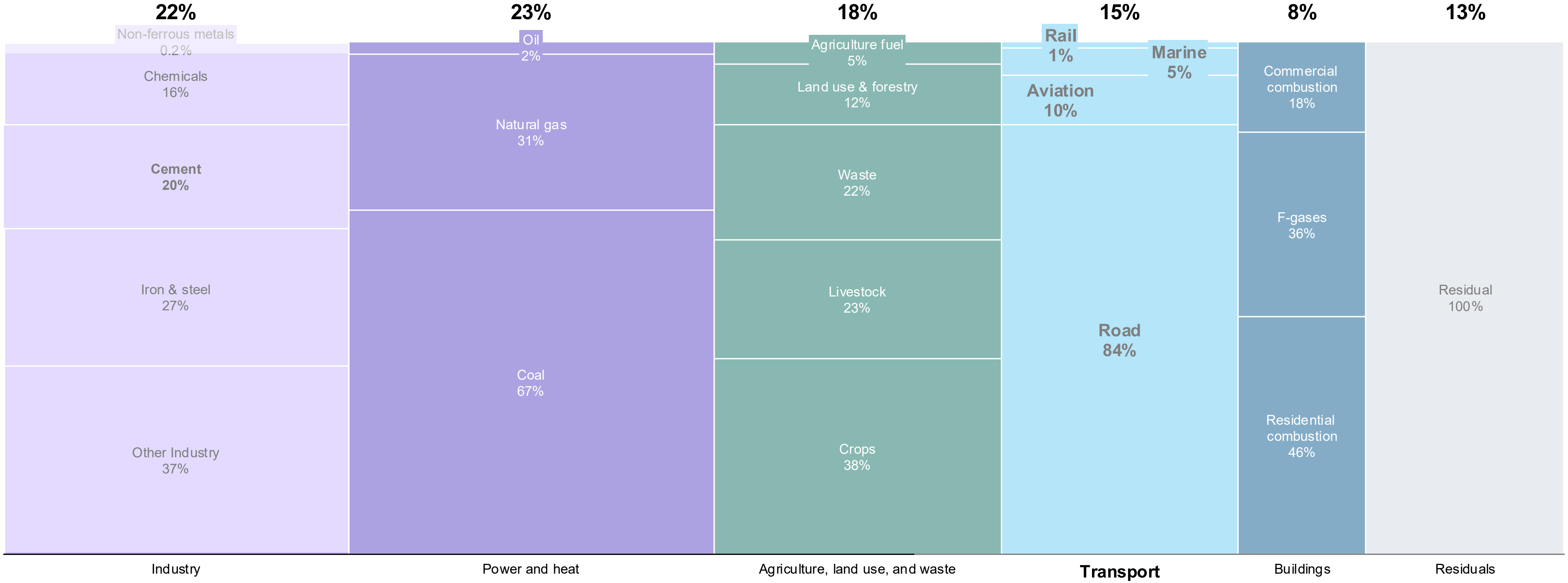
- An integrated, across-the-value-chain approach is needed to address plastics' climate impact
- Five key decarbonization levers are: (1) reducing demand; (2) enabling substitution; (3) scaling recycling; (4) electrifying production; and (6) applying carbon capture, utilization, and storage (CCUS)
- Solutions vary in overall impact and feasibility, driven by investment needs, technology readiness, policy alignment, and key barriers to scale

Key requirements to unlock change: Finance and policy

- Current capital is concentrated in downstream segments, while upstream innovation and infrastructure remain underfunded despite their mitigation potential
- Fragmented or outdated regulation, such as lack of mandates for recycling and inconsistent public procurement standards, can delay or block viable alternatives from scaling

Plastics account for around 4% of global CO_2 emissions

CO_2e emissions in 2025: ~55 billion tons



Source: Network for Greening the Financial System, NGFS 2025 climate scenarios (2024).
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Decarbonizing plastics could help uphold development and quality of life, while reducing negative externalities from overconsumption

Plastics have enabled human development and economic growth …

Food security

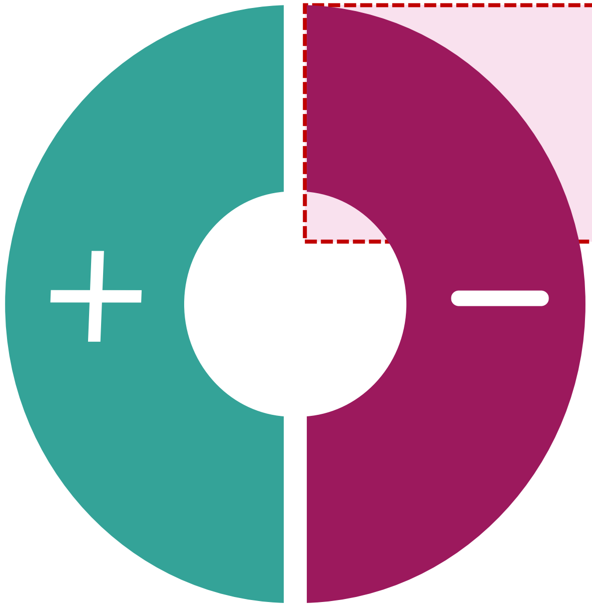
Packaging extends shelf life and reduces spoilage in transit. This enables affordable food distribution to remote and low-income regions.

Critical healthcare

Sterile, single-use medical plastics lower infection rates and make scalable care possible in low-resource settings.

Economic development

Plastics have democratized everyday goods by driving down material costs. Low- and middle-income consumers can now afford products that were once out of reach.



… while overconsumption has created multidimensional costs; this deck focuses on decarbonization

Focus of this deck

Climate & environmental degradation

Growing GHG emissions (2.5%-4% annually) contribute to a warming climate. Insufficient waste management leads to pollution and other environmental costs.

Social & health harms

Pollution burdens fall disproportionately on low-income, frontline communities. Microplastics have been detected in human blood, lungs, and placentas.

Economic burden

Externalized costs of cleanup, healthcare, and lost ecosystem services total billions of dollars annually. Emerging economies that import plastic waste bear a disproportionate share of the cost.

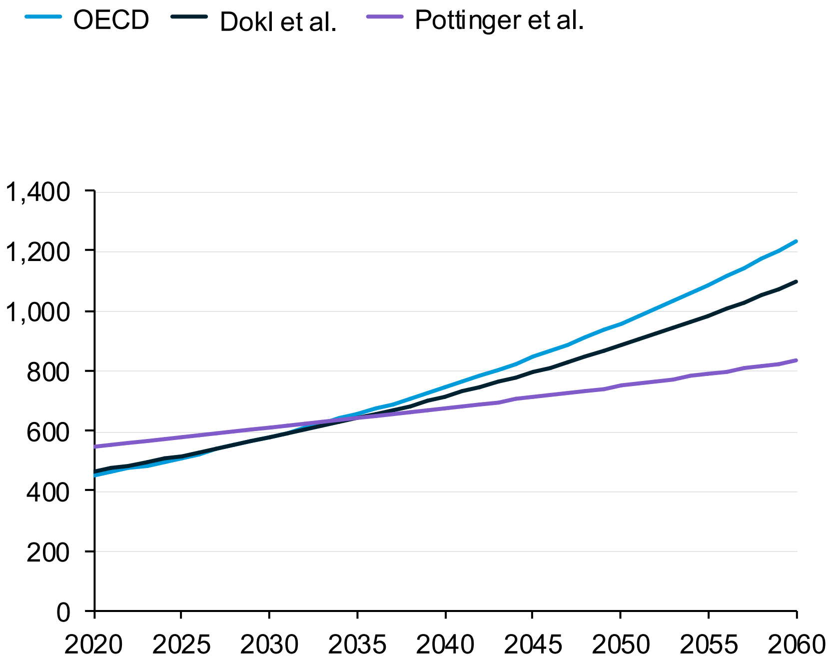
The opportunity: Reposition plastics from single-use applications to high-quality materials with an extended lifetime, supported by system-level post-use infrastructure

Sources: Strategies to reduce the global carbon footprint of plastics (Zheng & Suh, 2019).
Credit: Anika Behrndt, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Rethinking Plastics” (20 July 2026).

Current system generates ~450 Mt of plastics and ~2 Gt CO_2e; projected to grow significantly if current trends continue

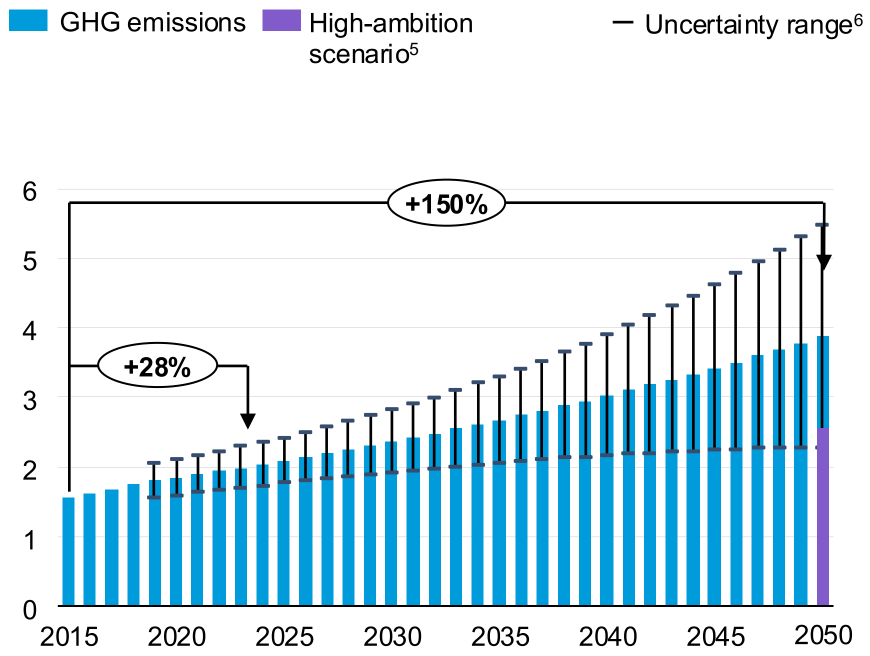
Plastics demand expected to grow ~2 to 3x by 2060 under "business as usual" projections

Plastics production[1] (million metric tons/year)



Plastics emissions increased ~28% in the past five years; projected to grow 150% by 2050

Total annual emissions and future projections from plastics[5] (Gt CO_2e/year)



Key Assumptions

- Plastic demand projections assume no changes in production technologies or regional demand structure. They reflect three forward-looking scenarios:
  - OECD (2022): ~2.5% to 4% annual growth driven by income and population growth in non-OECD economies
  - Dokl et al. (2024): CAGR of ~2.2%; regression-based optimization on historical trends (extrapolated to 2060)
  - Pottinger et al. (2024): CAGR of ~1.1%; machine learning + Monte Carlo; explicitly more conservative than OECD
- All three exclude microplastics (tires, textiles), PFAS, behavior/system change, and informal-sector waste flows
- Emissions based on OECD projection, which assumes 2.5% annual demand growth and current recycling trends

Sources: Global projections of plastic use and potential changes to 2050 (Dokl et al., 2024).
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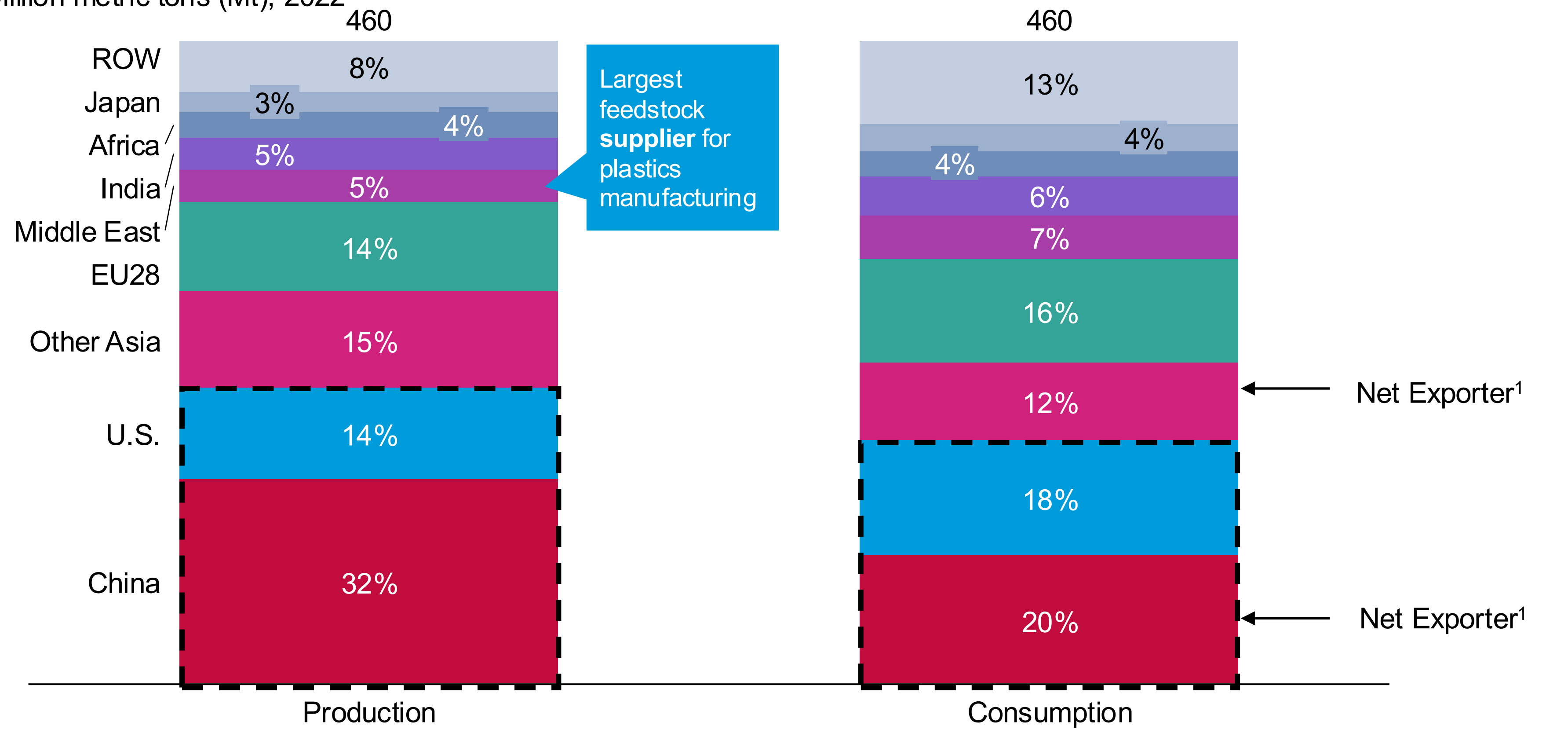
China and the United States are the leading plastic producers (~50%) and consumers (~40%)

Global plastic production and consumption by geography

Million metric tons (Mt), 2022



Observations

- **The scale of China's dominance is larger than it appears.** It has a production surplus of 12% of the global total
- **The consumption gap highlights global dependency.** The ROW is the most dependent, with those countries consuming more than they produce by over 60%
- **Geopolitical concentration of the plastics value chain:** A small number of Middle Eastern oil-rich nations control the feedstock but just two countries (the U.S. and China) operate half of the global manufacturing of primary plastics
- Africa has **18% of the world's population** but represents just **4% of global production**

[1]Net Exporter occurs when a country's production volume is larger than consumption volume; global consumption of plastic is considered equal to production based on global material flow accounting.

Source: Complexities of the global plastics supply chain revealed in a trade-linked material flow analysis (Houssini et al., 2025).

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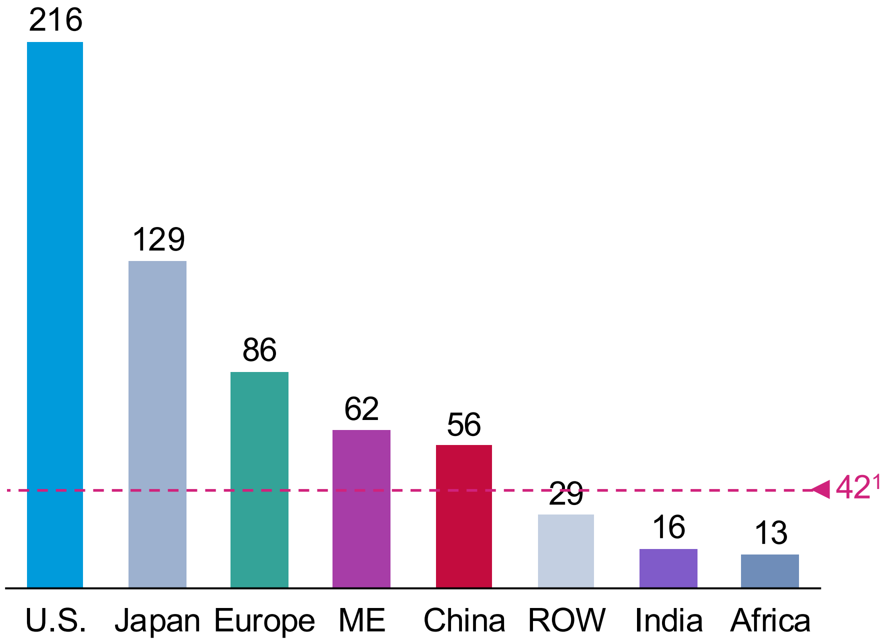
Plastics demand is concentrated in a few countries, with the U.S. leading both current use and future growth at ~3% CAGR

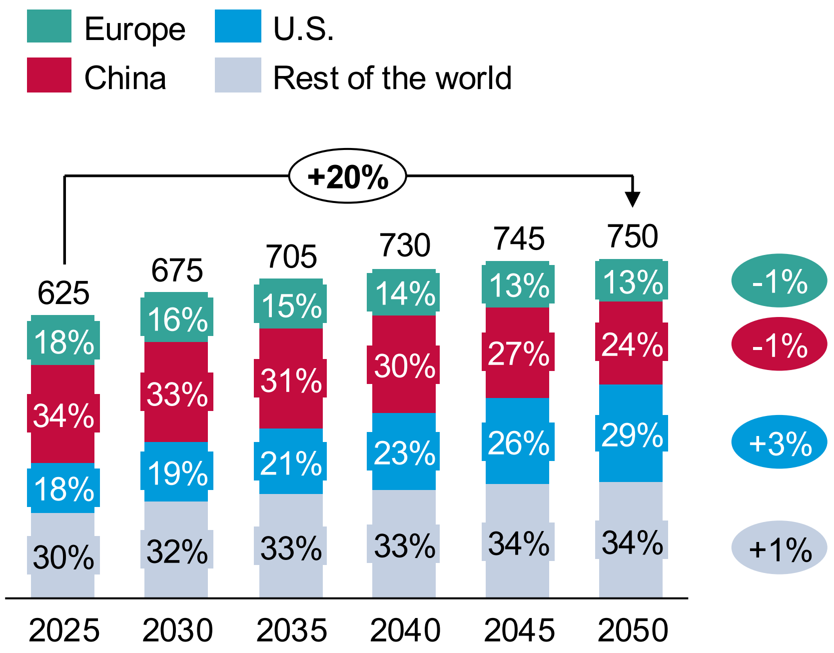
High-income countries, led by the U.S., have the highest per-capita plastics consumption

Global plastic consumption, kg per capita, by country, 2022



Plastics demand expected to rise >20% by 2050, with the U.S. driving the largest growth

Projected plastics market demand per region, Million metric tons per region, per year[2]



Observations

- **There is a stark disparity in plastics consumption between developed and developing nations,** with the **U.S. positioned as the highest per capita,** highlighting a critical area for environmental concern and policy intervention
- **Several factors likely to contribute to elevated plastic consumption** in the U.S. are:
  - **The convenience and low cost** of plastic materials, which have made them ubiquitous in daily life
  - Strong **single-use plastic** packaging for food, beverages, and other goods
  - **Widespread use of plastics in industries** such as construction, automotive, and textiles

[1] World average. [2] Values shown correspond to the business-as-usual (BAU) scenario that assumes continued consumption and waste management trends, driven by historical use patterns, sectoral applications, and population growth, without transformative interventions or GDP growth after 2023.
Sources: Complexities of the global plastics supply chain revealed in a trade-linked material flow analysis (Houssini et al., 2025); Pathways to reduce global plastic waste by 2050, (Pottinger et al., Science, 2024).
Credit: Yosafat Partogi, Mariana Castaño, Anika Behrndt, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

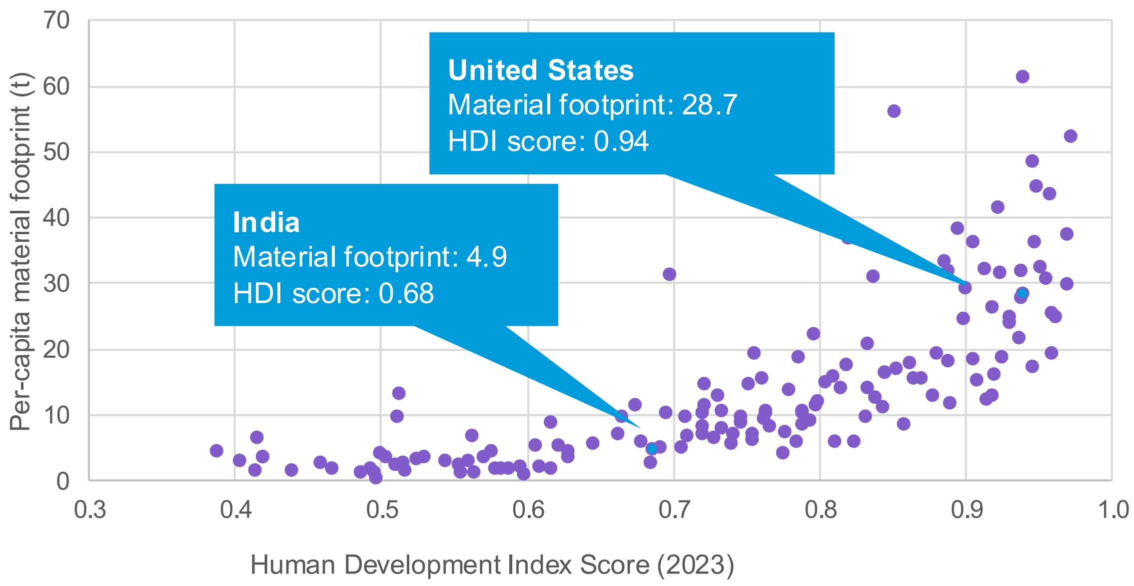
Material demand will rise with economic development; efficiency efforts should target excessive use

Plastic supports build-out of basic services in lower HDI regions

Water & Sanitation	**Challenge:** Access is still incomplete in lower HDI countries (e.g., only 90% in India) **Role of plastics:** Plastics enable affordable pipes, storage systems, and sanitation infrastructure
Healthcare	**Challenge:** Infection control and sterile care capacity remain limited **Role of plastics:** Single-use medical plastics enable sterile delivery of diagnostics, medicines, and care
Housing	**Challenge:** Poor housing quality and thermal efficiency affect health and energy outcomes **Role of plastics:** Insulation and affordable construction materials improve building performance
Food Security	**Challenge:** 20% to 25% of food is lost before consumption due to poor storage and transport **Role of plastics:** Packaging reduces spoilage and contamination where cold chains are weak

Human development rises quickly at low levels of material use

Per-capita material consumption vs. Human Development Index (HDI)



- Early increases in material use strongly improve human development, but gains diminish at higher consumption levels
- **Implication:** Demand-reduction strategies should prioritize high-consumption economies, while allowing targeted growth in essential plastic use in lower HDI countries to support development

Sources: Global Material Flows Database (International Resource Panel, 2025); Human Development Index (HDI) by Country 2026 (World Population Review, 2026); Valuing Plastics (UNEP, 2014); Turning Off the Tap (UNEP, 2023).

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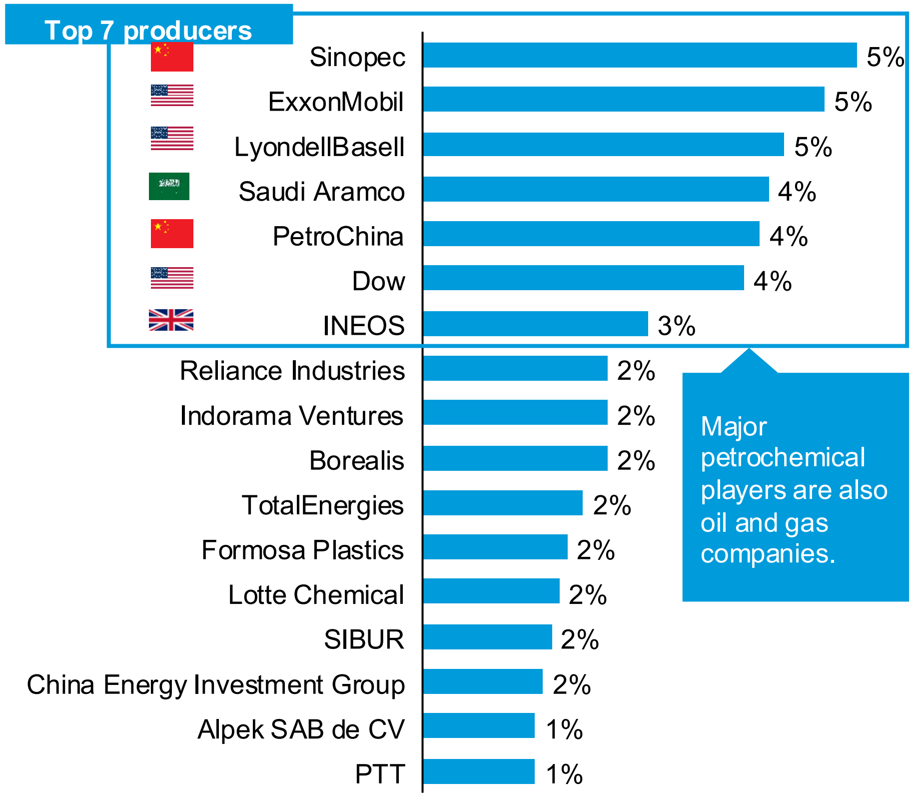
Investment in plastics is projected to grow, led by petrochemical companies with strategic interests to prolong demand

Seven firms account for ~30% of global plastic production



~50% of production from top 17 plastic producers globally, 2023

Oil and gas companies continue to invest in new single-use plastics assets (2023)

Company	Project Name	Location	Cost	Polypropylene	Ethylene	Polyethylene
ExxonMobil	Corpus Christi	U.S.	$10B		x	x
ExxonMobil	Baton Rouge	U.S.	$0.5B	x		
ExxonMobil	China Petroleum Complex	China	$10B	x		
Total Energies	Port Arthur	U.S.	~$2B		x	x
Chevron Phillips Chemical	Ras Laffan Petroleum Complex	Saudi Arabia	$6B		x	x
Chevron Phillips Chemical	Golden Triangle Petrochemical Company	U.S.	$8.5B		x	x
Shell	Pennsylvania Petrochemical Hub	U.S.	$6B		x	x
LyondellBasell	Thailand Parnets HMC Polymers	Thailand	N/A	x		
LyondellBasell	Ulsan PP/ Poly Mirae	South Korea	$0.42M	x		

Single-use applications

Sources: Plastic Waste Makers Index (Minderoo Foundation, 2023); Majority of the world's plastics (Zero Carbon Analytics, 2025); Once Seen as Industry Savior, Petrochemicals Losing Financial Appeal (IEEFA, 2024).
Credit: Yosafat Partogi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

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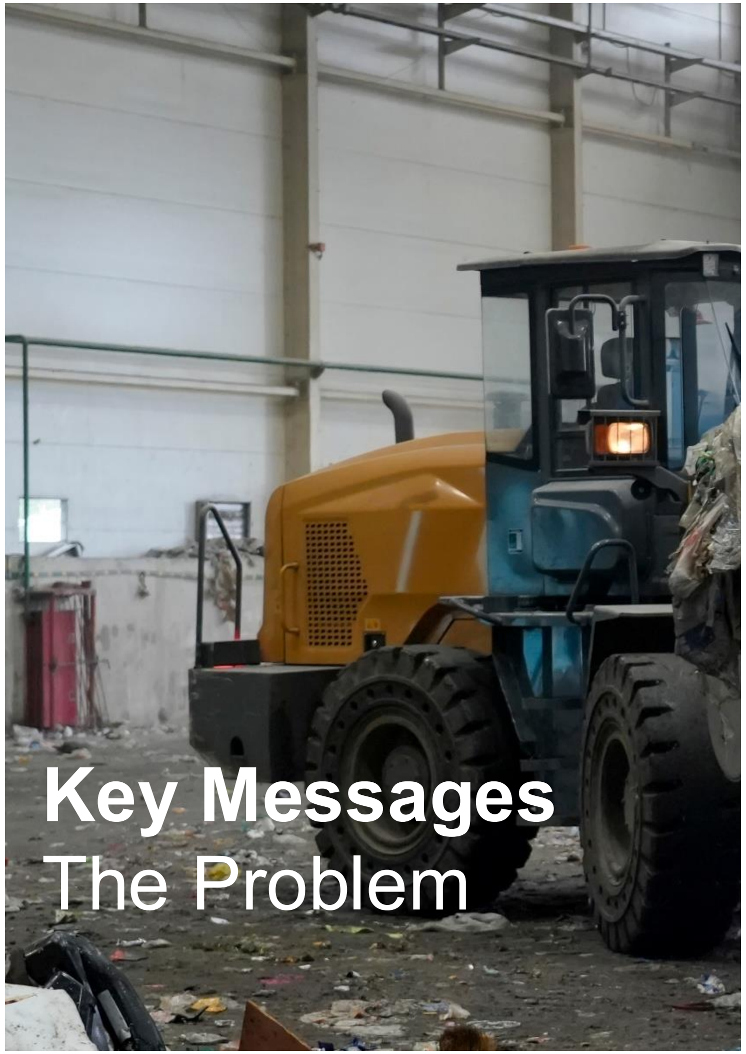
The Plastics Problem



Emissions intensity is linked to dual fossil dependency for feedstock and process fuel

- Plastics are overwhelmingly fossil-based, with approximately 99% of plastics derived from fossil fuels. ~20% of plastic emissions are tied to upstream feedstock extraction/mining
- ~70% of emissions are tied to the energy-intense production process, which requires high temperatures. Polymer cracking is the most energy-intense stage, with >30% of emissions coming from this production stage

Plastics are difficult to substitute, driving persistently high consumption

- Plastics' versatility means they can be used for multiple applications across nearly all industries
- Plastics remain substantially cheaper than most substitutes and can outperform many alternatives with more favorable strength-to-weight ratios, durability, insulating capacity, and resistance to breakage
- Low cost and low weight enable widespread single-use applications, encouraging "disposable" consumption patterns that lead to excessive use

End-of-life systems fail to address plastics management

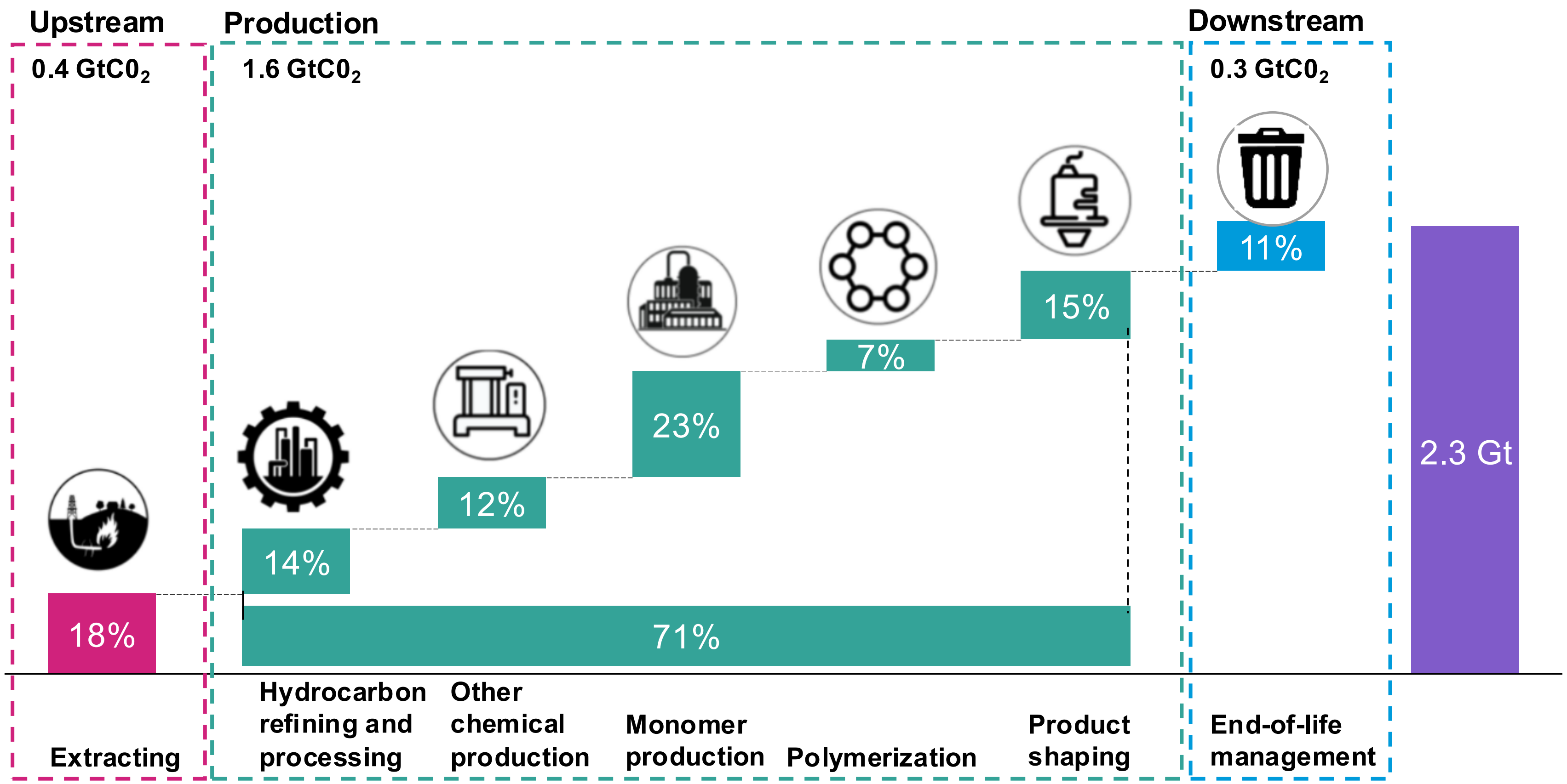
- Structural weaknesses in collection, sorting, and recycling economics result in avoidable GHG emissions, loss of material value, and widespread terrestrial and marine pollution
- Globally, ~23% of plastics are landfilled, ~19% are incinerated, ~49% are mismanaged, and >10% are recycled

Uncontrolled pollution deteriorates environmental health

- ~50% of global plastics are mismanaged at end of life, leading to significant pollution across different ecosystems
- Microplastics impair plants' photosynthesis and the ocean's carbon-sequestration capacity

~70% of plastic lifecycle emissions come from the production process, ~20% from fossil feedstocks, ~10% from end of life

Breakdown of emissions by lifecycle stage in traditional fossil fuel-based plastics



Key Decarbonization Challenges

- **Stage 1 (upstream):** Around 18% of emissions come from the extraction of fossil fuels, used as feedstock and fuel energy sources of plastic production. Extraction of fossil fuels causes direct emissions, like CH_4 leakage and flaring, along with emissions from fuel combustion
- **Stage 2 (production):** Around 71% of CO_2 emissions are generated in the production phase, where fossil fuels are burnt to achieve the high temperatures needed for the production of monomers and subsequent final plastics materials
- **Stage 3 (downstream):** The remaining emissions come from end-of-life management, primarily from incinerating plastic waste using fossil fuels, the most common disposal method

Source: Strategies to reduce the global carbon footprint of plastics (Zheng and Suh, 2019).
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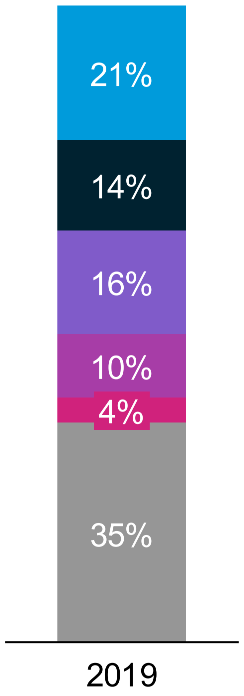
PE, PP, PET, PVC, and PS are the dominant types of plastic polymers produced and have common uses across industries

+50% of global plastics production comes from PE, PP, and PET

(% of global primary plastic production by polymer type, 2019)



Type of plastic	Common uses	Classification	Identification
PE (all types of polyethylene)	Food packaging films, shopping bags, insulation layers, and shampoo bottles	Single use	2, 4
PP (polypropylene)	Rigid containers, automotive parts, and construction materials	Durable	5
PET (polyester[1])	Beverages bottles and textile fibers	Durable	1
PVC (polyvinyl chloride)	Pipes, window frames, and medical tubing	Durable	3
PS (polystyrene)	Food disposable packaging and insulation	Durable/ Single use	6
Other polymers[2]	Foams, engineering plastics, and specialty coatings	Single use	7

[1]Include fibers. [2] Include marine and road marking coatings, elastomers tires, AB, ASA, SAN, PUR, and bioplastics, among other polymers.
Sources: Plastic Use by Polymer (OECD, 2019); How Plastic Is Made, (British Plastic Federation, 2025).
Credit: Mariana Castaño, Anika Behrndt, Ariela Farchi, Hyae Ryung Kim, Gernot Wagner. Share with attribution: Wagner et al., “Rethinking Plastics” (20 July 2026).

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Packaging has the largest share of plastic waste and consumption; textiles and construction have the highest associated emissions

High — Share of materials — Low

Global plastics consumption by industrial sector (Mt/year)		Main types of plastics consumed*			Avg. emissions (kg CO_2e/kg material)	Annual emissions (MtCo2e)	Estimated annual waste generated (Mt)	Lifetime (in years)
4%	Electronics							
10%	Other							
10%	Textile	PET	ACR	NYL	21	666	43	~5
11%	Consumer products	PE	PP	PET	2	224	47	~3
14%	Transportation	PP	PUR	PA	3	103	48	~13
19%	Construction	PVS	PP	EPS	7	995	38	~35
32%	Packaging	LDPE	PP	PET	2	364	156	~ 0.5
474 (total)								

Sources: Projections of Plastic Use (OECD, 2019); Microfibres from apparel and home textiles (Beverley et al., 2019); Carbon Footprint of Textile and Clothing Products (Rana et al., 2015) Deployment of mechanical and chemical recycling in European automotive plastics (Arca et al., 2025); Life-Cycle Assessment of Polypropylene Production (Alsabri et al., 2021); Building and Construction Plastics Market Size; All Plastics Aren't Created Equal (Market.us, 2024); Assessment of carbon emission potential of polyvinyl chloride plastics (Liang et al., 2023); Production, use, and fate of plastics (Geyer et al., 2017); Factors Influencing the Recycling of Plastic and Composite Packaging Waste (Torkelis et al., 2024); Clean Energy 101: All Plastics Aren't Created Equal (Rocky Mountains Institute 2023).
Credit: Anika Behrndt, Isabel Hoyos, Hyae Ryung Kim, Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Plastics remain difficult to replace because of significant material and cost advantages compared with alternative materials

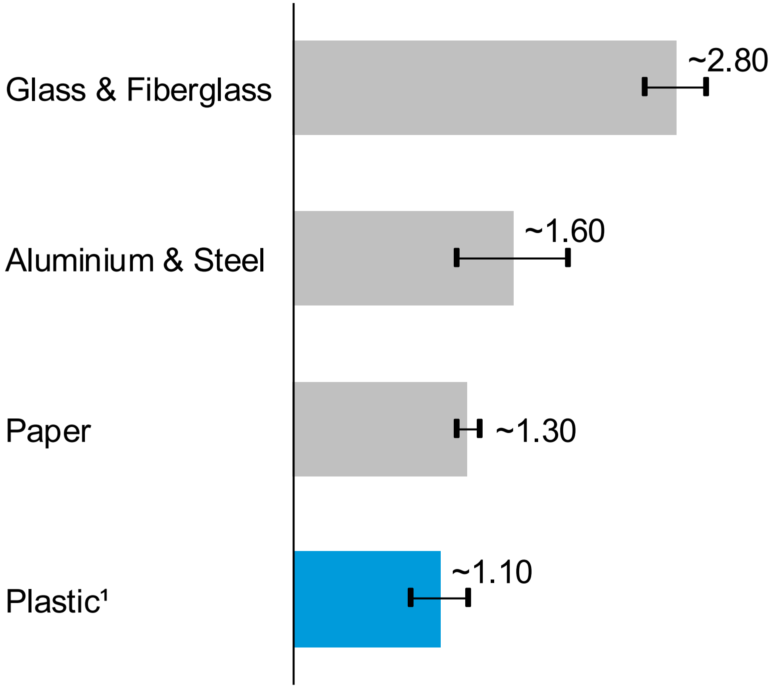
Plastics have a higher insulating capacity and are significantly more resistant and lighter than alternative materials

Relative behavior of selected chemical capabilities of other materials compared with plastics

	Insulating Capacity	Impact Resistance[2]	Corrosion Resistance	Weight[3]
Plastics	Poor conductivity of plastics make it a good thermal and electrical insulator, increasing design flexibility	Durable properties of plastics help them absorb and distribute energy from sudden impacts or shocks	Plastics resist damage when exposed to acids, lubricants, paint strippers, and other substances	Plastics' flexible qualities allow for the production of ultra-lightweight materials
Other materials	Metals, paper, and glass do not have the same insulating capabilities as plastics	Metals and glass, which can crack or fail over time, are less resistant to fatigue compared with plastics	Chemical substances may cause rust or corrosion in other materials, such as metals and paper	Material density of metals and glass result in heavier materials

Plastics are 2 to 3x cheaper than other materials with similar use cases

Average cost of materials in the U.S. ($/Kg)



[1]Using PE as a proxy for overall plastics prices, representative given high market share. [2]Impact resistance (robustness): The ability to withstand sudden force or shock without breaking, cracking, or deforming. [3]Comparing the weight of a 0.5L container using different materials.

Sources: Climate impact of plastics (McKinsey, 2022); The Advantages of Plastics Compared to Other Materials (Atlas Fibre, 2023); Aluminum (Trading Economics, 2025); Steel (Trading Economics, 2025); Spot Offers (The Plastics Exchange, 2025).

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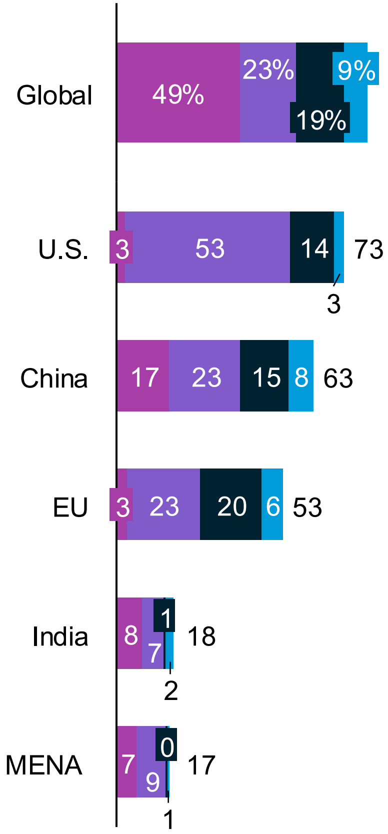
Global plastic waste remains largely unrecovered; treatment varies by region, but recycling stays low everywhere

Breakdown of end-of-life treatments for plastic waste, by method and region (Mt, 2019)

	Landfill	Incineration	Recycling	Mismanagement
Description	• Burial of plastics, alongside other mixed waste, in designated facilities	• Combustion of plastic waste	• Collecting, sorting, and processing for reuse as new feedstock	• Waste uncollected or improperly disposed of (open dumping, burning, leakage into environment)
Pros	• Limits waste to a delimitated area • Well-engineered facilities can have low emissions and capture methane	• Less land intensive then landfilling • Limits pollution and leakage	• Reduces pollution and emissions compared with other waste practices	• Low cost in absence of formal systems
Cons	• Poorly mantained facilities may cause leakage of hazardous materials into the environment	• High direct CO_2 emissions, limiting its role in long-term decarbonization	• Requires social-behavioral changes, which can be hard to adopt	• Major source of pollution (oceans, soils) • Direct human health impacts



Observations

- **U.S.:** Landfilling dominates, locking in long-term environmental liabilities (methane, land use, and leakage) despite relatively strong collection systems
- **Europe:** High reliance on incineration reflects constrained landfill capacity, creating significant CO_2 emissions and limited circularity
- **Asia and MENA:** Mismanagement remains the dominant pathway, driven by insufficient collection and waste infrastructure, presenting the largest source of environmental leakage

Sources: Annual plastic waste by disposal method: World, 2000 to 2019 (OECD – Our World in Data, 2023).
Credit: Anika Behrndt, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Plastics pollution exacerbates negative ecological impacts and further accelerates global climate change

Difference in size of plastic pollution creates diverse environmental and climate impacts, many of which remain poorly understood

Macroplastics

Kills **~100,000 marine mammals annually** due to ingestion or entanglement, affecting **>65% of marine mammal species**

Plastics in dumpsites block drainage systems, release GHGs, and leak toxic chemicals into soil and water

Floating macroplastics **reduce PAR[1] by up to 80%**, impairing CO_2 production, carbon uptake, and primary productivity

Microplastics & Nanoplastics

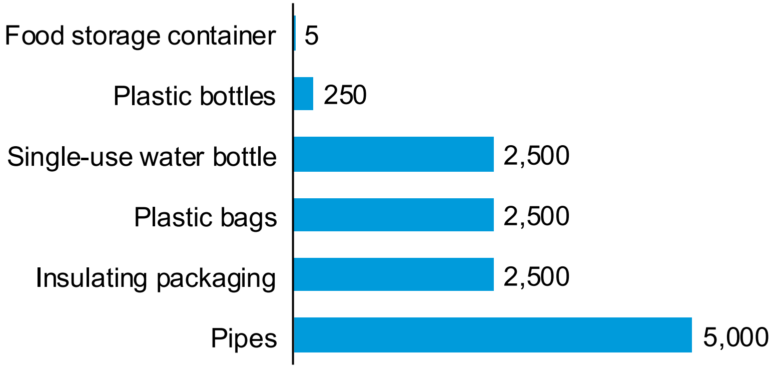
Reduce photosynthesis by **7%-12%** in algae and terrestrial plants, stunting primary production

Can **decrease surface albedo by 28%-77%**, accelerating glacial melting and releasing microplastics previously stored in ice

Emit up to **5.8 nmol of methane** and **14.5 nmol of ethylene** daily per gram of plastic during degradation

Long half-lives extend the warming potential of plastic

Estimated fragmentation half-lives of common plastic items (years)



- Macroplastics degrade via sunlight, heat, and wave action — but breakdown ≠ elimination.
- Smaller fragments = faster per-gram methane and ethylene release
- Long half-lives commit the atmosphere to centuries of continuing emissions — a long-tail climate cost lifecycle analyses miss
- Micro/nanoplastic effects on carbon cycling (photosynthesis, ocean carbon pump, albedo) are still nascent research

[1]Photosynthetically active radiation is the range of sunlight (400-700 nm) used by plants and algae for photosynthesis.

Sources: Plastic in Our Oceans (WWF, 2023); Multiecosystem photosynthesis losses under microplastic pollution (Zhu et al., 2025); Direct radiative effects of airborne microplastics (Revell et al., 2021); The fundamental links between climate change and marine plastic pollution (Ford et al., 2022); Microplastics in sandy soils (Aminzadeh et al., 2025); The links between marine plastic litter and the air-sea flux of greenhouse gases (Goddijn-Murphy et al., 2023); Degradation Rates of Plastics in the Environment (Chamas et al., 2020).

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Plastics Decarbonization Solutions

Reduction

- Demand reduction measures can curb demand for fossil-based short-lived plastics
    - Overall plastic waste can be reduced by ~30%; elimination and reuse models can reduce demand by 10% and 20%, respectively
- The most significant opportunities to reduce demand lie in the packaging and consumer goods plastics sector
- Scaling reuse needs industry alignment and policy support to overcome logistical and behavioral barriers

Substitution

- Bioplastics could abate 20% to 70% of CO_2 emissions, depending on the production feedstock
- Bioplastics make up <1% of production capacity due to cost and performance constraints. Within bioplastics, packaging is the largest segment at ~45%

Recycling

- Only ~10% of plastic waste is currently being recycled, and ~60% is deemed “unrecyclable”
- 20% to 35% of total plastics emissions can be abated if 40% to 50% of plastics are recycled
- Scaling chemical and mechanical recycling requires redesigning products for recyclability, improving collection and sorting systems, scaling existing infrastructure, and developing physical infrastructure

Electrification

- Steam cracking is the most carbon-intensive part of the value chain; electrified steam cracking (E-SC) offers a potential solution
- E-SC monomer production is bottlenecked by heat intensity, power infrastructure, cost parity, and TRL

Carbon capture, utilization, and storage (CCUS)

- CC can be applied during steam cracking or end-of-life incineration to reduce up to 25% and 9% of chain emissions, respectively; captured carbon can replace fossil fuels upstream in the plastics chain
- Use remains limited, but targeted policies and a coordinated CO_2 value chain can improve viability

Plastics decarbonization will need five levers to decouple from fossil fuels and reduce production emissions

Multi-tiered breakdown of solutions for plastics decarbonization

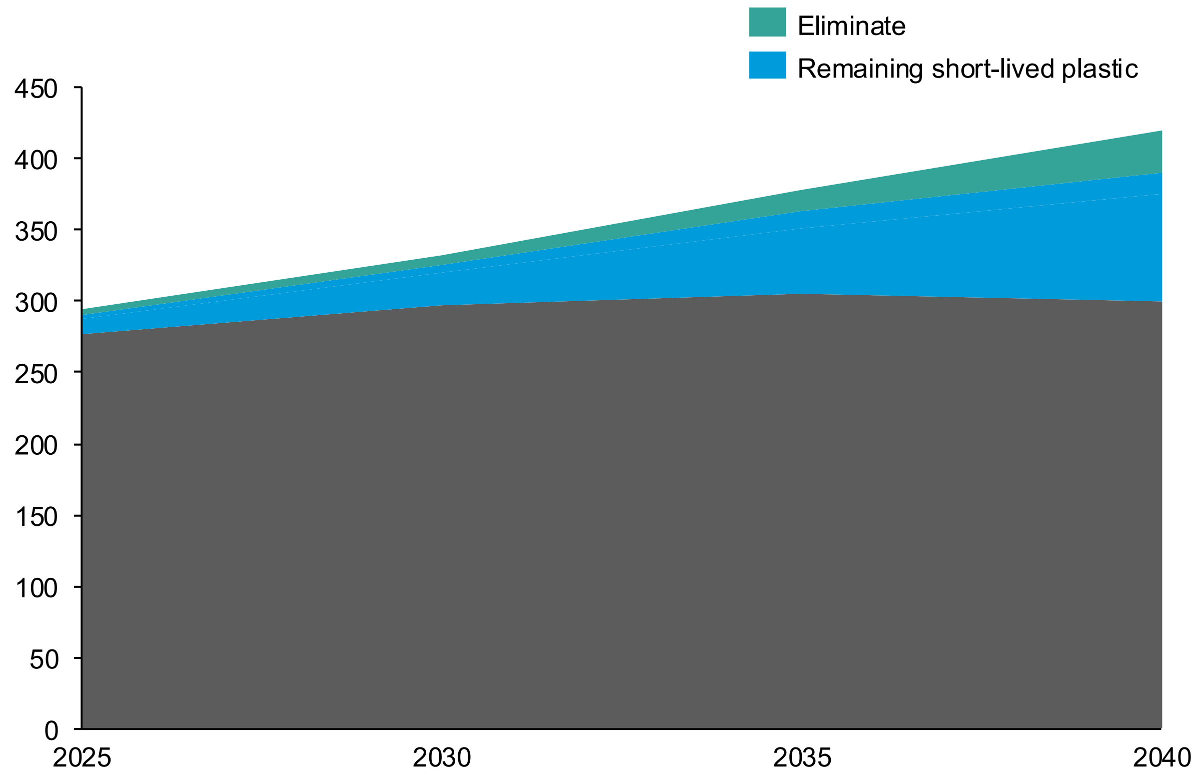
Goal	Reduce reliance on virgin fossil fuel feedstock				
			Decarbonize production processes		
Intervention	Reduce	Substitute	Recycle	Electrify	Carbon capture
Description	Eliminate redundant plastics and switch to reuse models where possible	Replace virgin fossil-based plastics with bio-plastics and other lower carbon alternatives	Scale mechanical and chemical recycling to extend material lifetime and reduce emissions-heavy incineration	Switch energy inputs for industrial processes from fossil fuels to renewable energy	Capture process emissions and repurpose CO_2 to offset hard-to-abate residual emissions in production
Impact (Mt of CO_2)[1]	6,000-9,000	900-3,800	2,800-4,100	250-3,300	210-380
Cost (US$B)[2]	~150	Medium	~160	~700	Medium
Implementation complexity	Medium	Medium to high	Medium to low	Medium	High
Challenges	Strong policy alignment required	Technology readiness level still low; more R&D required	Requires high up-front investment	High up-front investment for infrastructure investment	Technology highly ambiguous, expected to be ready in next 10 years

[1]All values are indicative, rounded, non-exhaustive, and based on current trajectory. See **Appendix 1** for detailed notes of sources and assumptions. [2] Low: $0 to US$50 billion; Medium: US$51billion to US$300 billion; High: US$301 billion+. Refer to section "Key requirements to unlock change" for more cost details and assumptions.
Sources: Plastic Waste by region and end of life fate (OECD, 2023); Plastic Recycling: Techno Economic Analysis (Salahuddin et al., 2023);
Credit: Anika Behrndt, Isabel Hoyos, Hyae Ryung Kim, Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Eliminating unnecessary plastics and scaling reuse models can reduce demand for short-lived plastics by up to ~30%

Elimination and reuse can reduce the need for short-lived plastics[1] by ~10% and ~20%, respectively, ~125 Mt in total

Million metric tons of plastic produced per year; BAU scenarios



	Elimination	Reuse
Market Levers	• Removal of **redundant, problematic[2], or virgin** plastics from products and supply chain • **Redesign** of packaging to use **less plastic** or avoid it entirely	• Scaling of **reusable/refillable** packaging • Ecodesign to improve product **durability** and **lifespan** • Market shift toward **service-based reuse/refill systems** (e.g., dispensing stations plastic washing pool systems)
Policy Levers	• Controls (e.g., taxes, phaseouts, complete bans) on the **highest polluting plastics** • **Taxes or caps on virgin plastics production** to make secondary markets more competitive • **Tax breaks** for secondary plastics • Removal of fossil fuel subsidies	• Develop **product standards** at the international level for longer lifespan and improved durability • **Invest in coordinated reuse** systems, reverse logistics, and delivery model infrastructure • Advance **research on environmental impacts** to inform better product design • **Educate citizens** on environmental benefits of reuse models through awareness campaigns

[1]Short-lived plastics are packaging and consumer products; average use cycle is 0.5 to three years, with the highest likelihood of ending up as plastic pollution. [2] Plastics that contain hazardous chemicals, hinder circularity, disrupt the environment, or are non-reusable or recyclable.

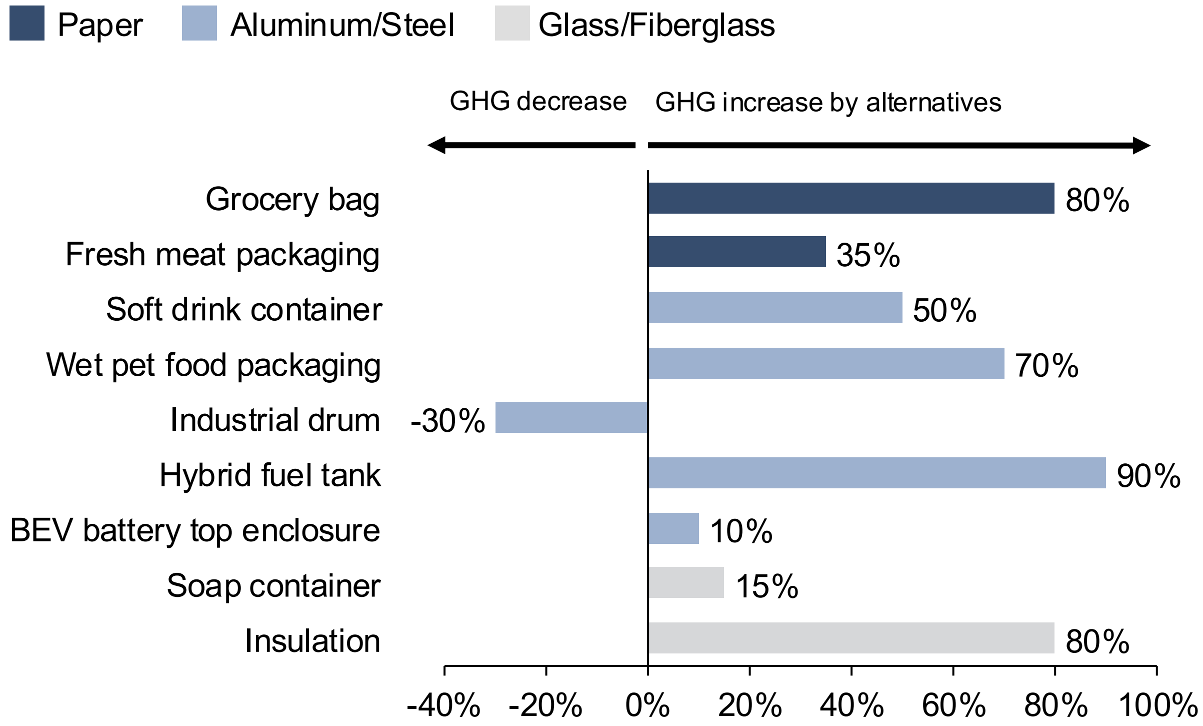
Sources: Turning off the tap (UNEP, 2023); Policy Scenarios for Eliminating Plastic Pollution by 2040 (OECD, 2024); Plastics and the circular economy – deep dive (EMF, 2019); Reshaping Plastics (Systemiq, 2022); How Can We Incentivize Plastics Reduction (Sustainability Directory, 2025).

Credit: Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Rethinking Plastics” (20 July 2026).

Plastics often show lower per-item emissions, but excessive use adds significant avoidable emissions

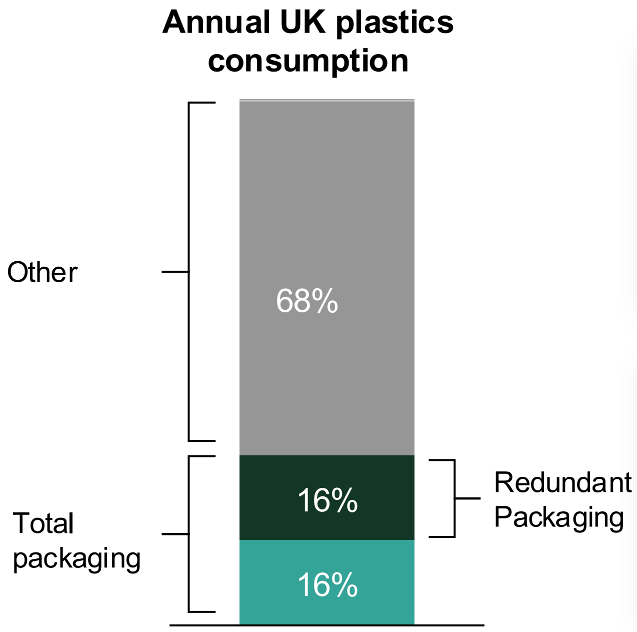
Plastics have lower weight, material input, and emissions when compared with alternatives across use cases

GHG increase from substituting plastics with alternative materials



UK example: Redundant plastics packaging is especially prevalent in food and consumer goods items

Excess plastics packaging, at 16% of total annually consumed plastic



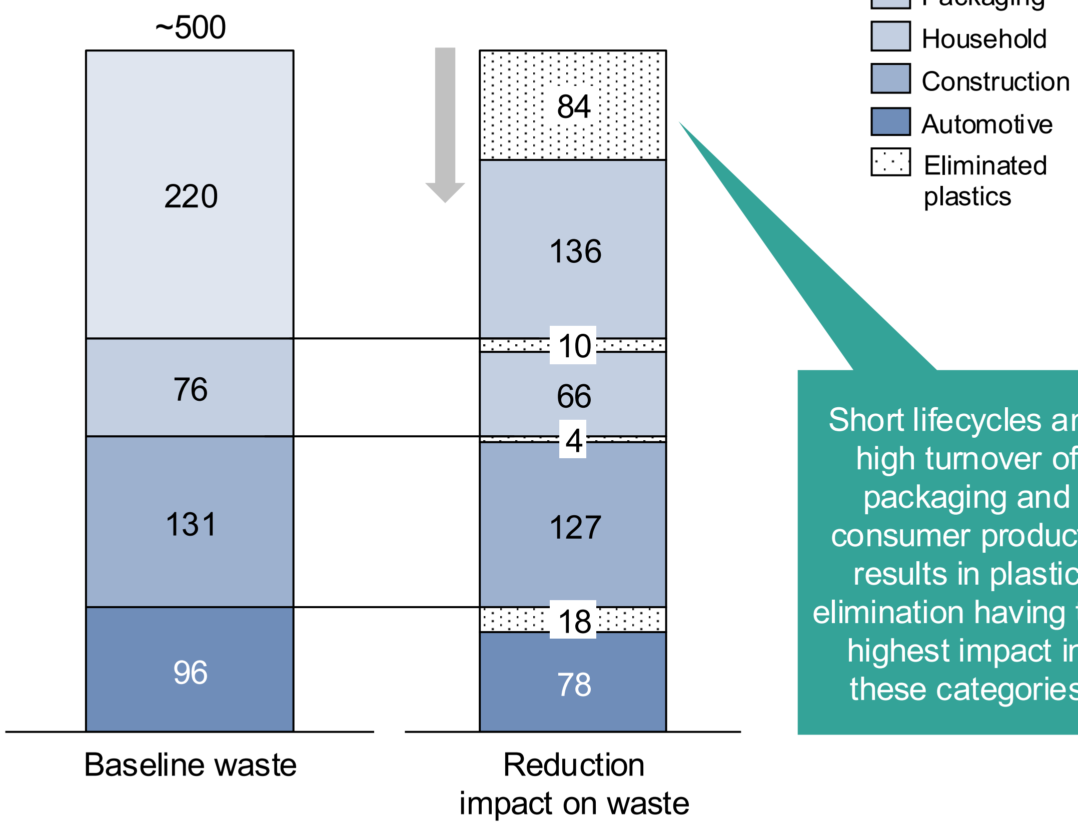
Packaging and consumer products with the highest potential for plastic reduction

Plastic elimination is most relevant for packaging and household products, while reuse applies across industries

✓ Applicable[1]	*Elimination*	*Reuse*
Packaging	✓	✓
Household	✓	✓
Construction		✓
Automotive		✓
Responsible stakeholder	*Retailers, consumer goods brands*	*Consumer goods brands, OEMS, construction companies*

Elimination and reuse measures can reduce plastic waste by ~30%, with the highest reduction in packaging[2]

Mt plastic waste in 2050[3]



Short lifecycles and high turnover of packaging and consumer products results in plastic elimination having the highest impact in these categories

[1] Can be more easily implemented/adapted and lead to a higher impact. [2] Absolute values for global plastic waste reductions are approximated by applying EU sectoral reduction rates from Systemiq's Circularity Scenario to global plastic-use baselines. [3] Based on the four largest contributing sectors, which together account for ~80% of total plastic waste generated.

Sources: Reshaping Plastics (Systemiq, 2022); Pathways to reduce global plastic waste mismanagement and greenhouse gas emissions by 2050 (Pottinger et al., 2024).

Credit: Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

By using a concentrate-based model, Replenish reduces plastic packaging volume by up to 90% and lowers transport costs

Overview	• U.S.-based company founded in 2010 • Provides customizable packaging platform for liquid concentrates
Product	• The company offers a reusable, durable spray bottle that attaches to pods with concentrates; ingredients are 99% plant-derived • **One pod** provides enough product for **six bottles**
Business model	• Replenish retails ~50% below competitors' premixed cleaners; one truckload of pods = 17 truckloads of conventional bottles, cutting freight and warehousing costs proportionally
Results	• The concentrate model also reduces resin input costs by ~90% per unit of cleaner delivered • The reduced volume of packaging shipped results in lower transport costs and emissions • Water transport distances are reduced due to concentrate product • Integration into online shopping platforms maximizes consumer convenience and incentivizes adoption

Refill-on-the-go models similarly reduce transport costs and emissions by lowering the volume of packaging shipped; however, widespread and accessible refill stations are essential to drive consumer adoption

[1]As of 2020.

Sources: Rethinking Packaging (EMF, 2019); A smart reuse system for household products: Replenish (EMF, 2021); Replenish homepage.

~33% of packaging is hard to recycle and poorly suited to current reuse formats, creating the need to redesign for circularity

Four main packaging plastic segments most easily targeted for redesign

Plastic segment	Examples	Share of packaging	Key barriers	Redesign examples
Small format packaging (40-70 mm)	Straw packages, sweet wrappers, lids, tear-offs, sachets, films	10% **~20 Mt**	• Easily escapes collection due to small size • No viable economic reuse or recycling pathway	• Edible or water-soluble films (Notpla seaweed sachets for condiments; dissolvable detergent pods) • Refill/bulk dispensers for sauces, cosmetics, and personal care
Multi-material packaging	Plastics in inseparable layers with other materials - e.g., pouches, snack packaging	13% **~26 Mt**	• Cannot be economically recycled • Recycling causes significant loss of material value	• Mono-material recyclable pouches (all-PE or all-PP stand-up pouches — e.g., Amcor AmPrima, Mondi Retort Pouch Recyclable)
Uncommon materials	PVC, EPS, and ES[1]	10% **~20 Mt**	• Small volumes in market prevent economies of scale	• Replace EPS (Styrofoam) with molded pulp, mushroom mycelium (Ecovative), or corrugated inserts
Nutrient-contaminated	Coffee capsules, organic waste bags, to-go food packaging	**Not quantified**	• High contamination with organic materials makes cleaning and high-quality recycling difficult	• Industrially compostable coffee capsules (Halo, Notpla, Nespresso) • Reusable to-go container schemes (DeliverZero, Vytal)

[1] Count accurate as of 2020. [2] CAGR calculated using FY2024 revenue of £690 million and 2007 revenue of US$292 million, with the 2007 figure converted from U.S. dollars to pounds using average 2007 USD/GBP exchange rate of ~2.00 over a 17-year period.

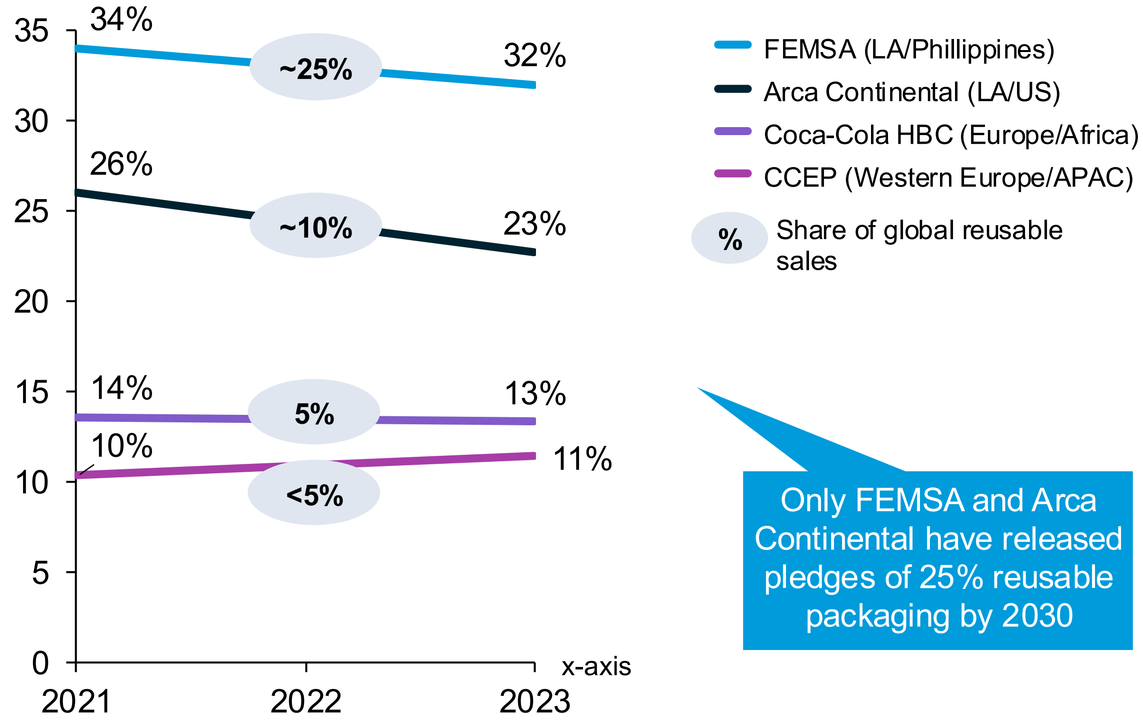
Sources: Naked Products (Lush, 2025); Environmental policy (Lush, 2025); Create a cosmetic revolution (Lush, 2025); Lush pays customers to recycle plastics cosmetics packaging (Wink, 2024); Clean Scrub (Forbes, 2007); Lush Fresh Handmade Cosmetics Financial Report FY24 (Lush, 2024).

Credit: Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Coca-Cola's Latin America rollout shows the three enablers reuse needs: shared infrastructure, standard design, and digital tracking

Despite declines since 2021, Latin America retains the highest reusable share per bottler and largest share of global reusables

Share of reusable packaging in Coca-Cola bottler company 2021 to 2023, %



Favorable reuse infrastructure, enhanced bottle tracking, and standardized design support Coca-Cola rollout in Latin America

Favorable landscape & economics

- Reuse infrastructure **maintained since 1990s** because refillable bottles remained cost-competitive with virgin packaging, particularly for lower income consumers (especially with deposit return schemes)
- Reusable packaging market valued at **$9 billion in 2024**; estimated CAGR of ~5% to 2030
- National goal of 30% of bottles to be reusable by 2026 in Chile; public-private Colombia Plastics Pact

Standardized design

- Standard **"universal bottle" design** to streamline collection, cleaning, and refilling process; introduced in Brazil in 2018
- Made from refillable PET

Enhanced tracking

- Coca-Cola scales reusable and refillable bottles in Latin America by **laser-engraving each bottle** with a **unique QR code** using GS1 Digital Link, developed in partnership with WIPTEC and OPTEL
- Enables **full tracking** of every bottle's refill cycles and lifecycle

Sources: GS1 Coca-Cola's reusable bottles, refillable bottles benefit from innovative QR codes powered by GS1 (GS1, 2024); Coca-Cola fails to increase reusable packaging (Oceana, 2024); Coca-Cola Latin America's reusable refillable bottles (GS1 UK); Latin America shows the world (Business Reporter, 2025); Colombia Plastics Pact (Cembre, 2024).

Credit: Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Return models are driving customer adoption of reuse and plastic elimination by offering at-home returns and financial incentives

Return at home

DabbaDrop

Overview	• Founded in the UK, 2018
Product	• Stainless steel food container (Dabba)
Business model	• Food is delivered weekly to customers; with each delivery, the previous Dabba is collected, cleaned, and put back into circulation for future deliveries • Meals are delivered by electric bikes
Results	• Has saved **>203,000 plastic containers** from being used, avoided **18,360 kg** of GHG emissions and **2,500 kg of food waste**[2] • **Unit economics:** Container amortizes in ~10 deliveries (~2.5 months for a weekly subscriber). Over a Dabba's 100- to 200-cycle useful life, it displaces ~40-80 pounds of disposable packaging — a 10 to 20x return on container CapEx. Across the 203,000 containers saved to date, ~£60K to £100K in packaging costs have been avoided, before counting waste disposal and plastic tax savings

Return on the go

Coca-Cola

Overview	• Founded in the U.S., World Without Waste initiative launched in 2018
Product & business model	• Reusable PET bottle; can be reused **up to 25 times** • **US$425 million** has been invested in redesign and reuse infrastructure • Customers pay an indirect deposit upon bottle purchase and receive a discount on the next purchase once the bottle is returned
Results	• **1.2%** of bottles company-wide are reusable as of 2023; **7% of reusable bottles** by volume are sold in Latin America • **>90%** return rate; 15% higher likelihood of repurchase. In Brazil, **reduced** new bottle **production by 1.8 billion units annually** • **Reduces** emissions by **47%** and water use by **45%** • Refillable bottles break even at about three to five cycles. Over a 25-cycle useful life, each displaces ~24 single-use bottles and saves Coca-Cola ~$1.00 to $1.50 in net materials cost — a 6 to10x return on the incremental bottle CapEx. At Brazil's 1.8 billion bottles per year displaced, annual materials savings are ~$70M to $110M, implying a four- to six-year payback on the $425M infrastructure investment

[1] Count accurate as of 2020. [2] As of December 2025.

Sources: Rethinking packaging (EMF, 2019); Can Coca-Cola once again become a leader in refillable bottles (PIRG, 2025); Coca-Cola's 25% reusable packaging goal (Beverage Daily, 2022); Coca-Cola lowers ambition with new 2035 packaging sustainability targets (Packaging Dive, 2024); DabbaDrop homepage (2025); DappaDrop (Planetfood.news, 2024); How It Works (DabbaDrop, 2025); A reusable bottle design for multiple brands: Universal bottle (EMF, 2021).

Credit: Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

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Reduction is constrained by packaging redesign and infrastructure gaps, higher upfront costs, and uneven consumer adoption

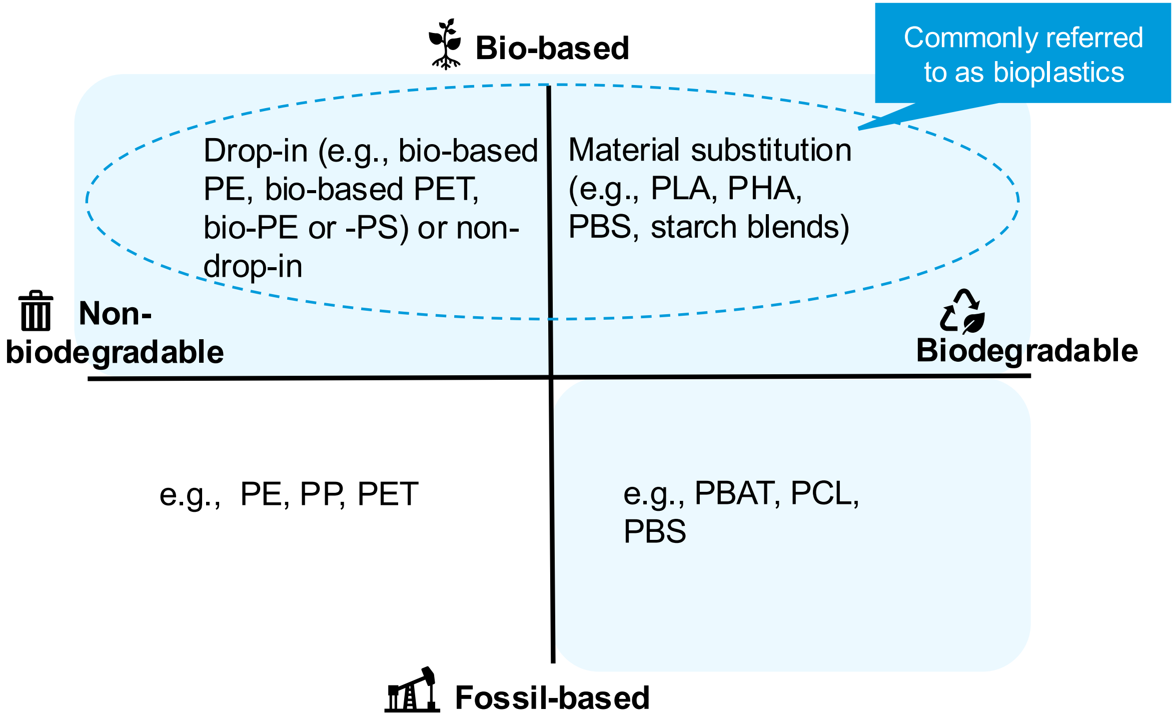
	Lack of necessary infrastructure	Consumption behavioral patterns	Economic limitations	Legacy design systems
Bottlenecks	• Investment skewed downstream toward recycling • **Limited reverse logistics** infrastructure	• **Disposable models quicker and more familiar** to consumers • Reuse models still **expensive for users,** disincentivizing adoption	• Reuse and elimination **unprofitable for certain plastics** • **High upfront costs** for reuse models	• **Lack of standardization** in plastic products • **~30%** of plastics designed to be disposed of, unrecoverable, or non-reusable
Solutions	• Pool resources • **Prioritize mature sectors** to roll out infrastructure more quickly • Institute deposit return schemes (DPRs) for easier collection	• **Incentivize adoption** of reuse by making models more convenient (e.g., standardized DPRs, return-at-home models) • Design out hard-to-collect plastics in consumer products	• Government subsidies **to de-risk investment** • **Resource pooling to** share collection and sorting costs • **Maximizing return and reuse rates**	• Government measures to **disincentivize single use** (taxes, bans, EPR schemes) • Investment in **product standardization** and education campaigns

‘Bioplastics’ refers to a wide range of materials that emerge as a lower emission substitute for traditional plastics

Polymer material matrix, categorized by source and biodegradability

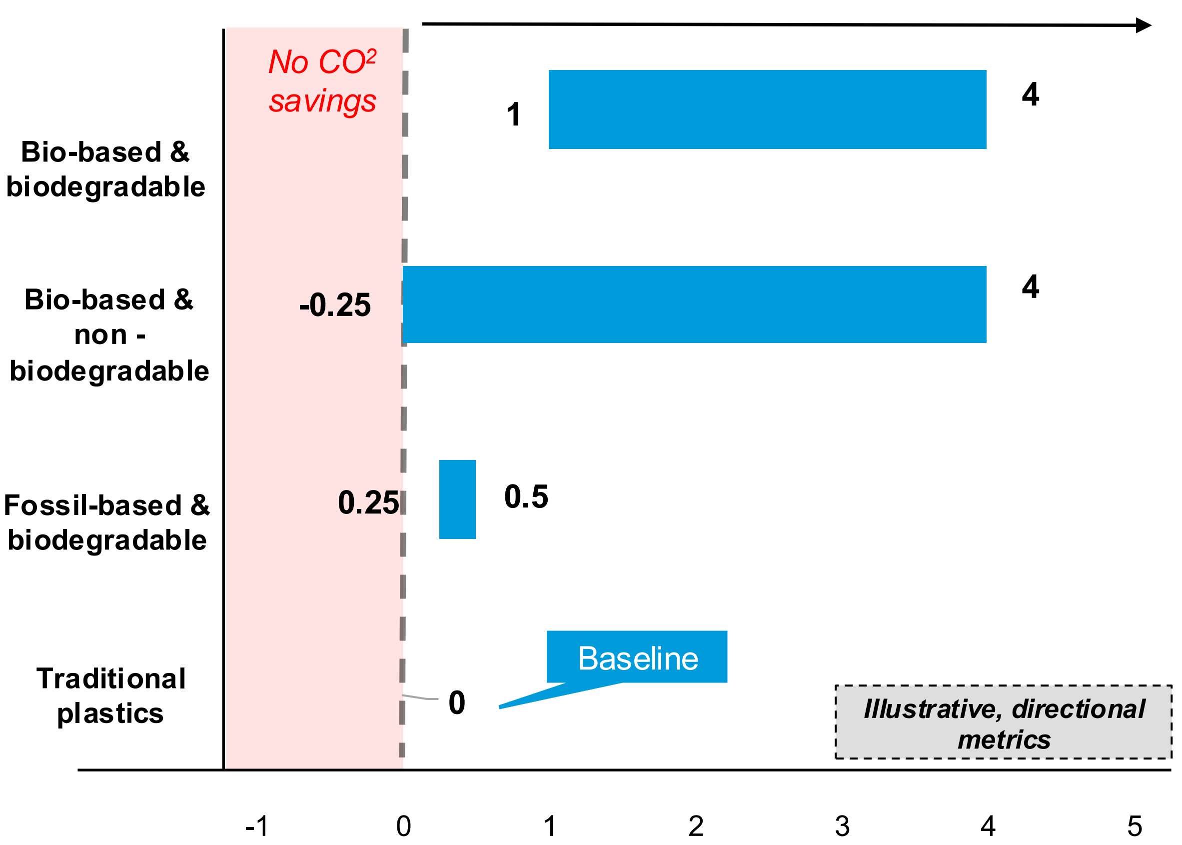
Bioplastics | Traditional plastics

Bioplastics is an **umbrella term; “drop-in” bio-based materials** are chemically **identical** to petrochemicals, while **new polymers** have different structures



Abatement potential

Kg of CO_2e saved per kg of polymer produced, against traditional plastic



The emission reduction potential of bioplastics depends significantly on the type of feedstock used for production

	1st Generation	2nd Generation	3rd Generation
Feedstock type	Traditional **agricultural crops**: • Corn • Sugarcane • Beets	**Cellulosic crops** and agro-industrial **waste**: • Corn and wheat straw • Sugar cane bagasse • Beet pulp	Novel, **non-land-based**: • Algae • Biowaste
Advantaged and challenges	• Potential for **lower emissions compared to fossil-based** plastics – Depending on crop used and land management practices • Can be **land-efficient**[1] if the land management practices are optimized for crop growth • Can lead to **land-use change**, if land is adapted for feedstock cultivation	• **Reduces land-use change** pressure by leveraging by-products as key feedstock – Removes problematic feedstock vs. food competition • Can have **lower emissions** compared to 1st generation • Can be **less land-efficient** compared to 1st generation (requires more land per ton of plastic produced)	• **Potential for carbon-negative** outcomes • **Low technological readiness and high costs** compared to 1st and 2nd generation
Bioplastic applications	Lactic acid, PLA, thermoplastic starch, PHA	PHA, lactic acid, reinforced composites	PHA, PLA, functional additives, fillers for polymers

Key considerations

- The environmental **impact** of a feedstock **cannot be determined by generation** alone
  - Must be assessed on an individual basis to evaluate the specific impact on land-use change, local socio-economic trade-offs, etc.
  - Must be considered for regionally specific impacts
- The **productivity and efficiency** of a feedstock – which are key determinants of its environmental impact – **varies greatly by feedstock type and region**

[1] Hectares of land used per ton of plastic produced

Sources: Leveraging biogenic sources for plastic decarbonization (Roijen & Miller, 2025); Feedstocks fact sheet, (Bioplastics Feedstock Alliance, 2020); Biofuels (ScienceDirect, 2024).

Credit: Ariela Farchi, Sean Lee, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner et al., “Rethinking Plastics” (20 July 2026).

Bio-based and biodegradable plastics lead on climate; cost and fossil system lock-in keep all bioplastics under 1% of capacity

Key features of bio-based and biodegradable plastics

	Bio-based		Fossil-based	
	Biodegradable	**Non-biodegradable**	**Biodegradable**	**Non-biodegradable**
Main use cases	Food service packaging, agricultural mulch, and 3D printing	Bottles, caps/films, textiles, and auto parts	Compostable films/bags and some medical uses	Packaging, construction, automotive, and electronics
Global production capacity *(Mt)*	~1.0 Mt (0.25%)	~1.1 Mt (0.27%)	1.2 Mt (0.30%)	> 400 Mt
Polymers	PLA, PHA, PBS, starch blends	Biobased PE, PET, PA, PTT	PBAT, PCL	PE, PP, PET
End of life/ pollution	Industrial composting	Landfill, recycle	Industrial composting	Landfill, recycle
Biodegradability life	2-6 months	Not biodegradable (>100 years)	3-6 months	Not biodegradable (>400 years)

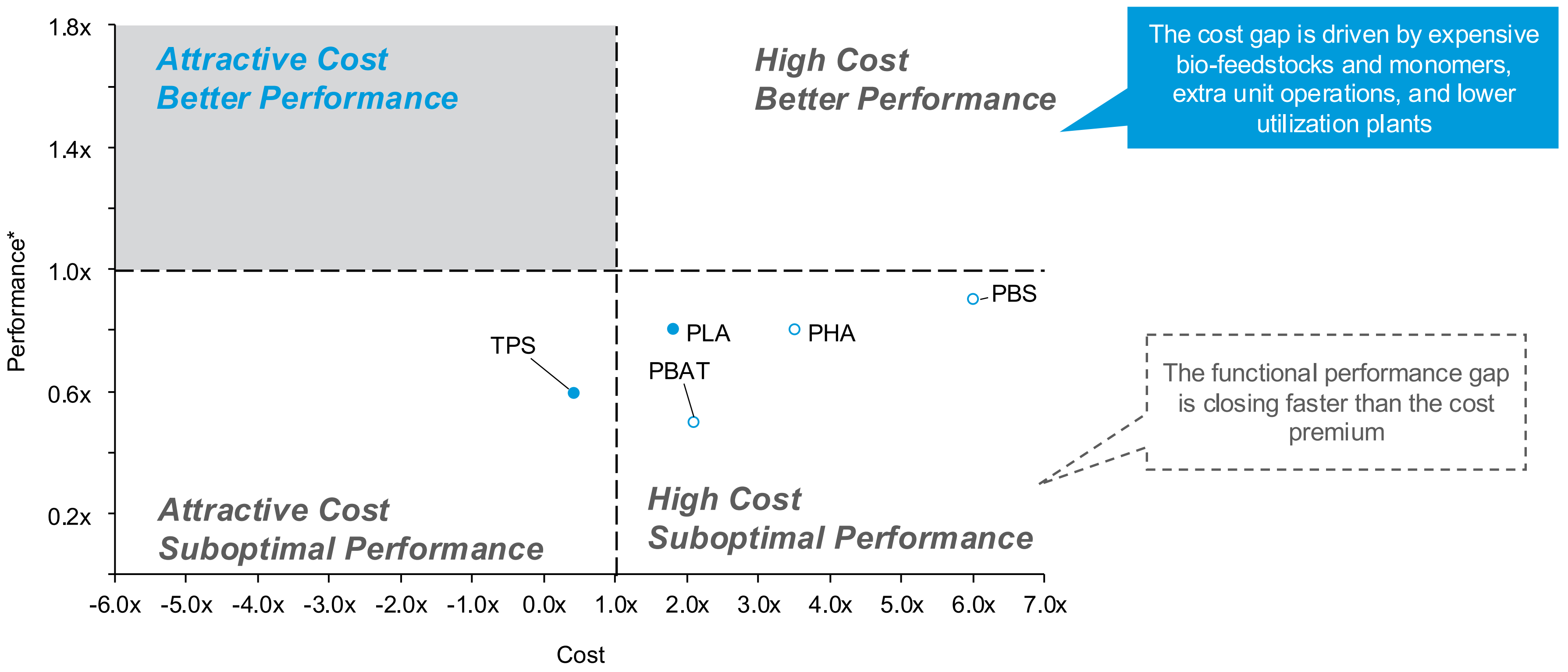
Observations

- **Bioplastics plants aren't fully utilized.** Global capacity is ~2.47 Mt (2024) with **average utilization of ~58%** (~1.44 Mt produced); capacity is projected to be ~5.73 Mt by 2029
- **Fossil plastics** are a century-old, **massively optimized system** (~400 Mt per year of output), with **resin prices often roughly half those of biopolymers (with end prices 2 to 3x the prices of traditional plastic)**. The whole system is tuned to their properties
- **Substitutes** must beat both **cost and system lock-in**, not just match **performance**

Narrowing performance and cost gaps is key for scaling bioplastics adoption; polylactic acid is closest to reaching parity

Bioplastics face two key parallel challenges: reducing costs and improving performance[1]

Performance and cost of bioplastics compared with traditional plastics



Observations

- **20+ FDA-approved** products show **polylactic acid's (PLA) highest technology readiness is in medical applications**
- **Bio-resins** still carry a clear premium vs. commodity petro-plastics
- **PLA is often quoted at $3 per kg, PBS at $3.20, PHA at $4 to $6, and PBAT (lower cost biodegradable) at about $1.85 to $1.90**; in contrast, PP generally trades close to $1 to $1.30 per kg

[1]Performance is measured considering tensile strength, elongation at break, heat deflection, and water vapor permeability.

Sources: CKI analysis; BusinessanalytiQ; Physical and thermal properties (Nazrin et al., 2020); Tensile Behavior of High-Density Polyethylene (Amjadi and Fatemi, 2020); Poly(Butylene Adipate/Terephthalate-Co-Glycolate) (Wang et al., 2020); A review on bio-based polymer (Rajendran et al., 2024); Poly(Lactic Acid)-Based Microparticles (Vlachopoulos et al., 2022).

Credit: Smarth Galhotra, Paula Sánchez, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

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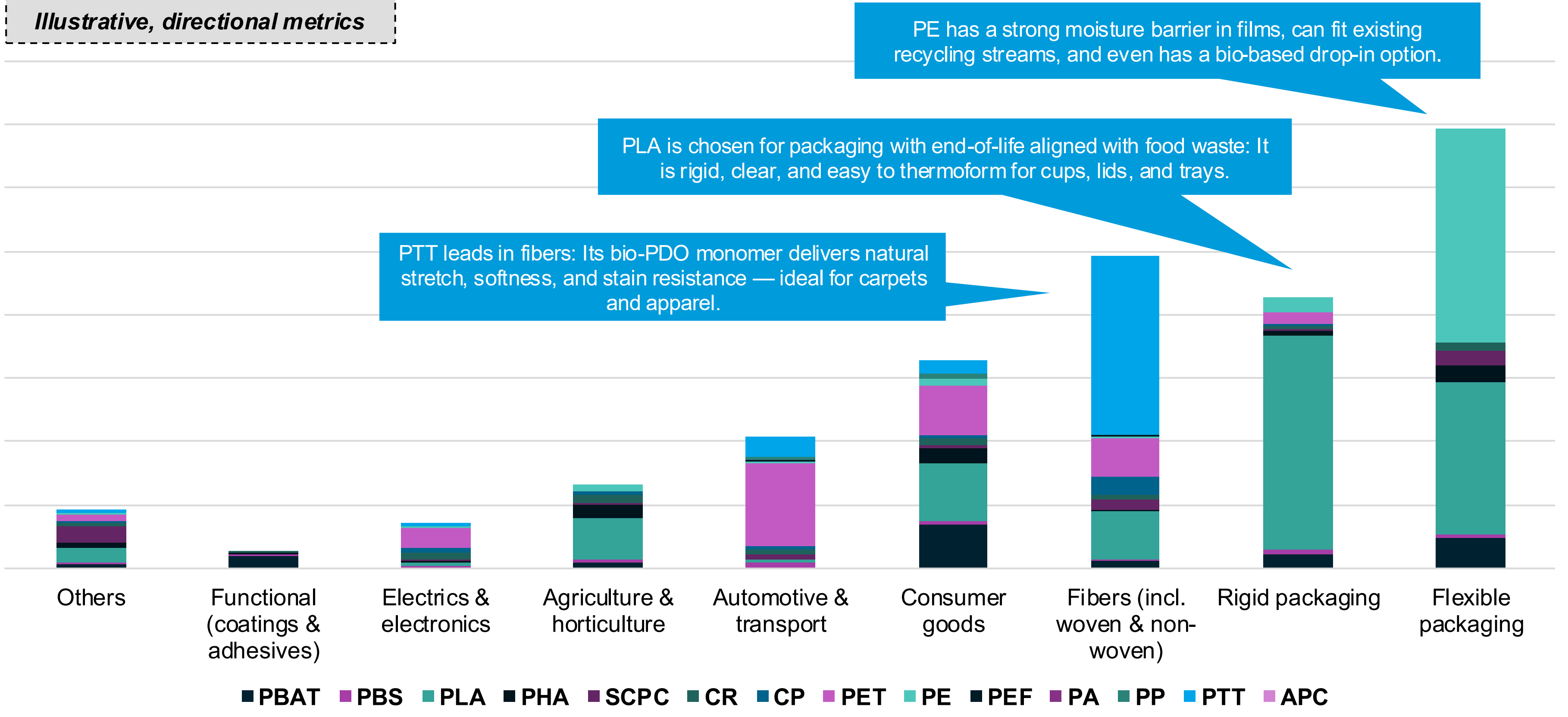
Bioplastics remain niche but are growing, with performance-matched materials winning and packaging leading adoption (~45%)

Global production capacities of bioplastics in 2024 by market segments, showing a variety of applications

Illustrative, directional metrics



Observations

- **Adoption is still small but concentrated in packaging.** Bioplastics are ~**0.9%** of global plastics. Within bioplastics, **packaging is the largest segment at ~45%** (~1.12 Mt)
- In 2024, **biodegradable** resins were **56.3% of capacity** (PLA 37.1%, PHA 4.1%)
- **Bio-based drop-ins are 43.7% of capacity** (bio-PE 11.0%, bio-PET 2.7%, PTT 13.2%). By 2029, **biodegradables are forecast to reach 66% of plastics** (PLA 42.3%, PHA 17.0%)
- **PLA** is a key resin for **rigid** and **flexible food packaging and food service items** in that mix, which makes it a winner, as packaging is the main use case

Sources: Processing technologies (European Bioplastics); A Review of Bioplastics (Di Bartolo et al., 2021); Drop-in plastics (Sharada et al., 2022).
Credit: Paula Sánchez, Ariela Farchi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Rethinking Plastics” (20 July 2026).

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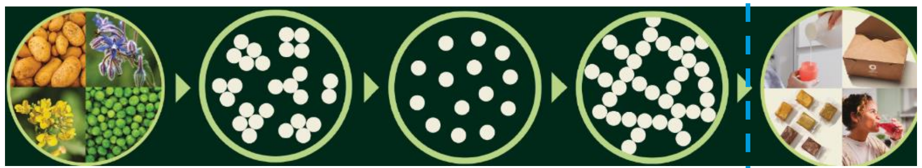
Drop-in plant protein technology makes Xampla a key player in the plastic-replacing natural polymer industry

Xampla

Funding	**£25.8 million** (Emerald Technology Ventures, Amadeus Capital Partners, BGF, Matterwave Ventures, Horizons Ventures, Cambridge University)
Founded	Cambridge, U.K., 2018

Xampla's materials are made from plant feedstocks

Abundant feedstock → **Natural plant protein** → **Unfolded structure** → **Rearranged structure** → **Multiple applications**



On track to replace 10B+ plastic units in the next five years.

Materials with "no chemical modification"

- Morro TM coating, used to **coat paper and board for packaging**
- Morro TM edible film, used as a **single-use sachet**
- Morro TM soluble film, for **home care and personal care pods**

Overview & mission	• Developing natural **polymer materials from plant proteins** to replace polluting single-use plastics with **scalable (drop-in) biodegradable technology**

Core differentiation & technology	• **Morro**TM **materials**: World's first plant-protein polymer, derived from abundant feedstocks (e.g. peas, rapeseed)
	  • **Completely plastic-free**, fully biodegradable, and home-compostable
	  • **High performance, drop-in material replacement** matches plastic functionality, is ready for at-scale production on existing manufacturing lines
	  • **Multi-patented technology** delivers high barrier performance

Business model	• **Materials innovation and R&D:** Develop new materials made from plant proteins • **Manufactured by global licensed partners** (e.g., 2M Group of Companies) to enable rapid market entry • **Capital-light, licensing/supply** model **leverages partners'** existing **production capabilities and distribution** networks for scale
Market opportunity	• Global **bioplastics and biopolymers** market is projected to **grow from $17.6 billion in 2025 to $45 billion by 2030 (20% CAGR)** • The **barrier coatings** segment alone is estimated at **$30 billion+ by 2032** • **Market dynamics:** Strong demand, regulatory support for eco-friendly materials
Market competition	Notpla, Lactips, danimer scientific, CORUMAT BETTER MATERIALS, SWAY, FOOTPRINT, greenfib
Challenges	• **Industry mind-set:** Single-use plastics can be overengineered; alternatives don't need to match this yet are often measured against it • **Greenwashing:** Misinformation causes confusion and distrust • **Regulation:** Needs to support new materials

[1]Cambridge University spin-out (backed by 15+ years of research).

Sources: Xampla (Cambridge Enterprise, 2024); Xampla (2025); Demonstrating that Xampla's paper coatings are plastic free (NPL Case Studies); Xampla (LinkedIn, 2025).

Credit: Paula Sánchez Encinar, Ariela Farchi, Hyae Ryung Kim, and Gernot Wagner.

Both product- and system-side gaps must be closed for bioplastics to become a mainstream decarbonization lever

	Product limitations[1]		System limitations[2]	
	High costs and limited scale of biopolymers	Material performance and feedstock issues	Waste management and recycling gaps	Lack of standards and misconceptions
Bottlenecks	• **Cost gap vs. fossil plastics** • **Small global production capacity:** Less than 1% • **Underutilized plant capacity:** Average utilization below 60% of installed capacity	• **Barrier properties:** Higher permeability, variability • **Thermal and mechanical limits:** Lower heat tolerance, weaker durability • **Feedstock availability:** High dependency on biomass	• **Recycling incompatibility:** Bioplastics require a separate recycling process • **Lack of infrastructure** • **Landfill danger:** Due to poor or missing infrastructure	• **Terminology confusion:** Bioplastics are a big group of varied materials • **Unstable demand** • **Patchy policy and standards:** Varied across market
Solutions	• **Increase scale and efficiency:** Through higher risk investments • **Carbon pricing:** To support low-carbon alternatives	• **Biopolymers R&D support:** Develop blends, copolymers, and additives to boost heat deflection and toughness • **Explore non-food feedstocks**	• **Build composting and collection:** Invest in industrial composting and separate biowaste/compostable streams • **Design for end of life**	• **Consumer education:** About fossil and bioplastics • **Stable long-term policy:** Consistent regulations of minimum bio-content

[1]Production limitations: Product-level barriers inherent to bioplastic materials and manufacturing. [2]Systemic limitations: Broader external barriers in the surrounding system.

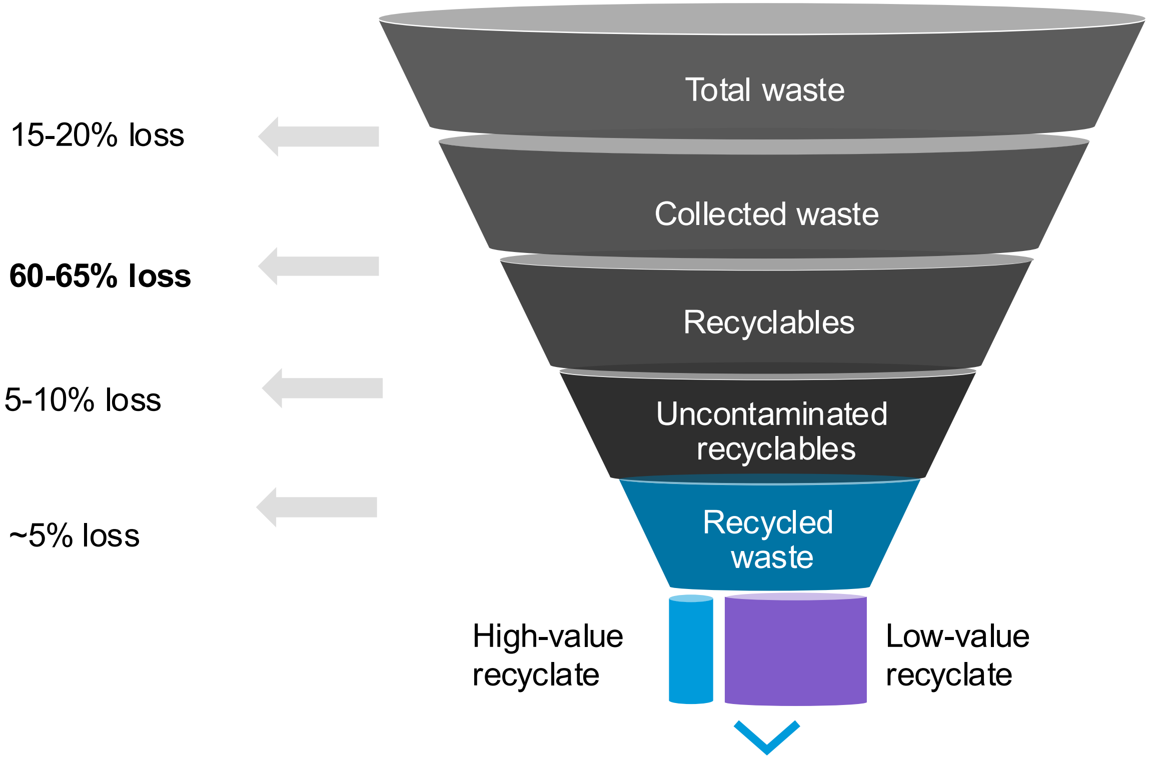
Sources: What Challenges Hinder Bioplastics Adoption (Sustainability Directory, 2025); Applications (European Bioplastics), Biodegradable Plastics (360 Research Reports, 2025); Cost competitiveness (Wellenreuther et al., 2022); The Truth About Bioplastics (Columbia Climate School, 2017).

Credit: Paula Sánchez, Ariela Farchi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Rethinking Plastics” (20 July 2026).

Only ~10% of plastic waste is recycled; design and sorting issues render over 60% of collected plastics unrecyclable

Global plastics recycling stages (material flow and losses)

Incurred losses | **Plastic waste across recycling stages**

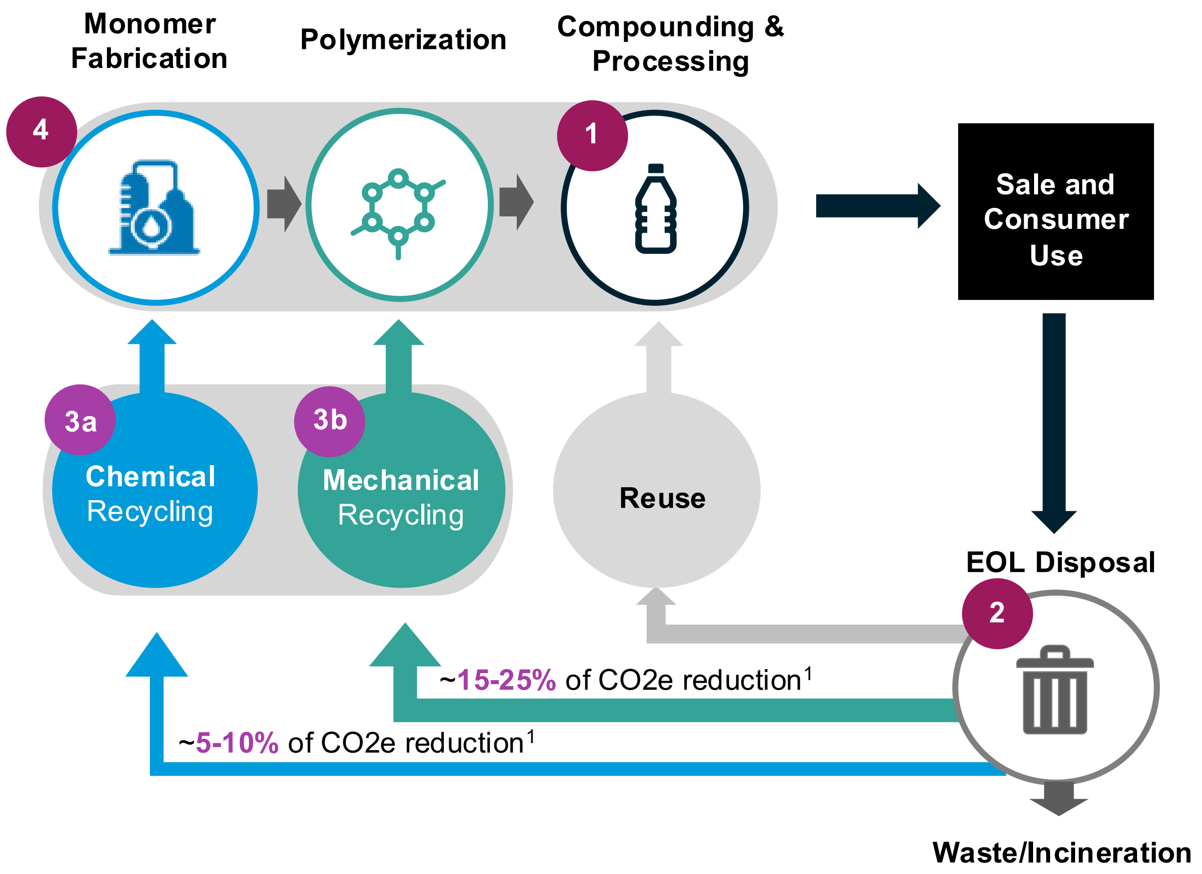


Amount (in Mt)	% of total waste	Description
350	100%	Total annual post-consumer plastics waste
280-300	80-85%	All plastic waste formally collected; the remaining share is mismanaged
55-65	20-25%	Plastics sorted as recyclables
40-55	10-15%	Yield after removing contamination from food and beverages
30-40	5-10%	Washed, shredded, and pelletized for resale
~30	~5%	Cascaded recycling: Recycling into other, lower value recycling applications
>10	<2%	Closed-loop recycling: Recycling into same or similar value material

Sources: Policy Scenarios for Eliminating Plastic Pollution by 2040 (OECD, 2024); Plastics and the circular economy – deep dive (Ellen MacArthur Foundation, 2019).
Credit: Anika Behrndt, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Recycling can abate 20% to 35% of total plastics emissions

Scaling mechanical and chemical recycling methods has the potential to abate up to 35% of total lifecycle emissions…



…but requires redesign, collection, infrastructure, and stimulating demand

1 **Design for recyclability**

>70% of plastics remain non-recyclable due to complex design and mixed materials

2 **Develop collection systems**

Around 2 billion people lack access to regular waste collection, leading to widespread mismanagement

3 **Scale recycling infrastructure**

a) **Scale chemical recycling:** New facilities in regions with limited processing infrastructure

b) **Advance mechanical recycling:** Improve efficiency and operations

4 **Stimulate market for recycled materials**

Policies are needed to enforce both recycling as an end-of-life methodology, as well as mandatory use of recycled materials

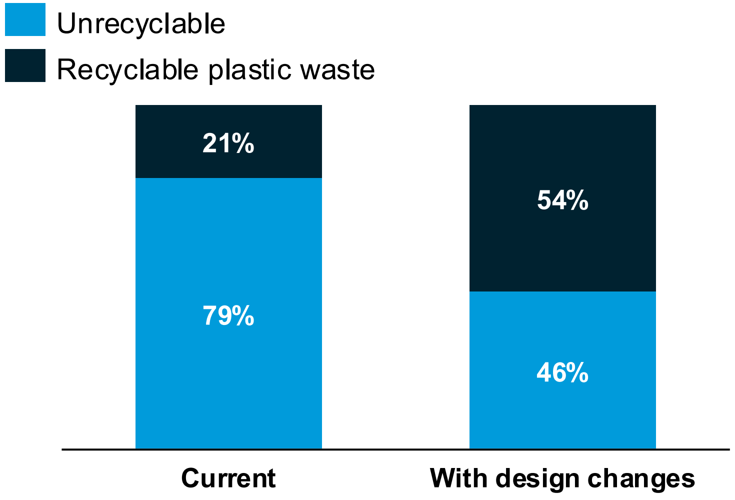
[1] Mechanical recycling can reduce the lifecycle emissions of plastics by ~40% compared to incineration and chemical recycling by around 20% compared to incineration.
Source: Breaking the Plastic Wave (Pew, 2020).
Credit: Anika Behrndt, Ariela Farchi, and Gernot Wagner. Share with attribution: Wagner et al., “Rethinking Plastics” (20 July 2026).

Redesigning can improve recycling by reducing material complexity, preventing contamination, and improving product quality

>70% of collected plastic waste is deemed unrecyclable

- Most plastics remain unrecyclable due to material complexity, contamination, and product design
- With better design, recyclability could increase by >30 percentage points
- Design changes are a low-cost lever with outsized impact

Total collected plastic waste



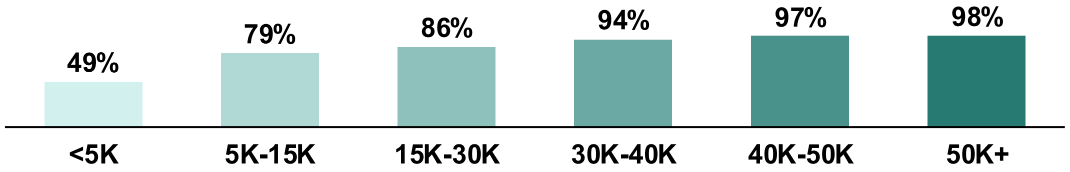
Key challenges	Possible solutions
Material complexity 1,000+ combinations of mixed and layered plastic types make separation and recycling technically complex and economically unviable	**Standardization** 1) Adopt mandatory design-for-recyclability standards that phase out non-separable, multilayer, and incompatible polymer combinations 2) Incentivize producers to use mono-material or compatible blends
Contamination Up to 40% of packaging plastics are food-contaminated, making them unrecyclable without additional cleaning and processing	**Clear guidance** 1) Implement clear, harmonized labeling systems (e.g., “recyclable/not recyclable,” disposal instructions) to reduce consumer error 2) Promote deposit return systems for food containers 3) Support advanced washing and decontamination technologies for food-grade recyclate
Low-value, single-use items About 30% to 40% of plastics are single-use packaging — too cheap and thin to reuse or recycle economically	**Abatement of single-use** 1) Set minimum durability targets for packaging 2) Substitute ultralightweight, non-recyclable plastics with recyclable mono-material formats 3) Encourage reuse models (refillable, returnable) and fiscal incentives

Sources: Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics (Uekert et al., 2023); Breaking the Plastic Wave (Systemiq, 2020).
Credit: Anika Behrndt, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Rethinking Plastics” (20 July 2026).

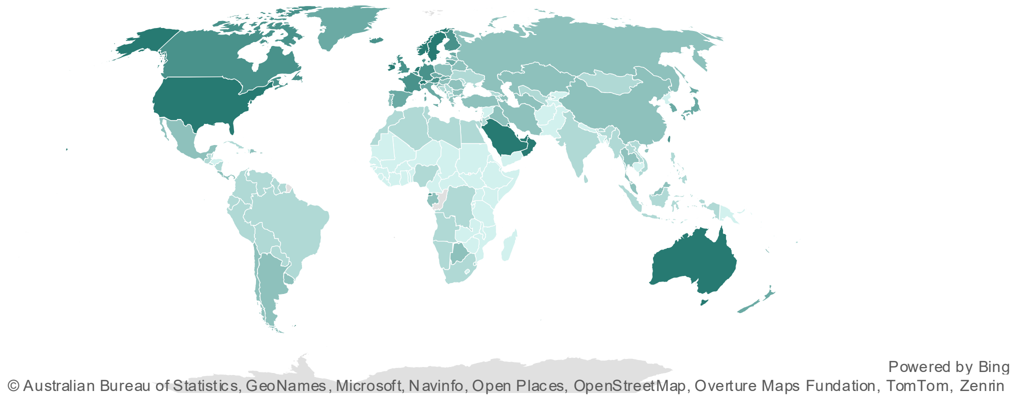
Better collection and sorting systems, supported by infrastructure and behavior change, are needed to fully capture plastic waste

+20% of the global population lacks collection coverage, especially in rural areas of emerging economies

Coverage of waste collection, as % of total waste*



GDP per capita worldwide; a visual proxy for waste collection coverage



The dark areas are the high-coverage countries from the bar chart; the light areas reflect collection gaps

	***Developing** economies need better collection infrastructure*	***Developed** countries need behavioral and technological changes for sorting*
Bottlenecks	• **Collection coverage remains below 60%** in many regions across Sub-Saharan Africa and South Asia • **Informal waste pickers** handle **40% to 80% of recyclables** in many cities • Rural and island states lack the economic density to justify large infrastructure investments	• Behavioral confusion: **25% to 30% of recyclables in the U.S. are contaminated by non-recyclables** • Aging sorting infrastructure: Many MRFs still operate with 1990s-era mechanical systems • **Fragmented collection standards** hinder consumer participation
Solutions	• **Invest in collection logistics** (transfer stations, trucks, bins, data systems) • **Formalize the informal** sector via cooperatives or social enterprise models • Leverage extended producer responsibility (**EPR**) to fund local collection	• **Use AI-based sorting tech** to improve material purity • **Standardize collection systems** • **Use pay-as-you-throw schemes** to reduce contamination and incentivize correct sorting

*Based on World Bank data on a global waste study; not all countries are represented – only about 52 countries for this statistic.

Sources: What a Waste Global Database (World Bank, 2024); 2019 Impact Report (Closed Loop Partners, 2020); An Assessment of the U.S. Recycling System: Financial Estimates to Modernize Material Recovery Infrastructure (EPA, 2024); Women and men in the informal economy: A statistical picture: Third edition (International Labor Organization, 2018).

Credit: Anika Behrndt, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Rethinking Plastics” (20 July 2026).

A new door-to-door waste collection system achieved a 100% waste collection rate in Indore, India

Waste collection hauler in Indore, India — Sources: Shreya Khaitan

Context	Indore, the ninth biggest city in India with a population of 3.5 million, has a growing waste issue: Daily waste is expected to grow from 1,200 metric tons to 2,000 within 10 years. The city is also subject to the new national Solid Waste Management Rules from 2016
Timeline	The first pilot project launched in January 2016, with full rollout to all 84 wards achieving 100% waste collection by January 2017
Project cost	~US$20 million (₹180 crore) in capital investment for collection, transport, and processing infrastructure[1]; recurring operating expenditures of ~US$18 million (₹155 crore) per year during early implementation

Build-out of a door-to-door waste collection infrastructure

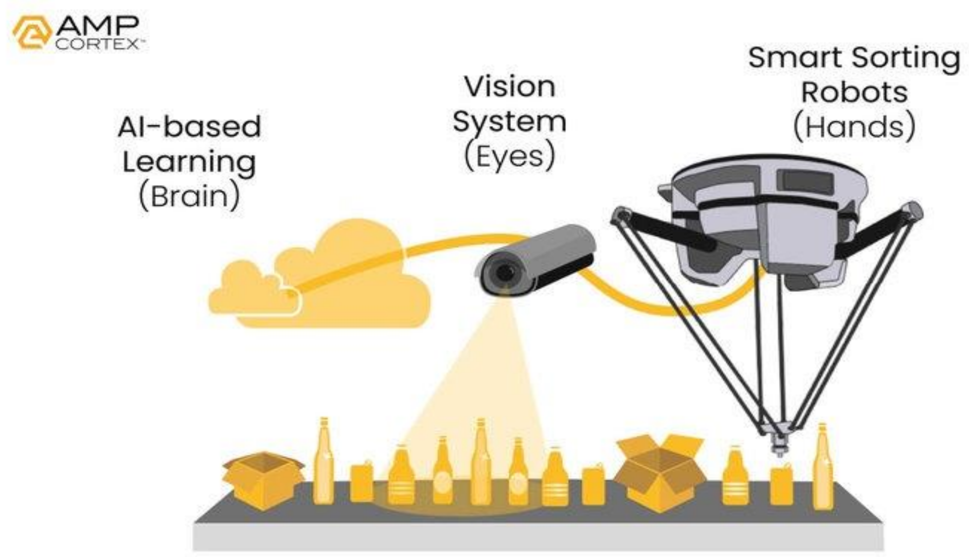
Overview & mission	Ensure full collection of up to ~1,500 metric tons of municipal waste per day while enabling upstream segregation and downstream recovery, particularly for plastics and organic waste
Measures	1) **Citywide door-to-door waste collection rollout:** Replacement of communal bins with daily, household-level collection, covering residential, commercial, and institutional waste 2) **Mandatory source segregation at household level:** Two-stream (wet/dry) segregation enforced through bylaws, inspections, and penalties, enabling efficient downstream processing 3) **Decentralized collection infrastructure and routing optimization:** Deployment of dedicated collection vehicles (handcarts, auto-tippers, compactors) and optimized ward-level routing to ensure full coverage 4) **Formalization and expansion of the sanitation workforce:** Recruitment and training of sanitation workers with clear role definitions, uniforms, and performance monitoring 5) **Strong enforcement and behavior-change mechanisms:** Public awareness campaigns and fines for non-segregation and littering 6) **Digital monitoring and accountability systems:** GPS-tracked vehicles, attendance systems, and real-time ward-level reporting
Results	Since 2017, Indore has consistently been ranked India's number one cleanest city (>100,000 population), reflecting sustained system performance. Collection costs declined from ~₹2,900 per ton to ~₹1,660 following the update

[1] Capital investment included fleet expansion, transfer stations, material recovery facilities, decentralized composting, and digital monitoring systems.

Sources: Municipal solid waste management in the City of Indore: A case study (Singh R., 2021); Solid Waste Management in Indore, Madhya Pradesh, India: Insights from a Survey of Literature (Saifi et al., 2023); How Indore Became India's Cleanest City (And How Others Can Follow) (Indiaspend, 2019); Solid Waste Management in Indore (Centre for Science and Environment, 2019).

AMP Robotics can automate up to ~75% of manual sorting with AI-driven computer vision

The AMP Cortex combines off-the-shelf robots with machine vision and AI in the cloud. Source: AMP Robotics



History	Founded in 2014 by Matanya Horowitz and James Bailey, AMP Robotics is a company focused on modernizing and scaling the recycling infrastructure using artificial intelligence and automation

Automated sorting systems with AI robots – AMP Robotics

Overview & mission	AI-supported robotic sorting system to increase recycling purity and efficiency of single-stream waste (plastics, paper, aluminum, etc.)
Technology	Three key components: 1) **AMP Cortex™** high-speed robotics system automates the identification and sorting of recyclables from mixed material streams 2) **AMP Neuron™** deep learning computer vision (CNNs) is trained on millions of material images — not generative/LLM-based. Identifies materials by type, polymer, color, and brand. Hardware is commodity (ABB/Omron delta arms); IP is the perception model and training dataset 3) **AMP Clarity™** provides data and material characterization
Efficiency	Can process up to 68,000 tons of waste annually, with >95% identification accuracy; has up to 200%+ higher pick rates vs. manual sorting; reduced labor requirements by ~75%
Drivers	Labor shortages in MRFs, rising demand for cleaner recyclables, EPR rollout in U.S., and rPET demand
Total capital + valuation	≈US$267 million, current valuation of $424 million to $612 million
Timeline	AI robots launched 2016; >400 AI systems installed by 2025 across North America, Asia, and Europe
Cost	~ $300,000 per machine, lasting 5-10 years; break even at 2-3 years

Sources: Advanced-sorting-technologies in the waste sector (IEA Bioenergy, 2024); AMP Named to 2025 Global Cleantech 100 (Amp Sortation, 2025); AMP Company Profile (Tracxn, 2025); Rise of the Recycling Robots (Forbes 2020); AMP Robotics applies AI, robots to mounting recycling challenge (The Robot Report, 2019); AMP to Operate Waste Connections Recycling Facility with AI-Powered Sortation Technology (AMP Sortation, 2024).

Mechanical recycling is the most cost- and energy-efficient solution to treat plastic waste, followed by chemical recycling

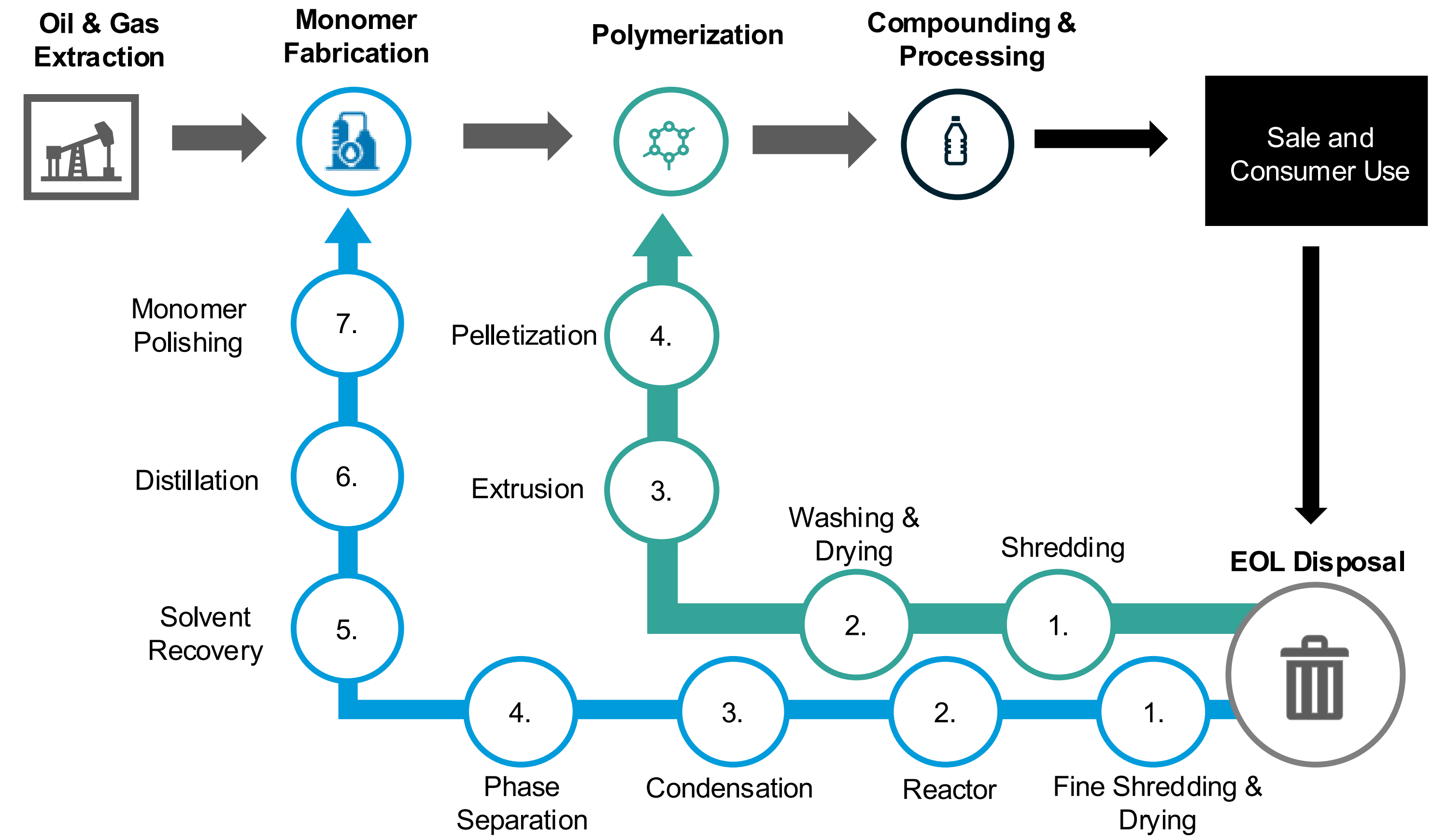
Overview of different recycling methods

Technology	Description	Common use cases	Energy use per kg processed (MJ/kg)	Global capacity (M tons)	TRL	Cost (in $) per ton processed (indicative)	Challenges
Mechanical	Processing plastics to be **reused in new products**	Bottles, HDPE crates, PP packaging	~ 6	~50	green	120-250	Backbone of today's system but **limited to clean, single-polymer streams** (e.g., PET bottles, HDPE crates)
Chemical	**Breaking down into** their **basic chemical** components using heat or chemicals	Plastics not suited to mechanical recycling	~25	< 1	yellow	~500-700	Fills a gap for mixed or hard-to-recycle plastics, but **costs and energy demand remain high**
Thermal	Using waste **plastics as** a source of **fuel**	Non-recyclable, contaminated plastics	~ 4	>400	green	103	Manages large volumes of contaminated waste (>400 Mt), but it **locks in emissions** and should be treated as a last-resort pathway
Biological	Breaking down plastics **using natural microorganisms**	Biodegradeable, single-use products	~10	< 1	red	> 1K	Emerging for biodegradable plastics and specific single-use items; **current impact is marginal**, but future innovations (e.g., microbes) could broaden scope

Sources: Technical, Economic, and Environmental Comparison of Closed Loop Recycling Technologies for Common Plastics (Uekert et al., 2023); Techno-economic assessment of mechanical recycling of challenging post-consumer plastic packaging waste (Larrain et al., 2020).
Credit: Anika Behrndt, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

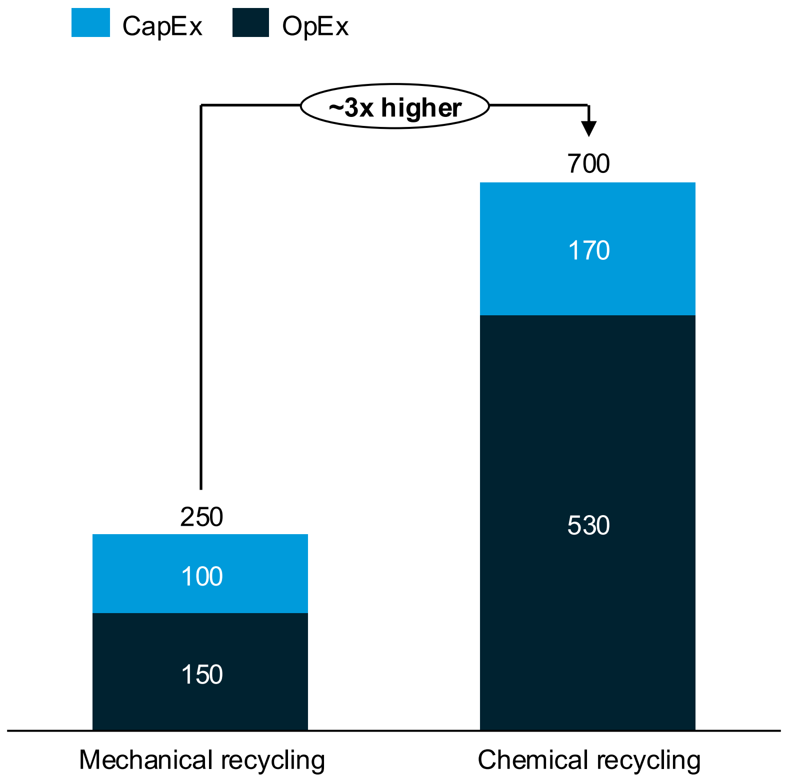
Chemical recycling costs 3 to 4x more than mechanical recycling but is necessary to process less standardized waste streams

Process flows of mechanical and chemical recycling



High energy use and chemical inputs drive costs (€700/ton)

Cost of plastics recycling in €/ton processed*



*CapEx and OpEx are based on an average from different survey results, detailed in Larrain et al., 2020 (below).

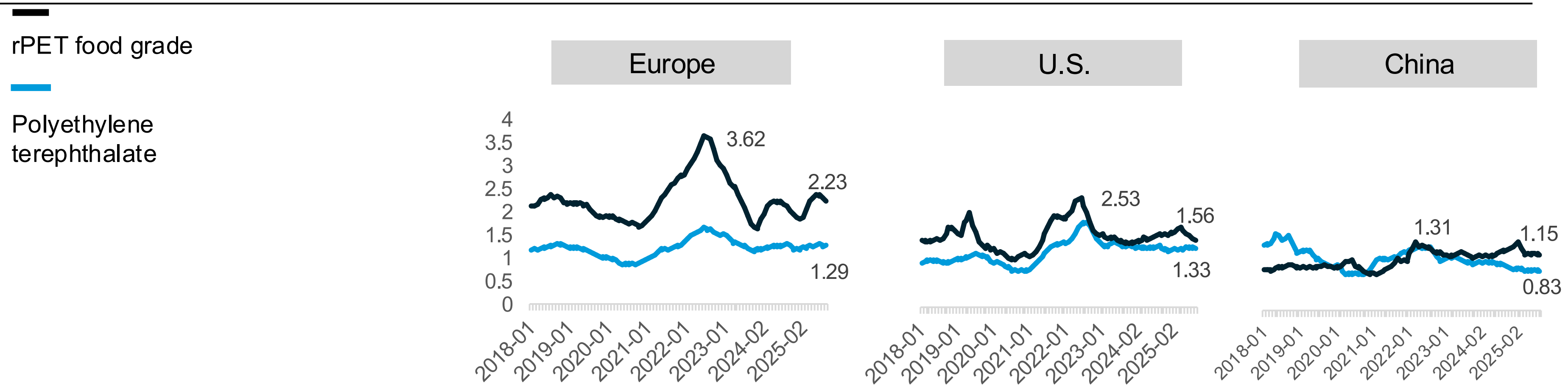
Sources: Environmental and economic assessment of plastic waste recycling (European Commission, 2023); Techno-economic assessment of mechanical recycling of challenging post-consumer plastic packaging waste (Larrain et al., 2020).

Credit: Anika Behrndt, Isabel Hoyos, Hyae Ryung Kim, Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Columbia Business School
Climate Knowledge Initiative

Alongside price parity, policy drivers are needed to drive large-scale adoption of recycled plastics

Costs of virgin polyethylene terephthalate (PET) vs. recycled PET (food grade), *US$/kg*



Policy intervention levers	Europe	U.S.	China
Collection and sorting infrastructure	High	Low-medium	High
Scale and efficiency of recycling	Low-medium	Low	High
Policies for mandatory use of recyclates	High	Low	Medium
Policies for mandatory recycling	High	Low	High
Plastics recycling rate per region, % of total waste			
	12%	5%	13%

Observations

- **Europe:** rPET remains structurally more expensive than virgin plastic, yet demand persists due to binding recycled-content mandates
- **U.S.:** rPET has reached near price parity, but weak mandatory use leads to oversupply and depressed prices
- **China:** Large-scale infrastructure and mandatory use policies enable a cost-efficient and stable rPET market

[1] Regional averages taken into account for country and state level ranges.
Sources: Plastic waste by region and end of life (OECD, 2023); Plastic Recycling: A review on life cycle (Salahuddin, 2023); Virgin PET prices (Businessanalytiq, 2025); rPET prices (Businessanalytiq, 2026); Exploring Plastic-Management Policy in China: Status, Challenges and Policy Insights (Liu et al., 2023); Recycled PET Prices Trending Down Amid Weak US Demand (PlasticsToday, 2023).
Credit: Anika Behrndt, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Recycling must overcome product complexity, collection, and sorting challenges to scale successfully

	Design for recycling	Collection and sorting infrastructure	Scaling chemical and mechanical recycling	Ensuring market stability of recyclates
Bottlenecks	• **Material complexity:** Multi-material products hinder recycling • **Contamination:** Food residue leads to >40% sorting losses • **Low value:** ~30% of plastics refer to single use	• **>20% of plastics waste remains uncollected globally** • **Inefficient sorting** leads to >70% of collected waste not being recycled • Most economies lack behavioral incentives to change	• **Mechanical recycling** is more energy-efficient but requires clean, standardized waste streams • **Chemical recycling** has 2 to 3x higher CapEx and significant operating costs	• **Low demand for recyclates:** Virgin plastics remain cheaper and more predictable, leading to underinvestment in recycled-content markets • **Quality concerns:** Inconsistent quality of recycled materials reduce buyer confidence
Solutions	• **Standardize packaging** to reduce sorting complexity and enable higher quality recyclate streams	• **Invest in curbside collection and access:** Target underserved regions with collection systems • **Upgrade MRF technologies:** Deploy AI-based sorting, NIR spectroscopy, robotics	• **Scale mechanical recycling wherever feasible** to maximize low-energy, low-cost circularity • **Deploy chemical recycling selectively**, colocated with existing industrial assets to improve economics	• **Enforce policy** to make use of recyclates mandatory, e.g., minimum recycled content standards • **Improve material quality and certification systems** to increase buyer confidence

Electrifying plastics production could tackle >50% of emissions; monomer fabrication is the largest lever but has lowest TRL

Value chain stage	**Feedstock processing** (extraction of non-renewables and refining to produce naphtha, ethane, etc.)	**Monomer fabrication** (cracking hydrocarbons to produce monomers such as ethylene)	**Polymerization** (converting monomers to polymers such as polyethylene)	**Product manufacturing** (fabrication of finished plastic products)	**End-of-life disposal** (incineration, landfill, leakage of plastics waste)
Key electrification levers & implications	• **Petrochemical feedstock production** using **carbon-free generated electricity** • **Electrification tech is commercially available** but in pilot phase for large-scale furnaces	• **Significant emissions abated by avoiding burning fossil fuels** in steam cracking • **FOAK crackers in pilot**, to be powered with renewables	• **Electric heating** available • **Mature technology, given lower temperatures**, but not industry-standard	• **Stage already largely electrified** • All-electric machines are **mature and should use low-carbon electricity**	• **Limited impact from electrification** • **Embedded carbon released** in incineration
Limiting factor	Retrofitting cost	High temperatures required	Retrofitting cost	Retrofitting cost	Emissions inherent to combustion
TRL	◕	◑	●	●	◕
Retroffiting cost range	$$$	$$$	$$	$$	$
Abatement potential	~15%	>20%	~10%	~15%	0-5%

Sources: Tackling heat electrification (McKinsey, 2024); Can carbon help decarbonize chemicals (BCG, 2023); Seadrift (X-Energy); Electrification (ETA, 2022); Levelised cost of petrochemicals for selected feedstocks and region (IEA, 2018); Carbon capture, utilization & storage in the energy transition (Energy Transitions Commission, 2022).
Credit: Paula Sánchez, Ariela Farchi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Electrified steam cracking (E-SC) could decarbonize monomer fabrication but is limited by renewable energy availability

~25% of emissions from plastic production come from steam cracking at >850ºC

Fossil hydrocarbons

After extraction, separation, and purification…

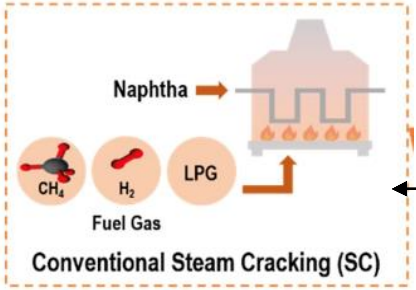
Steam cracking*

…hydrocarbons are then broken down into monomers

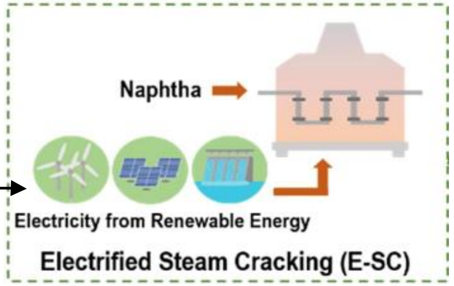
Polymerization

Monomers are then chemically bonded into long-chain polymers, the base material for plastics

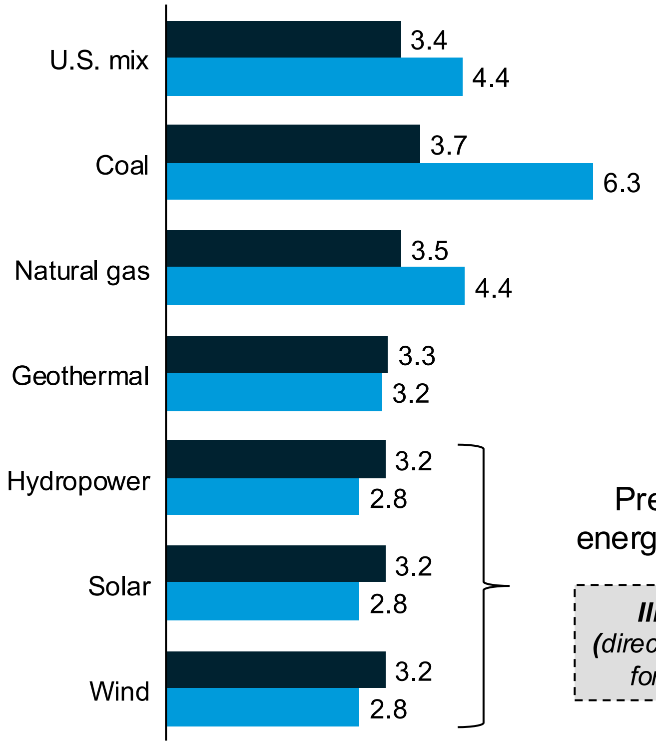
Conventional steam cracking



Electrified steam cracking[1]



CO_2 emissions of steam cracking and E-SC by electricity generation method ($KgCO_2$ kgC_2H_4[1])



Preferred energy sources

Illustrative *(directional metrics for ethylene)*

Observations

- E-SC powered by renewables could **decrease CO_2 emissions from ethylene production by 18%***
- The share of renewables in net U.S. electricity generation is set to grow from **24% in 2024** to **~70% in 2050.** As E-SC remains energy intensive, renewable generation will be key for at-scale production
- Production facilities can implement **on-site renewable power generation** to ensure source of energy for on-site E-SC

[1] Still in the pilot and demonstration phase.

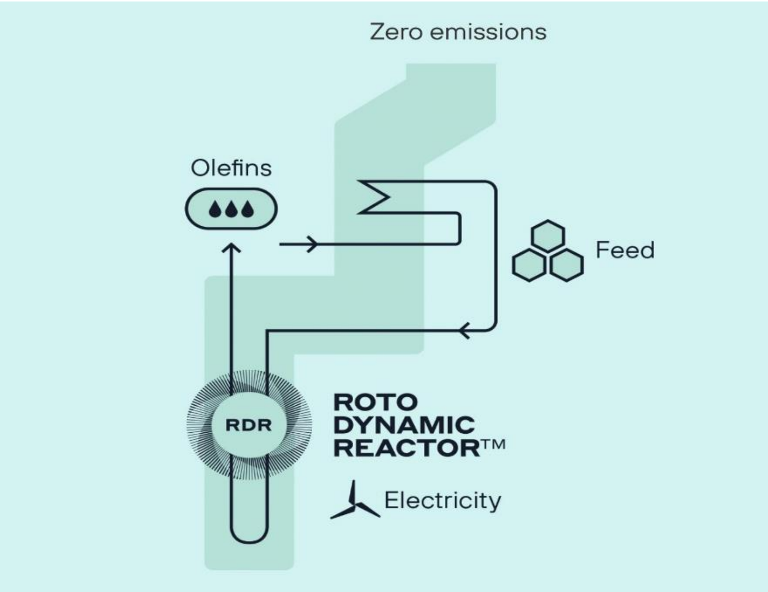
Sources: Electrified steam cracking for a carbon neutral ethylene production process (Gu et al., 2022); Annual Energy Outlook 2025 (U.S. Energy Information Administration, 2025); Aligning the value chain to decarbonize plastics (McKinsey, 2025); Electric Cracking (Coolbrook); Piloting RotoDynamic Technology (Coolbrook).

Credit: Una Oljaca, Paula Sánchez, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Coolbrook's RotoDynamic Reactor (RDR) demonstrates E-SC potential in the short to medium term

Location & year	Founded in 2008, with dual headquarters in Espoo, Finland (corporate), and Geleen, Netherlands (pilot and R&D at Brightlands Chemelot Campus)
Funding	~**$59M raised** across multiple rounds; backers include Cemex Ventures, Norrsken VC, and Plug and Play

RotoDynamic Reactor schematic



Overview & mission	• Industrial decarbonization technology company commercializing electrified high-temperature heat. Mission: **Replace fossil-fuel combustion in the most carbon-intensive industrial processes** — steam cracking, cement, and iron and steel
Core differentiation & technology	• RDR uses high-velocity rotor blades to convert electricity into process heat above 1,700°C in milliseconds; **100% scope 1 emissions reduction** vs. conventional fired crackers, plus **~20% higher ethylene yields**, less coke formation
Business model	• **Technology licensing + equipment supply** to petrochemical, cement, steel producers • **Co-development partnerships** with anchor customers (SABIC for steam cracking, Cemex for cement) de-risk first-of-a-kind deployments • Revenue from RDR/RDH unit sales, licensing fees, and aftermarket service
Market opportunity	• Steam cracking alone: ~300 million tons of CO_2 per year globally and >$200 million in additional annual profit per million metric tons of ethylene from yield uplift • Broader addressable market: high-temperature industrial heat across chemicals, cement, and steel
Market competition	• Joint electric-cracker pilots from BASF-SABIC-Linde and Shell-Dow (resistive-heating designs); Technip Energies' electrified furnace concepts • Coolbrook's rotodynamic approach differentiates on temperature ceiling, footprint, and yield
Challenges	1. Scaling from pilot to commercial demonstration (2026: still in large-scale validation) 2. Access to abundant, low-cost renewable electricity at petrochemical-site scale 3. Customer willingness to commit before policy/carbon-pricing certainty

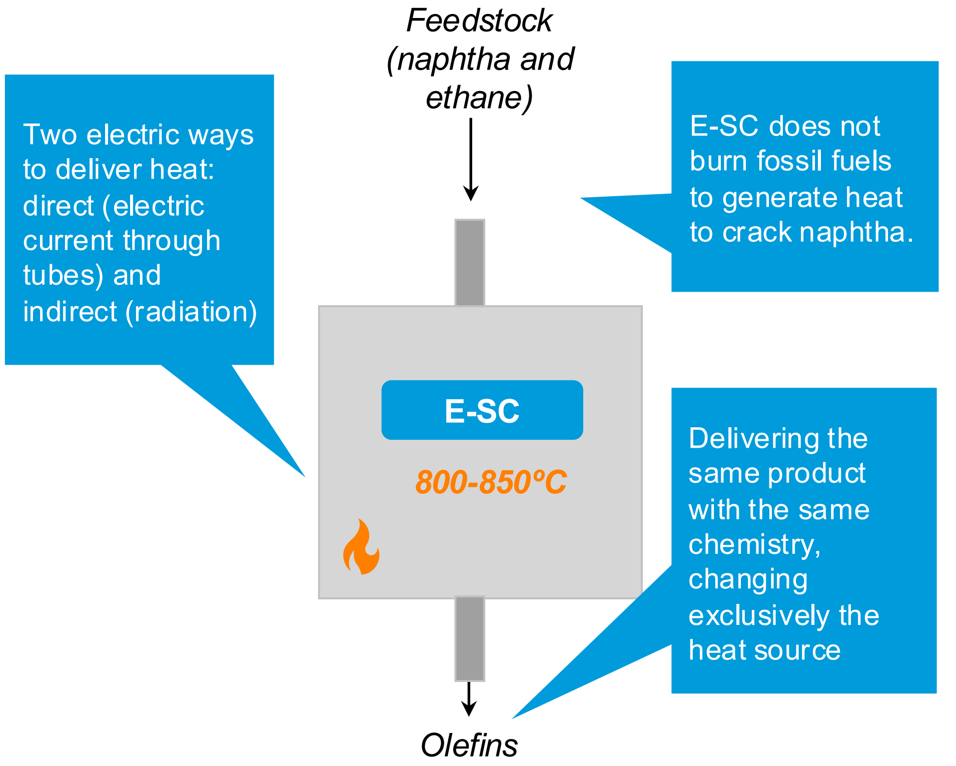
[1]Cambridge University **spin-out** (backed by 15+ years of research).
Sources: Electric Cracking (Coolbrook); Piloting RotoDynamic Technology (Coolbrook); Coolbrook 2026 Company Profile: Valuation, Funding & Investors (PitchBook, 2026).
Credit: Anika Behrndt, Una Oljaca, Ariela Farchi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

BASF-Sabic-Linde E-SC demonstration plant is built, operating, and able to abate 90% of emissions

BASF We create chemistry · sabic · Linde

Ownership	BASF-Sabic-Linde Partnership
Location	Ludwigshafen, Germany (BASF Verbund site)

E-SC process overview, proven to reduce 90% of emissions



Description	• **Pilot-scale e-steam cracking furnace integrated into existing BASF steam cracker** at Ludwigshafen, Germany
Technological overview	• **Process**: Electrified steam-cracking furnace(s) – two parallel heating concepts: (1) direct resistive heating (electric current through cracking coils), and (2) indirect/radiative heating (heating elements around coils) • **Feedstock/throughput:** ~4 tons hydrocarbon feed per hour collectively • **Electric power input/load:** 6 MW electrical input for the furnaces
Efficiency metrics	• **Target reduction of at least 90% CO_2 emissions** (versus conventional steam cracking) when powered by renewable electricity*
Key success drivers	• **Two heating modes** tested to compare flexibility and material behavior • **Fully integrated** into existing BASF steam cracker utilities
Funding	• Undisclosed private funding • **Received €14.8 million in public funding**
Unit economics	• **Cost competitive in principle:** Published TEA (Gu et al., 2022) puts electrified steam cracking at **~$790 per ton of ethylene vs. ~$832 per ton** for conventional — the process itself is not inherently more expensive • **Economics hinge on power prices, not technology:** Commercial viability is driven by the **industrial electricity-to-gas price spread**, not CapEx — implying a $0 to $170 per ton ethylene green premium (~$0 to $100 per ton of CO_2 abated) depending on geography and grid mix
Timeline	• Construction started in 2022. Final transformers were installed by the end of 2023, with commissioning in early 2024. No commercial deployment as of 2026

[1]BASF estimates that electrifying furnaces could cut about 750,000 metric tons of CO_2 per year.

Sources: News (2024); BASF (Industry Decarbonization, 2024); Electrified steam cracking for a carbon neutral ethylene production process (Gu et al., 2022).

Electrifying monomer production is currently bottlenecked by heat intensity, power infrastructure, and cost parity

	High-temperature process electrification	Power grid & renewable integration	Economic & capital discipline	Technology & value-chain readiness
Bottlenecks	• **Technology readiness:** Options being deployed are in early stages • **Engineering gap:** Adapting electric heating is non-trivial • **Reliability:** 24/7 operation with >99% uptime	• **Power demand:** E-SC (electrified steam cracking) requires 100 to 150 MW cont. power • **Grid readiness:** Legacy petrochemical hubs near feedstock and gas supplies • **Renewables integration:** Electricity must be low carbon to abate emissions	• **CapEx:** FOAK E-SC will likely carry a >20% to 40% premium • **OpEx:** Studies indicate a break-even point for electric furnaces when power price falls to ≈ $40 to $41/MWh	• **TRL:** E-SC is in pilot phase, and net-zero alternatives have been proven by industry leaders • **Adoption barriers:** Industry conservatism, safety, and lack of performance guarantees for new heating systems
Solutions	• **R&D of electric steam-cracking furnaces:** Government grants and industry consortia can accelerate FOAK • **Electric heating investment:** Early investment in lower heat to validate performance	• **Grid upgrades and firm power:** Private-public coordination to ensure power capacity • **Industrial heat storage:** Buffering intermittency and allowing for carbon-free energy	• **Phased retrofits and ROI-driven decisions:** Upgrade of existing assets, and phasing engineering and construction • **Incentives and risk-sharing:** Carbon pricing regimes and green premiums	• **Definition of shared standards**; alliances to promote TRL and market adoption • **Upstream-downstream integration:** Tying together the value chain to transition

Carbon capture can be applied to feedstock production, monomer fabrication, and end-of-life treatment with utilization

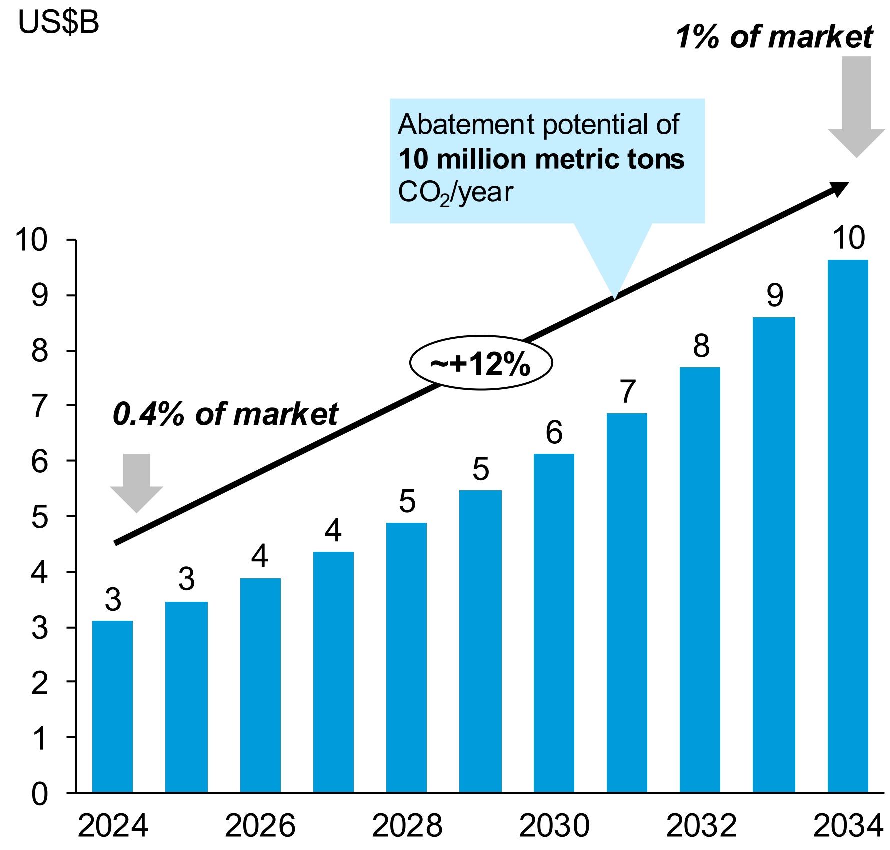
	Carbon Capture and Utilization (CCU)	Carbon Capture (CC)	
Value chain stage	Feedstock production	Monomer fabrication	EOL disposal
Application and reduction potential	• Conversion of CO_2 to precursors and/or monomers through chemical and biological pathways • Reduction varies with pathway, energy inputs, product grade, and regional economics	• Retrofit steam crackers with carbon capture systems	• Retrofit WtE incinerators with carbon capture systems
Cost – \$/ton CO_2 avoided	• CO_2-methanol: ~\$120 to \$300 • CO_2-ethylene: ~\$300 to \$1,880 • CO_2-to-formic acid: Highly variable, lab-scale only	• ~\$56 to \$108 per ton CO_2 saved	• Up to \$288 per ton CO2 saved, but economics can be improved through power and heat integration[1]
TRL	TRL varies with some pathways already reaching commercialization while other pathways being developed ●	Most plants in feasibility study phase ○	Most plants in development/ pilot phase ◑
Key challenges	• Stoichiometric limits for polymer (up to ~50% CO2 by weight) • High energy requirements; abundant, low carbon electricity necessary to significantly reduce footprint (ideally <6 g of CO_{2e} per kWh) • Most pathways not yet at parity	• Energy penalty of retrofitting CC lowers economic feasibility of capture • Small waste-to-energy (WtE) plant sizes limit economics when compared with alternative power generation	• Energy penalty of retrofitting CC lowers economic feasibility of capture

[1]Based on MEA capture and 60 MWe plant; LCA reduction for CCU based on GWP-100.

Sources: How the plastics industry can go green and at what cost (ING, 2023); Putting CO2 to use (IEA, 2019); Integration of CCUS in WtE plants (Acampora et al., 2025); Can the Plastics Industry become a carbon capture leader (IDTechEx, 2022); Life cycle assessment of polyols from polyurethane production using CO2 as feedstock (von der Assen et al., 2014); Achieving net-zero greenhouse gas emissions plastics by a circular carbon economy (Meys et al., 2021); Designing the Ethylene Factory for Products of CO2 Reduction (Pinto et al., 2025); Economic Feasibility tool for CO2 Utilization (NREL); Challenges and Opportunities of CO2 utilization (Pappjin et. al, 2020); Co2-based polyurethane foam (Karulf et al., CO2 Utilization, 2025); Current challenges and perspectives in Co2-based polymers (Liu et al, 2023).

For feedstock production, CO_2 to polyols is one of the most mature pathways

CO_2-based plastics market expected to reach ~$10B by 2034, accounting for <1% of market



Commercialized pathways[1]

CO_2 to polyols (chemical conversion)	covestro, econic, aramco
CO_2 to polyester (chemical conversion)	fairbrics
CO_2 to methanol (chemical conversion)	Carbon Recycling International
CO_2 to ethanol (bioconversion)	LanzaTech
CO_2 to PP (bioconversion)	LanzaTech, twelve

Observations

- CO_2-based plastics' projected abatement in 2030 is only **<5%** of 2024 emissions
- Maximum technical storage potential of CO_2 to plastics could reach up to 200 metric megatons of CO_2 per year, but only if:
  - Capture costs fall
  - Supportive regulation and incentives are implemented
  - CO_2 becomes a valuable resource through technological advancement
- CO_2 to polyols can lower up to 20% of plastics production emissions
- Polyols used to create polyurethane for foams, coating and semi-rigid plastics
- Methanol and ethanol converted to olefins through further multi-step processing

[1] Non-exhaustive.

Sources: Plastic market growth analysis (EMR, 2025); Plastics market 2025-2034 (Towards Chem & Materials, 2025); CO2-based plastics market size (IMARC, 2024); CO2-based plastics market size (Insight Ace Analytics, 2025); Driving CO2 emissions to zero and beyond with CCUS (McKinsey, 2023); Plastic Market (Grandview Research, 2025); Econic Technologies homepage; Twelve and LanzaTech partner to produce the world's first propylene from CO2 (LanzaTech, 2021); Fairbrics homepage.

Credit: Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Monomer fabrication can be decarbonized through pre- or post-combustion carbon capture, with capture rates of ~90%

Steam cracking to produce olefins is high emitting due to direct fuel combustion; post- and pre-combustion carbon capture can capture 85% to 95% and >90% of CO2, respectively

Option 1: Pre-combustion capture

Air →, Fuel → Reformer/ Gasifier (↑ H_2O) → H_2-rich syngas; CO_2 captured from a **~40** volume % stream

H_2-rich syngas replaces combustion fuel as lower emitting fuel

Business as usual

Feedstock (naphtha and ethane) → **Steam cracker** (*Fuel combusted at ~850°C*) → Olefins (mainly ethylene and propylene)

Naphtha: (**~1.6 to 2.4 tons CO_2** emitted/ton olefin)
Ethane: (**~0.4 to 1.2 tons CO_2** emitted/ton olefin)

Option 2: Post-combustion capture

Flue gas (N2, CO_2, H_2O, SO_X, NO_X, etc.) → CO_2 captured and compressed from a **3 to 15** volume % stream

Observations

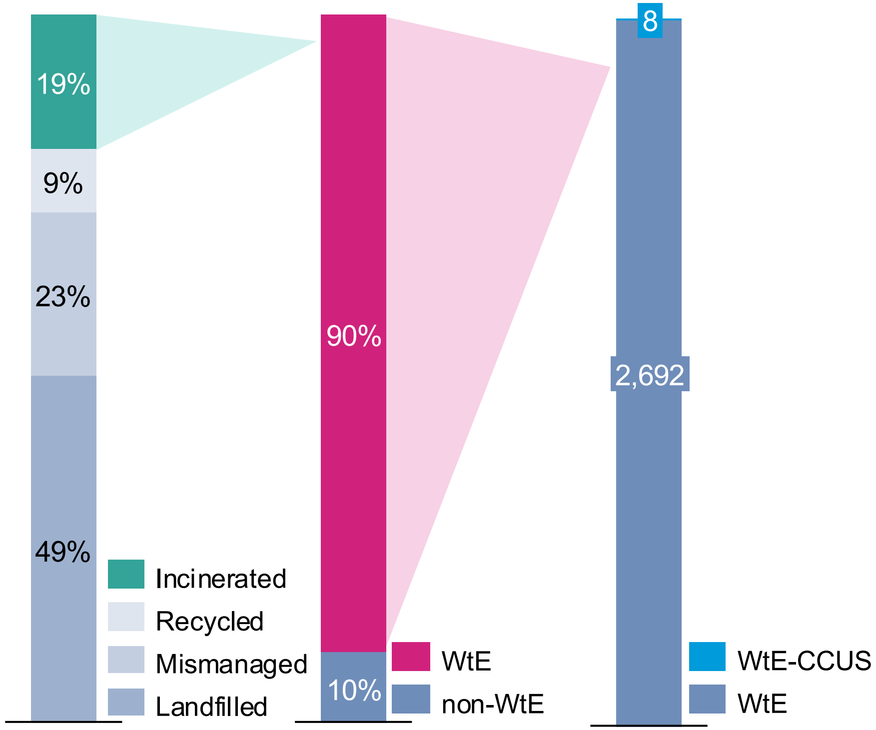
- Post combustion capture is a more mature technology, and is used in 80-90% of industries - largely due to easier retrofitting of facilities
- Carbon capture is less efficient when applied to downstream production, as emissions come mostly form electricity – not direct combustion
- Naphtha and ethane are traditionally sourced from oil and natural gas, respectively
- Methods for CO_2 capture vary widely
  - Chemical adsorption is the most mature for high-value chemicals like olefins
  - Other methods include absorption and membrane separation

Sources: Carbon Capture Utilisation and Storage (IEA, 2024); Capture and Reuse of Carbon Dioxide (CO_2) for a Plastics Circular Economy (Mada Costa et al., 2021); Carbon dioxide capture approaches (NETL); Plastic and Climate (CIEL, 2019); Pre-combustion Carbon Capture Research (U.S. DOE); Making Plastics Emissions Transparent (COMET, 2022); Methods and Techniques for CO_2 Capture: Review of Potential Solutions and Applications in Modern Energy Technologies (MDPI, 2022).
Credit: Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner.

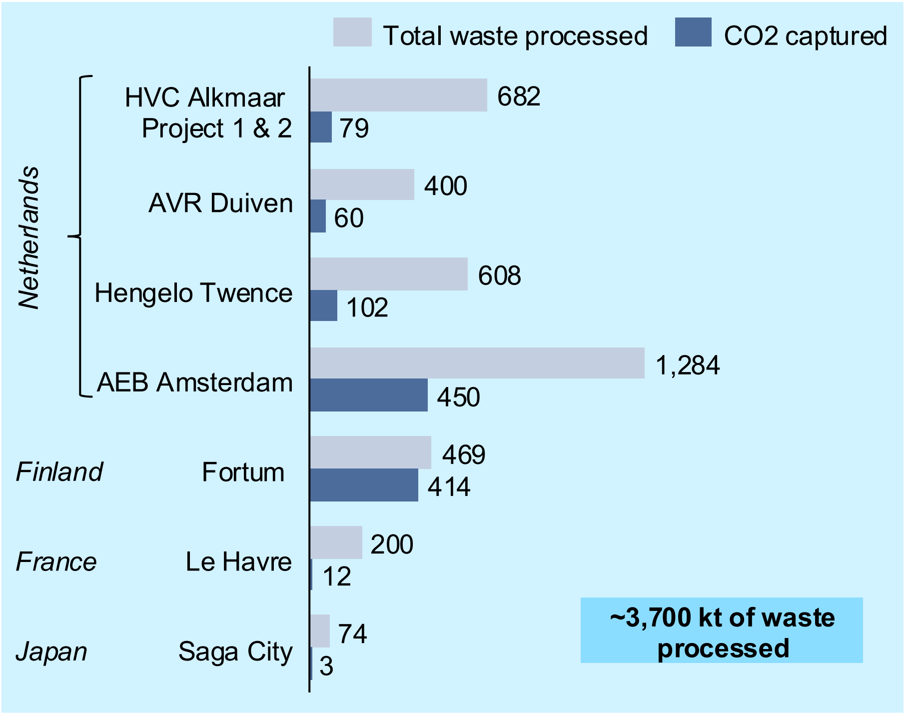
~20% of plastics are incinerated at end of life, primarily in WtE facilities; integration of CCUS is limited to <0.5% of plants

Most waste is incinerated in waste-to-energy facilities for energy recovery; most currently operating WtE-CCUS plants are located in Europe

19% of plastics incinerated | **>90% of incinerated waste in WtE plants[1]** | **<0.5% of WtE plants utilize CCUS**



All but one WtE-CCUS pilot plants are in Europe and process ~3,700 kt of waste per year



Observations

- WtE-CCUS is a **complementary solution, not a replacement one.** Best practice is to recover a significant share of plastic before incinerating:
  - Recovery and recycling are still preferred methods for EOL management according to circular economy models; **only unrecoverable plastics must be incinerated.**
  - Countries with high incineration rates also display high recycling rates, as landfilling is avoided.
- When incinerated, plastics emit ~ **1 - 3 kg CO_2 per kg** of plastic

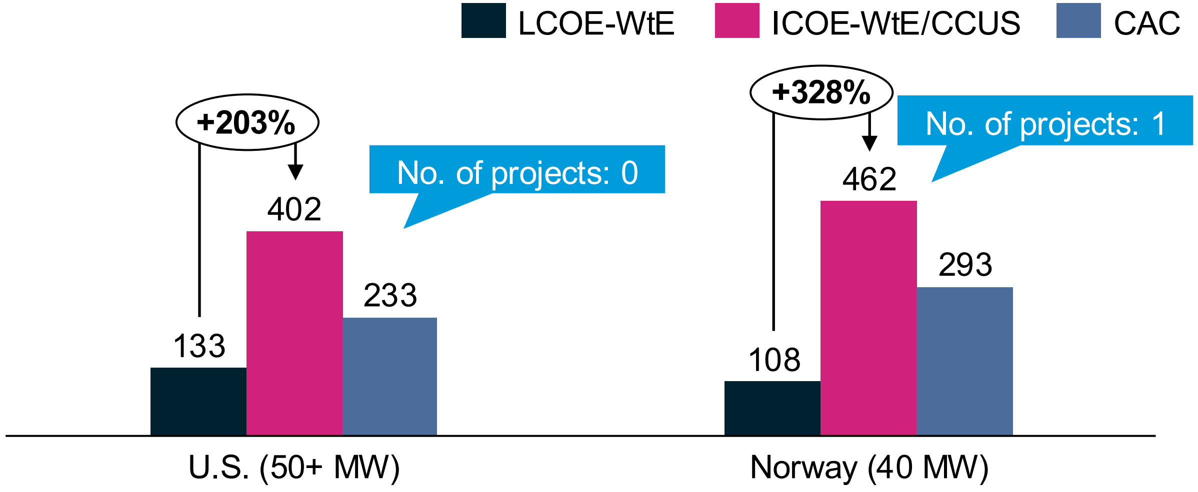
[1] Analysis based on Europe, North America, and OECD Asian countries.

Sources: CCS on Waste to Energy (IEA GHG, 2020); The integration of CCUS in WtE plants (Acampora et al., 2025); An Overview of WtE Incineration (Bertone et al., 2024); Making Plastics Emissions Transparent (Comet, 2022); Share of plastic waste that is incinerated (Our World in Data, 2023); 10+1 Things to know about CCUS and WtE (WWW, 2024); Waste to energy boom takes a break (Recycling Magazine, 2024); Waste incineration pollution and health impacts (GAIA, 2019).

Credit: Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Even in high-potential markets, WtE-CC[US] remains cost prohibitive, requiring state funding and a coordinated value chain

WtE-CCUS is cheaper in U.S., but only Norway has active projects



- Active CCUS market but no specific WTE-CCUS policies
- MSW plants lack nearby heat-offtake markets, limiting economical feasibility of district heating integration

- WtE profitability is limited due to low processing capacity
- Large heating market
- Almost all existing plants are considering WtE-CCUS retrofits

Norway benefits from coordinated CCS pipelines, innovative uses of CO_2, and state support; U.S. requires tailored incentives

	Norway Success factors	U.S. Levers to incentivize deployment
Economic and market measures	WtE-CCUS integrated as part of broader capture to storage pipelines to improve economics: e.g., Longship project	Innovative CCU pipelines for added revenue: e.g., production of biofuels from captured gas
	Exploration of innovative market mechanisms: e.g., sales of plastics certificates to incinerate unrecoverable plastics	Developing infrastructure for district heat market to improve profitability of WtE
Regulatory and policy measures	Significant state and international support: e.g., 1) the EU Innovation Fund; 2) waste taxed at 238 NOK/tCO2; tax exemptions available for captured CO_2 under ESR; tax to triple by 2030; 3) EU Projects of Common Interest initiative	Identification of CO_2 storage sites to benefit from IRA 45Q tax credit (*for projects constructed **before** 2033)
	Historical inclusion of WtE in national policy aimed to replace fossil fuels and enhance energy profitability	Inclusion of WtE in national carbon framework to incentivize adoption (e.g., rewards for carbon-negative emissions)

[1] U.S. prices calculated on inflation-adjusted 2012 dollar values at 41.11%.

Sources: The potential of WtE in reducing GHG emissions (Chandel et al,. 2012); Impact of Uncertainties on the Design and Cost of CCS from a WtE Plant (Roosanaly et al., 2020); Share of plastics that is incinerated (Our World in Data, 2023); 10+1 things to know about CCUS and WtE (WWW, 2024); Waste to energy boom takes a break (Recycling Magazine, 2024); EU funds acknowledge CC's potential (ESWET, 2024); WtE from municipal solid waste (U.S. DOE, 2019); Full-scale WtE CCS in Norway (IEA, 2025); Legislative framework and circular economy impacts (Nordic Council of Ministers); Can carbon capture make incinerators a net zero solution? (Waste Dive, 2022); 45Q Tax Credit (Carbon Capture Coalition, 2025).

Credit: Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

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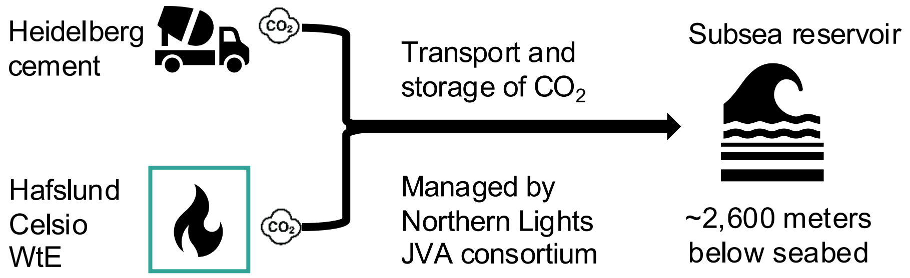
Norway's Longship project is the first open-source CO_2 transport and storage network

The Longship project connects industry capture to storage



Project timeline for Hafslund Celsio WtE-CCUS

- 2016: Feasibility study and pilot
- 2020: Parliament approves NOK 16.8B (~two-thirds of project costs)
- 2023: **Project halted** due to ballooning costs (+30% of initial budget)
- 2025: Microsoft and Frontier offtake agreements for carbon removal → Final investment decision
- Q3 2029: Anticipated operational start

Overview & mission	• First-ever cross-border, open-source CO2 transport and storage infrastructure network; Europe's first complete value chain for carbon capture and storage
Ownership	• Public-private collaboration spearheaded by Norwegian government
Location	• Norway
Business model	• Point source emissions captured and transported to offshore facility • Recovered heat from WtE to produce district heating and electricity • Exploring **Sales of Plastics certificates for incinerated plastics**
Capture opportunity	• Hafslund Celsio projected to capture **350 kt per year of CO_2** (~1% of Norway's annual total emissions)
Policy landscape	• ~60% of waste in WtE plants is biogenic, resulting in negative emissions; provides important opportunity for Norway to achieve emissions targets
Funding history	• NOK 22 billion in public funding • €131 million from the EU as a Project of Common Interest
Partner companies	Hafslund Oslo Celsio; Heidelberg Materials; TotalEnergies; equinor; Shell

Sources: Full-scale WtE CCS in Norway (IEA, 2025); About the Longship Project (Northern Lights, 2025); The Longship CCS Project (Gassnova, 2025); Longship project goes into operation (Norwegian government press release, 2025); EU funding awarded (Northern Lights, 2023).
Credit: Khande-Jae Fisher, Anika Behrndt, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

CCUS bottlenecked by costs, policy, and technology maturity but can scale with more targeted investment in CO2 use infrastructure

	Limited scaling and Infrastructure	Uncompetitive costs	Uneven regulation
Bottlenecks	• **Commercial development:** There are no commercial plants with CCUS during monomer fabrication; **less than 0.5% of WtE plants are retrofitted** • **Offtake:** There is weak demand for CO2-based products; CO2-based-plastics pathways are still nascent • **Transportation and storage:** Access to networks and large-scale storage is uneven	• **Capture at facilities:** Retrofits are complex, expensive, and energy intensive. Flue with low CO_2 concentrations amplify all three challenges • **Captured CO_2 as feedstock:** Monomer fabrication from captured CO_2 is **~10%** more expensive (>200% if sourced from WtE-CCUS) compared to conventional	• **Unaligned policies:** CCUS relies heavily on policy incentives, which remain **fragmented** globally • **Unalignment of policy-cost:** Policy in Europe for WtE-CCUS is more developed with more significant deployment, despite higher costs
Solutions	• **Development of regional pipelines:** An example is the Longship project, alongside retrofits to ensure end use for CO2 • **Leveraging initiatives:** Plastics facilities must **leverage existing cross-sector CO2 incentives** to support early scaling	• **Investment:** Billions of dollars in investment is necessary to achieve 2050 CCUS goals • **Unit economics:** Build integrated CO2 value chain to reduce per-ton costs	• **Inclusion of WtE-CCUS** in national carbon framework to improve economics • **Public-private co-financing** of projects to reduce upfront capital risk

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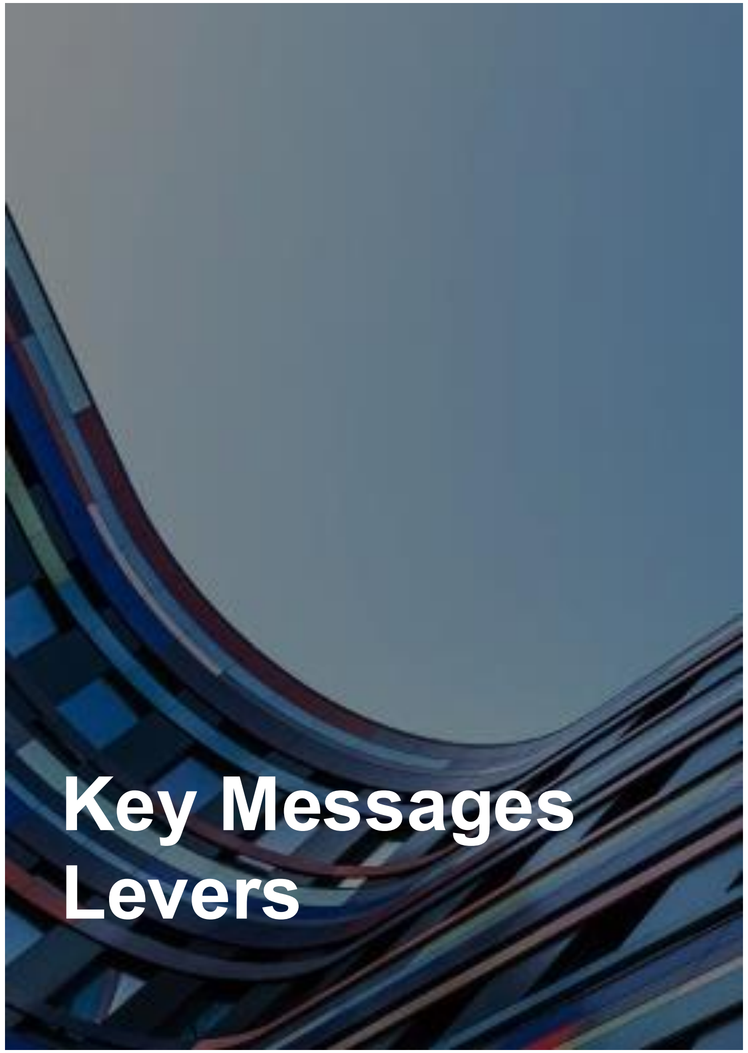
Finance and Policy Levers



Investment is skewed toward recycling, while upstream levers remain underfunded

- Over 60% of 2018-2023 investment went to recycling; unlocking full abatement (10 to 20.5 Gt CO_2) requires >$1 trillion and greater upstream allocation
- Reduce lever accounts for nearly 50% of total abatement potential and could lower required investment in other levers by ~30% if demand is reduced

Structural barriers, especially high CapEx and unclear business models, constrain feasibility across levers

- Reduce and Recycle levers show the strongest fundamentals with higher abatement potential and technology maturity
- Substitute faces critical feedstock and infrastructure limitations; Electrify is constrained by high CapEx; and CCUS by high investment needs and low maturity across business model and technology

Unlocking plastics levers requires risk-tolerant capital and blended structures to de-risk investments and attract traditional investors

- ~90% of plastics circularity capital comes from low-risk, return-oriented investors such as corporates, private equity firms, and banks
- Incentivizing early-stage capital and concessional structures is essential to unlock plastics decarbonization; in particular, attracting the public sector is key to supporting model testing and de-risking investment

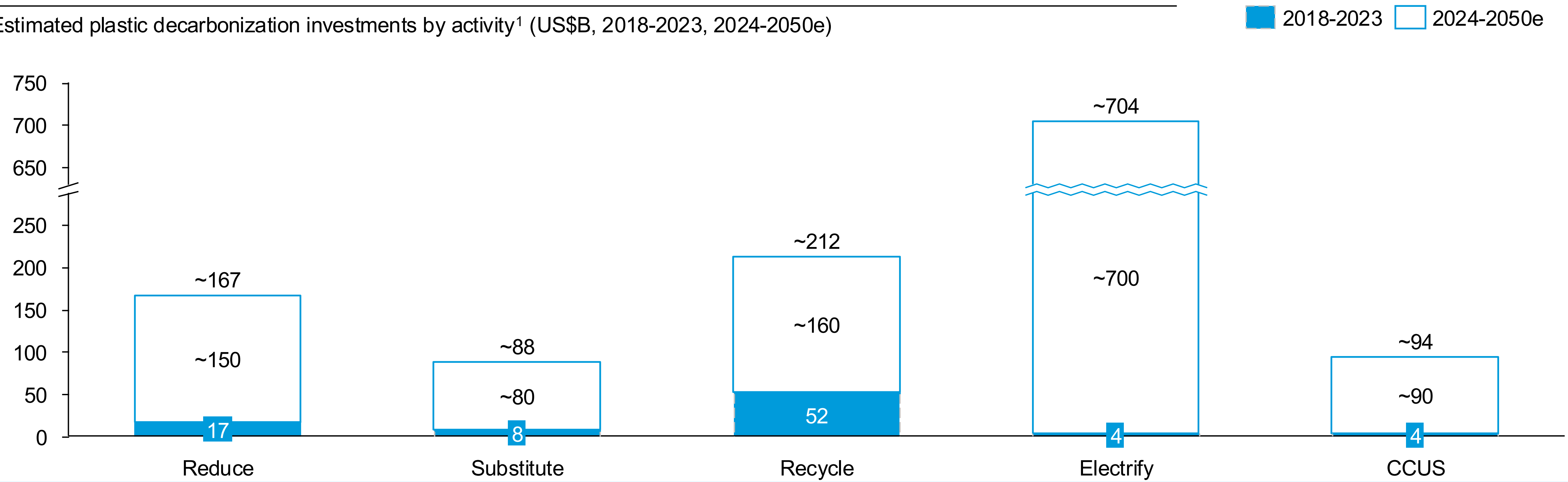
Policy clarity, enforcement, and alignment are essential to close the investment gap

- Policy efforts are more advanced in midstream and downstream, but upstream remains under-regulated and lacks long-term targets and enforcement
- Stronger national policies are needed to reduce virgin plastic use, increase uptake of recycled content, and limit production emissions

Current capital deployment is skewed toward recycling; greater upstream investment is needed to reach decarbonization potential

Investors favor more tangible, infrastructure-heavy and commercially familiar levers, while lower-demand and material-substitution pathways offer better abatement efficiency but get less capital

Estimated plastic decarbonization investments by activity[1] (US$B, 2018-2023, 2024-2050e)



	Reduce	Substitute	Recycle	Electrify	CCUS
Abatement potential, 2050 (~Mt of CO_2)	**6,000–9,000**	**900–3,800**	**2,800–4,100**	**250–3,300**	**210–380**

[1]All values indicative, rounded, non-exhaustive and based on current trajectory. See **Appendix 1** for detailed notes of sources and assumptions.
Source: Plastic demand could reduce by up to 30% in an accelerated energy transition scenario (Wood Mackenzie, 2024).
Credit: Mariana Castaño, Anika Behrndt, Paula Sánchez, Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Decarbonization levers must overcome key financial barriers for investment, especially high CapEx and unclear business models

Comparison of decarbonization levers across TLR, business model, finance, and policy

✓ Favorable factor ! Major constraint

Solution	Abatement potential	Required investment	Business model maturity	Technology maturity	Policy & regulation readiness	Key financial barrier
Reduce	✓ High	Medium	! Low	✓ High	Medium	Lack of scalable business models and limited policy[1]
Substitute	Medium	Medium	! Low	Medium	! Low	Scale-up limited by feedstock supply, downstream infrastructure, and weak policy
Recycle	✓ High	Medium	Medium	✓ High	Medium	High infrastructure costs from decentralized setup and dual system scaling[2]
Electrify	Medium	! High	Medium	Medium	! Low	High CapEx for low-carbon infrastructure and limited policy robustness
CCUS	Low[3]	Medium	! Low	! Low	! Low	Limited economies of scale and unclear monetization pathways

[1] Current reduction strategies face challenges including limited profitability, complex reverse logistics, behavioral inertia from consumers, and insufficiently robust policy frameworks to create demand or enforce adoption. [2] Recycling requires high capital due to asset-heavy infrastructure, the need for decentralized deployment, and parallel investment across mechanical and chemical technologies. [3] Abatement potential assessment for CCUS reflects only plastics' share of global CCUS deployment (~4%); global potential is substantially higher.

Unlocking key levers requires risk-tolerant capital and blended structures to de-risk investments and attract traditional investors

~90% of $170B circular plastics funding comes from low-risk, return-oriented investors

Patient capital | Low-return tolerant | Early-stage supporter

Plastic circularity investments by investor type[1] (%, 2018-2024)

Early-stage capital is critical to unlock potential; public sector investments should be incentivized to test models and de-risk upfront CapEx

✓ Investor fit

Investor type	Investor traits	Share	Can help fund high CapEx?	Can enable business model testing?	Can support commercial scaling?	Levers with unlock potential
Corporate investors		36%	✓ *If there's strategic fit			Recycle, Electrify, CCUS
Private equity		27%	✓ *If proven and scaling			Recycle
Commercial banks		24%				Recycle
Venture capital	Early-stage supporter	9%		✓		Reduce, Substitute
Public sector	Patient capital, Low-return tolerant, Early-stage supporter	3%	✓ *If co-investing with private capital	✓ *If enabled by policy	✓	Recycle, Reduce, Electrify, CCUS
Accelerators	Early-stage supporter	1%		✓		Reduce, Substitute
DFIs[1]	Patient capital, Low-return tolerant		✓ *If concessional structure available[2]		✓	Recycle, Substitute, Electrify, CCUS
Philanthropic inst.	Patient capital, Low-return tolerant, Early-stage supporter			✓		Reduce, Substitute
Family offices	Patient capital		✓			Reduce, Substitute, Electrify

[1] Development Finance Institutions are government-backed entities (e.g., IFC, EIB, IDB Invest) that deploy public capital through instruments like concessional loans, equity, and guarantees to mobilize private investment in emerging markets. [2] Financial instruments offered on below-market terms, like low-interest loans, risk guarantees or subordinated equity.

Sources: Plastics Circularity Investment Tracker (The Circulate Initiative).

Credit: Mariana Castaño, Ariela Farchi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Policy alignment, risk-sharing tools, and robust data are essential to mobilize capital toward plastics solutions

Comparison of current barriers and potential actions across critical enablers of plastics investment

	Policy & Regulation	Data & Tracking Systems	Investment Risk Mitigation
Why it matters	**Clear mandates, stable incentives, and long-term targets** provide visibility, demand certainty, and market signals that reduce investor risk	**Robust, standardized, and transparent data systems** enable investors to assess risks, track impact, and evaluate returns across the plastics value chain	**Targeted financial tools reduce exposure to early-stage risks**, enabling private capital to enter and scale innovative or unproven solutions
Current gap	Policies remain **fragmented across geographies and solutions**, with limited long-term clarity, weak enforcement, and scarce demand-pull mechanisms	Data is **inconsistent, siloed, and lacks standard formats** for emissions, material flows, and solution performance, limiting investor confidence	**Financial instruments** like concessional loans, guarantees, and insurance **remain underused**, especially for technologies with uncertain revenue streams or infrastructure lock-in
Enabling moves	• Align national policies across all levers • Commit to targets that reduce virgin plastic use and increase recycled material uptake • Enforce emission limits for plastics production	• Develop interoperable traceability platforms. • Standardize digital product passports[1] • Mandate emissions disclosure standards across the value chain • Ensure third-party impact verification	• Expand blended finance models • Deploy public guarantees[2] • Offer first-loss capital[3] • Co-design risk-sharing tools[4] with public-private investment vehicles

Focus of next section (Policy & Regulation)

[1] Digital profiles capturing content, emissions, and recyclability per product. [2] Government or multilateral guarantees that backstop investment risk, reducing downside exposure. [3] Public or catalytic actors that absorb early losses, improving the risk-return profile for commercial investors in the future. [4] Joint instruments like guarantees, subordinated debt, or insurance mechanisms.

Policy focus is uneven: Reduce and Recycle dominate today, with electrification and CCUS unevenly developed across jurisdictions

Effectiveness Level: 🟢 High 🟡 Mid 🔴 Low

	Reduce (Raw material)	Substitute	Recycle (Product design, manufacturing, and distribution)	Electrify	CCUS
U.S.	🔴 Patchwork of state and local bans on **single-use plastics (SUPs)**	🔴 **Only California, with federal procurement** for 100% recyclable or compostable packaging by 2032	🟡 Emerging state-level **Extended Producer Responsibility** laws 🔴 **Container deposit** laws in 10 states 🟡 **Recycling ordinances** in many cities and counties 🟡 Emerging state-level requirements for **recycled content**	🟡 **IRA + BIL:** $6B DOE Industrial Demonstrations Program **§48C tax credit** (30%) for clean industrial equipment	🟡 IRA provides **tax credits** for carbon capture
EU	🟡 **SUPs** Directive 🟡 Minimum **recycled content** targets for beverage bottles (25% by 2025)	🟡 Mandatory compostability for specific packaging from **Feb. 2028**	🟢 **Eco-design requirements** for durability, reusability, recyclability 🟢 Mandatory **EPR** for packaging 🟢 **Plastic Packaging Tax** levied on non-recycled plastic packaging 🟢 Mandatory **targets for plastic** packaging recycling (55% by 2030) 🟢 **Separate collection of plastic waste**	🟢 **EU carbon market reform:** Free emission permits for petrochemical producers phase out between 2026 and 2033, making fossil-fuel-based production increasingly expensive	
IN	🟡 Nationwide bans on identified **SUPs**	🟡 **BioE3 Policy (2024)** subsidizes bioplastics manufacturing to close cost gap	🟡 EPR framework requiring producers to finance **waste collection and recycling infrastructure**	🔴 No direct electrification policy	🟡 **~$2.4B for CC** in its 2026-2027 budget; captures CO_2 to make plastics feedstock
CH	🟡 Nationwide bans on production and sale of specific **SUPs**	🔴 Promotion of **biodegradable substitutes** in government procurement	🟡 Mandatory **waste sorting programs** in major cities like Shanghai and Beijing 🟡 National targets for **increasing recycling rates** 🟡 Ban on the import of most plastic waste, improving domestic recycling	🟡 National climate goals push for **electrification** in petrochemicals	🟡 State-owned enterprises investing in pilot projects CCUS

Sources: California SB 54 (CalRecycle, 2025); Impact Report (CRI, 2024); Plastics Strategy (EU Commission, 2025); EU Green Deal (EU Commission, 2025); Impact of China's National Sword Policy (Lin et al., 2022); China's Policies and Actions for Addressing Climate Change (Ministry of Ecology, 2022); India on Track to Plastic Waste Management (Banerjee et al., 2024).
Credit: Anika Behrndt, Yosafat Partogi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

U.S.'s decentralized model creates significant challenges for harmonization and building a national circular economy

A handful of pioneer states have moved first on bans, recycled content, and EPR, creating a domino effect since 2014

- **2014 – California enacts the first statewide plastic ban.** This scaled the municipal-level ban to the entire state of California, signaling a major shift in the political viability of statewide consumption-focused policies
- **2020 – Washington state passes a comprehensive recycled content mandate;** it requires a significant percentage of post-consumer recycled content in a wide range of products (e.g., beverage containers, dairy tubes)
- **2021 – Maine and Oregon pass the first EPR laws for packaging.** States were the first in the U.S. to place financial and operational responsibility for managing packaging waste directly onto producers, a model long established in the EU
- **2022 – California passes SB 54, the nation's strongest plastic law.** It combined EPR laws with an aggressive and mandatory target for source reduction, effectively setting the gold standard for state-level action
- **2023 onward – U.S. sees a domino effect of state action.** Following the lead of pioneering states, CA, CO, MN, ML, and WD have passed their own EPR laws, with others debating similar policies
- **2025 – Trump II targets federal plastics policy, not state EPR:** A paper straw executive order, a reversal of national parks phaseout, and an EPA pivot from preventing plastic pollution to "advanced recycling," but no federal preemption

State-Level Policies

Extended Producer Responsibility (EPR) law – California SB 54: Mandates a 25% reduction in SUP packaging and **food ware** by 2032 and requires 65% to be recycled

- Creates a producer-funded system to manage packaging and food ware waste
- Reinforces and builds on California's existing recycled-content mandate, strengthening demand for recycled plastics
- Pushes firms to go beyond "make it recyclable" and figure out how to use less plastic overall, while investing in advanced sorting and reprocessing capacity
- **Main limitation:** A single Producer Responsibility Organization (PRO) must define fee structures, manage data reporting, and coordinate thousands of brands, creating a major logistical and administrative burden
- **Timeline:** Implementing regs have been withdrawn twice (March 2025 and January 2026); statute is intact, with deadlines unchanged, but rollout is uncertain

Container deposit laws – "Bottle Bills": A fully refundable deposit is placed for the purchase of a beverage container at the point of sale (typically ~10 cents)

- Requires refundable deposit per container at purchase
- Reframes empty containers from "trash" into a "valuable asset," a more active approach than passive curbside recycling with no financial incentive
- Provides a powerful financial incentive that encourages consumers, individuals, nonprofits, and community groups to collect littered containers
- **Main limitation:** Cover only beverage containers, a narrow slice of total waste

Sources: California SB 54 (CalRecycle, 2025); Impact Report (CRI, 2024); Seven States and Counting: The 2025 Guide to EPR Packaging Compliance (Proskauer, 2025); Ending Procurement and Forced Use of Paper Straws – The White House (The White House, 2025); Administrator Zeldin in The Hill: The Trump EPA has a Plan to 'Unmake' Plastic Waste (EPA, 2026).
Credit: Yosafat Partogi, Anika Behrndt, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

EU leads global circularity policy and is closing the loop on production emissions via ETS, CBAM, and ETS2

EU has built a multifront policy package — from ETS to circular economy — tackling plastics emissions across the lifecycle

- **2005 – Emissions Trading System (ETS) launches.** Cap and trade system is the world's first major carbon market and the cornerstone of EU climate policy
- **2008 – Waste Framework Directive is revised.** It prioritizes waste prevention, followed by reuse, recycling, recovery, and last, disposal (landfill), fundamentally shifting the perspective on waste management
- **2015 – First Circular Economy Action Plan is adopted.** It introduces ambitions for higher recycling rates and better product design
- **2019 – Single-Use Plastics (SUP) Directive comes into force**
- **2020-21 – Green Deal era begins.** New Circular Economy Action Plan (2020); Fit for 55 strengthens ETS: faster cap reduction plus phaseout of free allowances for CBAM sectors
- **2024 – ESPR comes into force; PPWR is adopted.** Ecodesign for the Sustainable Products Regulation (July 2024) mandates durability, recycled content, and Digital Product Passports across most goods. PPWR, adopted Dec. 2024, includes mandatory recycled content and reuse targets
- **2025 onward – Clean Industrial Deal and plastics circularity push.** PPWR enters into force 2025; the Clean Industrial Deal (Feb. 2025) targets doubling the EU circularity rate to 24% by 2030; plastics circularity package (Dec. 2025) adds end-of-waste criteria for recycled plastics. ETS2 to launch 2027-2028

Key Policies

Packaging and Packaging Waste Regulation (PPWR) – Regulation (EU) 2025/40: Adopted Dec 2024, applies from Aug 2026. EU-wide rules across the full packaging lifecycle

- Mandatory **recycled-content targets** by 2030 (e.g., 30% in contact-sensitive PET, 65% in non-contact-sensitive); stricter targets by 2040
- **Reuse and refill targets** for transport, grouped, and beverage packaging; bans on specific single-use formats (e.g. hotel toiletries, fresh-produce wraps under 1.5 kg)
- **All packaging recyclable by 2030**, graded A/B/C by design-for-recycling performance; non-recyclable formats banned from market by 2035
- **Why it's working:** binding *Regulation* (not Directive), directly applicable in all 27 Member States, no transposition gap; combines design rules, content mandates, and demand-side reuse targets, closing loopholes that fragmented the old SUP

EU Emissions Trading System (ETS): Cap and trade system designed to reduce greenhouse gas emissions from energy-intensive industries, including petrochemicals:

- **Places overall cap** on the **total greenhouse gases** that the industrial system can emit. The cap declines annually; firms trade to cut emissions where it's cheapest
- **CBAM (transitional 2023; definitive Jan. 2026)** puts a carbon price on imports of cement, steel, aluminum, fertilizers, hydrogen, and electricity - closing the leakage loophole that justified decades of free allowances
- **ETS2 (compliance 2028)** extends carbon pricing to fuels for buildings, road transport, and small industry; paired with Social Climate Fund to cushion low-income households

Sources: Regulation EU 2025/40 - EN - PPWR - EUR-Lex (European Union, 2025); About the EU ETS – Climate Action (European Commission), Carbon Border Adjustment Mechanism – Taxation and Customs Union (European Commission); Climate Action: ETS2: buildings, road transport and additional sectors (European Commission).
Credit: Anika Behrndt, Yosafat Partogi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

China leads on plastic waste regulation, but no policy yet caps the production driving emissions

All policies to date target waste and circularity, not upstream production in China

- **2008 – First "Plastic Ban."** China announces a nationwide ban on the free distribution of plastic bags in all retail outlets and prohibits the production and sale of ultra-thin plastic bags (less than 0.025 mm thick)
- **2017 – National Sword Policy.** Reshapes the global recycling landscape. Bans the import of 24 types of solid waste, forcing China to reckon with its domestic plastic waste and build its own recycling infrastructure
- **2020 – New Plastic Ban: A Comprehensive Roadmap.** Landmark policy sets a multiyear timeline for the phased reduction and elimination of SUPs, providing a nationwide roadmap with specific deadlines for different types of plastics and regions
- **2021 – The 14th Five-Year Plan.** Included goals to strengthen the governance of plastic pollution, promote plastic alternatives, and develop the circular economy
- **2022 – Extended Producer Responsibility (EPR) pilot.** China begins to more seriously explore and pilot EPR schemes
- **2024 – INC-5 UN Plastics Treaty talks.** Aligns with oil producers against binding caps on virgin plastic production; talks collapse but resume at INC-5.2
- **2026 – 15th Five-Year Plan.** Consolidation phase for full-chain plastic governance; targets 4.5 billion tons of solid waste utilized by 2030

Key Policies

National Sword Policy (2017): Bans the import of most post-consumer plastic waste. Prior to 2017, China was the world's largest importer of plastic scrap

- Implemented in response to severe environmental and health concerns related to low-quality, contaminated imported waste that was difficult to process
- Asserted environmental sovereignty by signaling that China would no longer be the world's dumping ground for plastic waste
- **Why it's working:** Cutting off foreign scrap forced industries to rely on domestic plastic waste, driving investment in a more formal and efficient recycling system. Globally, the ban pushed other countries to build their own recycling capacity

15th Five-Year Plan (2026–2030): Moves plastic governance from the 14th FYP's "establishment phase" into a consolidation phase - full-chain regulation paired with concrete national circular economy targets

- Priority areas: Waste classification systems, recycled content uptake in key products, biodegradable mulch films, and formalization of EPR schemes. Aligns with China's "dual-carbon" goals (peak by 2030, neutrality by 2060)
- **Why it's working:** Keeps regulatory momentum after the 2021-2025 cycle; pivots from bans and targets to building a domestic secondary materials market

The gap these policies don't close: China produces ~32% of global plastic. Petrochemical capacity is mid-buildout. Global virgin plastic production is projected to almost double by 2050. None of the listed policies cap virgin production — and China actively opposed binding caps at INC-5

Sources: China's plastic import ban increases prospects of environmental impact mitigation of plastic waste trade flow worldwide (Nature Communications, 2021); Key Players and Positions in the Global Plastic Treaty Negotiations (Earth.org, 2025); Plastics – the fast facts 2023 (Plastics Europe, 2023); The Carbon Brief Profile: China (The Carbon Brief, 2023).
Credit: Yosafat Partogi, Anika Behrndt, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

For India, policy focuses narrowly on the waste crisis — with early EPR steps but little attention to production emissions

India's plastics policy now combines bans on high-litter SUP with early moves to formalize its vast informal recycling sector

- **2016-2022 (background).** PWM Rules establish the regulatory framework; the 2022 nationwide SUP ban and first EPR guidelines bring producers into scope
- **April 2025 – Mandatory recycled content takes effect.** Producers must use recycled plastic in packaging on a rising schedule: Category I rigid 30% → 60% by 2028-29; Category II flexible 10% → 20%; Category III multilayered 5% → 10%
- **July 2025 – Digital traceability.** All packaging must carry QR codes or unique identifiers linking each batch to its registered producer; 3,000+ PIBOs registered on CPCB's portal
- **2024-2025 – The fake certificate scandal.** CSE and CPCB audits find ~700,000 fraudulent EPR certificates — 38x the actual processing capacity of issuing recyclers. Investigations expose "ghost" recycling plants (31 of 41 audited e-waste units). NGT issues notices; CPCB orders environmental compensation
- **August 2025 – Geneva (INC-5.2).** India aligns with Saudi Arabia, China, Russia, and Iran to block binding caps on virgin polymer production in the UN Global Plastics Treaty. Treaty talks collapse
- **March 31, 2026 – PWM (Amendment) Rules 2026.** Brings resin and pellet "sellers" inside the framework for the first time; decentralizes enforcement to Urban Local Bodies with registered environment auditors; introduces reuse mandates (up to 85% for large rigid water containers); allows three-year carry-forward of unmet targets

Key Policies

The maturing EPR system — now the regulatory engine, not the SUP ban

- **Scope:** Mandatory recycled content and reuse targets across Categories I to III, plus QR-code-level traceability on every package
- **Mechanism:** Tradable EPR certificates clearing on CPCB's digital portal; resin suppliers (new in 2026) must register and report sales
- **Why it matters:** First serious attempt to make India's vast informal recycling sector legible to a compliance infrastructure
- **Main limitation:** ~700K fake certificates exposed; over 70% of registered PIBOs missed their plastic collection and recycling targets; the system's reliance on self-reported data is the structural weakness

Digital traceability via QR codes: From July 1, 2025, every plastic package placed on the Indian market must carry a QR code, barcode, or unique identifier tied to its registered producer

- **Mechanism:** Identifiers feed CPCB's centralized EPR portal; over 3,000 PIBOs already registered; registered environment auditors (added in the 2026 amendment) verify the chain
- **Why it matters:** Converts EPR compliance from paper claims into an auditable, data-based chain - directly responding to the ghost-recycler scandal that exposed the limits of self-reporting
- **Where it's straining:** Small producers and the informal collection layer still sit largely outside the QR-coded chain. Traceability works only if enforcement follows

Sources: India's Plastic Waste Management Rules 2025 (PolyNext, 2025); CSE Report Exposes Major Flaws in India's EPR System: 70k Fake Certificates and Missing Polluters (DownToEarth, 2024); Plastics treaty talks expose India's economic dilemma (PolicyCircle, 2025).

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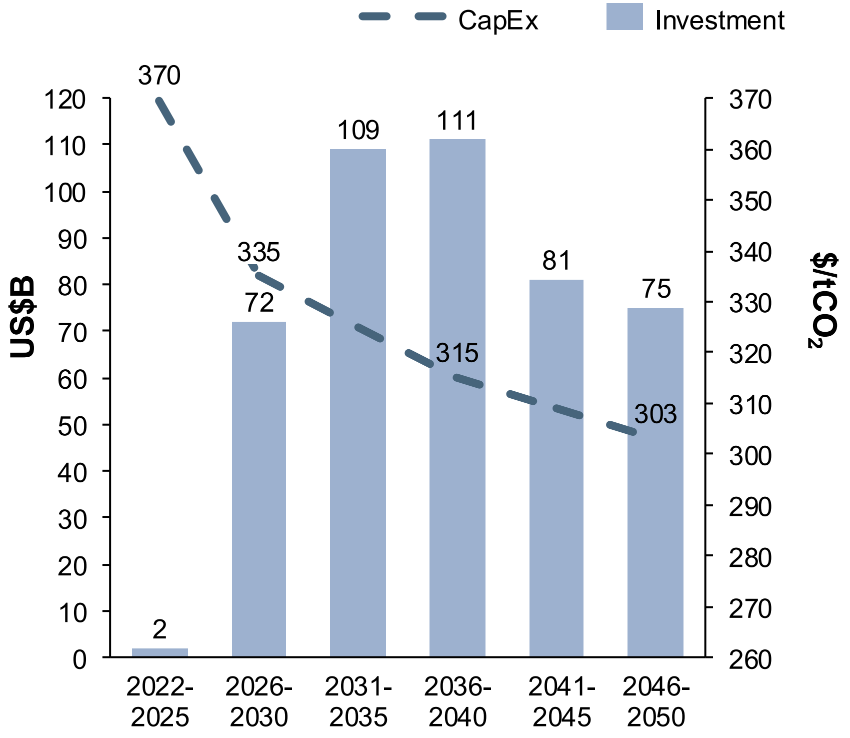
Glossary

ACR	Acrylic
APC	Aliphatic polycarbonates
BAU	Business as usual
CCUS	Carbon capture, utilization, and storage
CP	Casein polymers
CR	Cellulose regenerates
CX	Customer experience
EOL	End of life
EPR	Extended producer responsibility
EPS	Expanded polystyrene
E-SC	Electrical steam cracking
LDPE	Low-density polyethylene
MENA	Middle East and North Africa
NYL	Nylon
PA	Polyamides
PBAT	Poly(butylene adipate-co-terephthalate)
PBS	Polybutylene succinate and copolymers
PE	Polyethylene
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PLA	Polylactic acid
PP	Polypropylene
PTT	Polytrimethylene terephthalate
PUR	Polyurethane
PVC	Polyvinyl chloride
SCPC	Starch containing polymer compounds
SUP	Single-use plastic

Carbon capture has the potential to reduce up to 50% of monomer production emissions

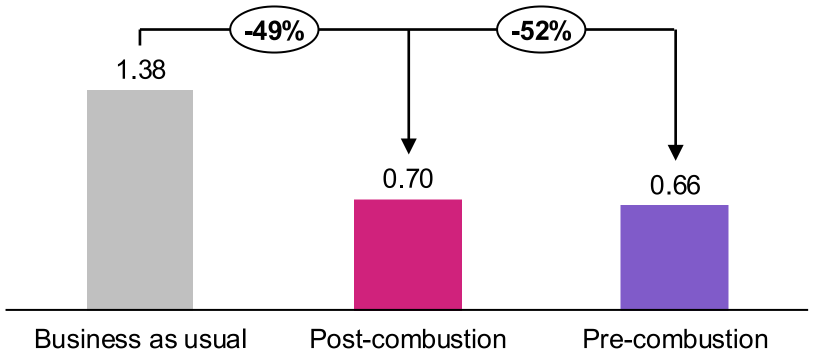
Average annual investment in CC to reduce fossil fuels processing costs by 18%[2]

Global average annual investment (US$B) and CapEx for CC in fossil fuels processing ($/t$CO_2$)

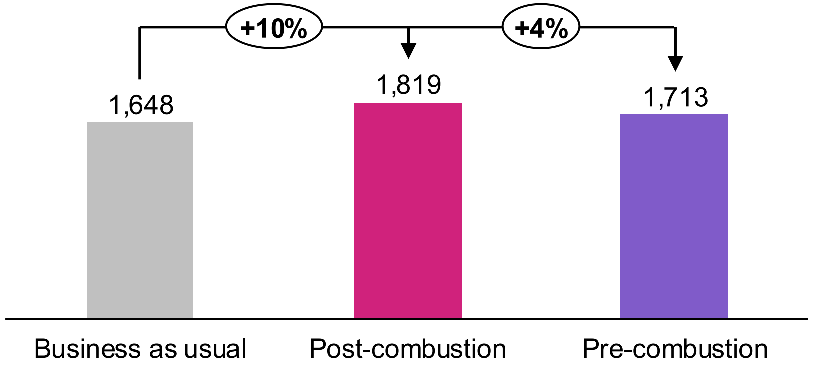


CC can reduce ~50% of emissions during SC but is up to 10% more expensive than BAU[1]

Impact of CCUS on emissions (ton CO2/ton olefin)



Impact of CCUS on cost (US$K/ton olefin)



Observations

- Costs for monomer fabrication as of today: **~$56 to $108** per ton of CO_2 .
- For pre-combustion, for the same amount of gas, more CO_2 can be captured (due to higher CO2 concentration), which leads to lower capital costs and smaller equipment sizes, making pre-combustion more cost effective.
- An uneven regulatory landscape, unestablished revenue streams, long lead times, and a lack of industry coordination for infrastructure build-out have limited scaling to date — coordinated government policy is necessary.
- 60% of future CCUS investment will go to capture (vs. transport, storage, and utilization).

[1] Point estimates based on ING analysis; assumptions: gas price (€55/MWh), carbon price (€85/ton), naphtha price (€620/ton), capture efficiency of 85% and 75% for pre- and post-combustion capture, respectively; dollar prices converted from euros at an exchange rate of $1 = $0.94. [2] Investments reflect McKinsey Achieved Commitments scenario.

Sources: How the plastics industry can go green and at what cost (ING, 2023); Scaling the CCUS industry (McKinsey, 2022); Global Energy Perspectives Outlook (McKinsey, 2023); Reaching net-zero carbon emissions from hard-to-abate sectors (ETC, 2018); Carbon dioxide capture approaches (NETL); Carbon Capture, Utilisation and Storage in the Energy Transition (ETC, 2022).

Credit: Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

U.S. and Netherlands lead in WtE-CCUS potential (1/2)

Desirability →
Score: 1-2 | 3-4 | 5-6 | 7-8 | 9-10

Criteria	Description	U.S.	Netherlands	Norway	India
All factors are given 10% weight for final score, except for CCUS/CCS and CCUS regulation (20%), WtE diffusion (15%), and plant size (5%)		**Overall score: 7.85 – U.S.** has high access to onshore CO_2 storage sites, large WtE plants, and high plant diffusion	**Overall score: 7.65 –** Hosts 4/7 of current WtE-CCUS plants; existing incentives for CC and common DH integration makes CC favorable	**Overall score: 7.65 –** Existing incentives, DH integration, and high social acceptance; however, smaller plant sizes	**Overall score: 3.8 –** Lack of CCUS policy, low DH integration, and low social acceptance limit deployment
Opportunity for CCU/CCUS	Availability of market to store and use captured CO2	High number of industry emission sources to incentivize CCS/CCU	North Sea basin projected to store up to 1,700 megatons of CO_2	High storage capacity in Norwegian continental shelf	Projects examining feasibility of CO_2-Enhanced Oil Recovery (EOR) and CO_2-materials
Integration with DH	Lower retrofit cost when integrated with existing district heating network	~30 plants integrated with DH	All plants have combined heat and power (CHP)	Incineration a key source of district heating	More wet solid waste than dry; WSW has a lower heating value
CO2 emissions factor	Higher local emissions factors result in higher CO2 avoidance benefits	~350 CO_{2eq}/kWh	~370 CO_{2eq}/kWh	18 g CO_{2eq}/kWh	716 g CO_{2eq}/kWh

Sources: Norwegian WtE in 2030 (2015); CCS in the Untied States (Congressional Budget Office, 2023); The potential of WtE in reducing GHG emissions (Chandel et al,. 2012); Impact of Uncertainties on the Design and Cost of CCS from a Wte Plant (Roosanaly et al., 2020); 10+1 things to know about CCUS and WtE (WWW, 2024); EU funds acknowledge carbon capture's potential (ESWET, 2024); Emissions Factors (EPA, 2024); TNO estimates storage capacity beneath the Nort Sea (TNO, 2025); Nowtricity (2025); CO2 baseline for the Indian Power Sector (CEA, 2023); India's largest WtE plant to come up in Gurugam (ET,2022); Why over 50% of Indiia's WtE plants have already shut down (BharatNama, 2025).

U.S. and Netherlands lead in WtE-CCUS potential (2/2)

Desirability →
Score: 1-2 | 3-4 | 5-6 | 7-8 | 9-10

Criteria	Description	U.S.	Netherlands	Norway	India
CCUS regulation	Favorable carbon pricing mechanisms increase retrofit attractiveness	Active regulatory landscape driven by tax credits, emissions standards, and federal funding programs	Strong framework with incentives and regulation for storage	Highly centralized and integrated framework	Policies under development but none currently enforced
WtE diffusion	Higher number of WtE plants indicates higher potential for local market	75 plants	12 plants	18 plants	12 operational, 8 non-operational
WtE/CCUS social acceptance	Public and general acceptance of CCUS	Mixed: Low familiarity with technology and some opposition	Higher acceptance than in U.S.; high opposition to CO_2 imports	High social acceptance; Longship project creates synergies for CCUS	Low acceptance due to toxins and ash from emissions gas
NOx/SOx emission limits	Low flue gas NOx/SOx emissions lower degradation of amine in CC	Stricter EPA standards for emissions as of 2024	Emissions limits strictly regulated by the EU	Strict national emissions limits and reporting requirements	Emissions are regulated but less stringent
Plant size	Higher capacity increases economies of scale	Plant sizes: 10-100 MWe	Plant sizes: ~40-100 MWe	Small plant sizes (average ~40 MWe)	Small sizes (up to 25 MWe)

Sources: Waste-to-energy plants are a small but stable source of electricity in the US (EIA, 2023); Norwegian WtE in 2030 (2015); Northern Lights (Total Energies); The potential of WtE in reducing GHG emissions (Chandel et al., 2012); Preferences and behaviors around CCS technology in different social and geographic contexts (Anders et al., Public 2024); Impact of Uncertainties on the Design and Cost of CCS from a WtE Plant (Roosanaly et al., 2020); 10+1 things to know about CCUS and WtE (WWW, 2024); EU funds acknowledge carbon capture's potential (ESWET, 2024); Energy Recovery from the combustion of MSW (EPA); Waste-to-energy as a source of renewable energy (Haush, 2024); How India can rejuvenate its WtE sector (ET, 2023); Factors shaping for more CC in the United States (Fikru et al., 2024); Common HW Incinerators (CPCB, 2025); Perspectives on CCUS Deployment on Large scale in India (Hupta et al., 2024); A comprehensive insight (Karmakar et al., 2023); India's largest WtE plant to come up in Gurugam (2022); Why over 50% of India's WtE plants have already shut down (BharatNama, 2025).

Credit: Khande-Jae Fisher, Ariela Farchi, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Rethinking Plastics" (20 July 2026).

Appendix 3 I: Investment and abatement sources and assumptions

Lever	Abatement assumptions and sources	Investment assumptions and sources
Reduce	Abatement potential was based on cumulative reduction across packaging, consumer products, transport, and construction — sectors representing ~80% of plastic waste (MDPI, link; Market.us, link; Science Direct, link; NIH, link).	Current cumulative investment is based on investments in “Redesign” and “Refill/Reuse” (The Circulate Initiative, link). Projected investment is derived by applying a scaling factor of 8% share of reduction levers based on Systemiq’s EU circularity scenario and $65B/year UNEP projected global investment needed (Systemiq, link; UNEP, link).
Substitute	Lower and upper abatement bounds assume 12% and 46% bioplastics adoption, respectively (Project Drawdown, link).	Projected investment reflects constant average production cost over 2020-2050, based on historical and projected price data (Project Drawdown, link).
Recycle	Abatement bounds, adapted from *Breaking the Plastic Wave*, are based on modeled improvements in collection, mechanical, and chemical recycling pathways (Systemiq, link).	Current cumulative investment assumes ~$120B across collection ($54B), mechanical ($32B), and chemical recycling ($35B) (Systemiq, link). Projected investment from 2024-2050 is calculated as a linear extrapolation of the 2021-2040 estimate, based on an average of $6.3B/year (Systemiq, link).
Electrify	Lower bound abatement assumes a 25% share of total plastics emissions (1,000-1,200 $MtCO_2$/year) from monomer production, considering 100% abatement efficiency (McKinsey, link). Upper bound abatement assumes linear ramp-up in abatement impact till 600 $MtCO_2$/year from 2030 to 2050.	Current cumulative investment assumes average CapEx of ~$2B/1 Mt per year electric steam cracker, based on the reported cost range of $1.3B to $3B applied to Dow and BASF projects (ScienceDirect, link). Projected investment until 2050 assumes the same level of average CapEx but reflects required CapEx to expand from 250 to 600 $MtCO_2$/year of abatement capacity.
CCUS	Lower bound abatement reflects announced WtE capacity adjusted by an estimated 2% share of plastic waste in total waste incinerated, using EU packaging waste share (~40%) and total waste generation as proxies (Europarl, link; OECD, link). An additional ~10,000 kt from announced CCUS and ~1,000 kt in monomer production is included (Dow, link; Mckinsey, link). Upper bound reflects IEA’s NZE scenario, assuming 8% of global CO_2 captured (~6,040 Mt/year by 2050), scaled down to ~4% for plastics sector (IEA, link). Starting in 2029, the Longship project is expected to contribute ~175 kt/year with an additional 350 kt per year thereafter (Gassnova, link).	Investment estimates apply same 4% plastics share to McKinsey’s cumulative CCUS capital projection (McKinsey, link).

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