



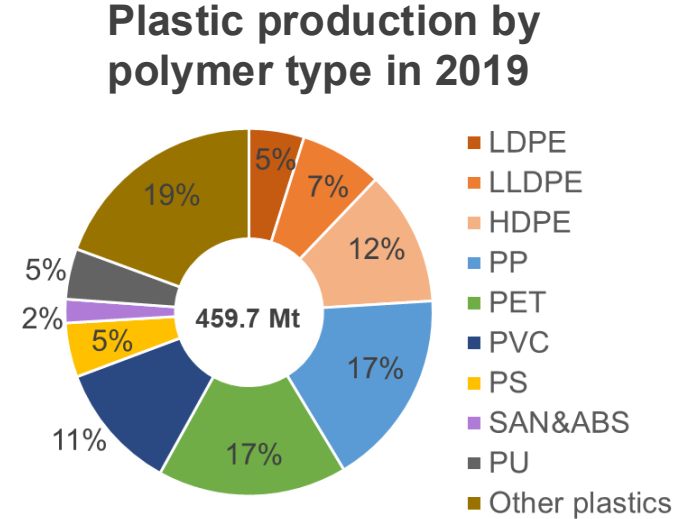
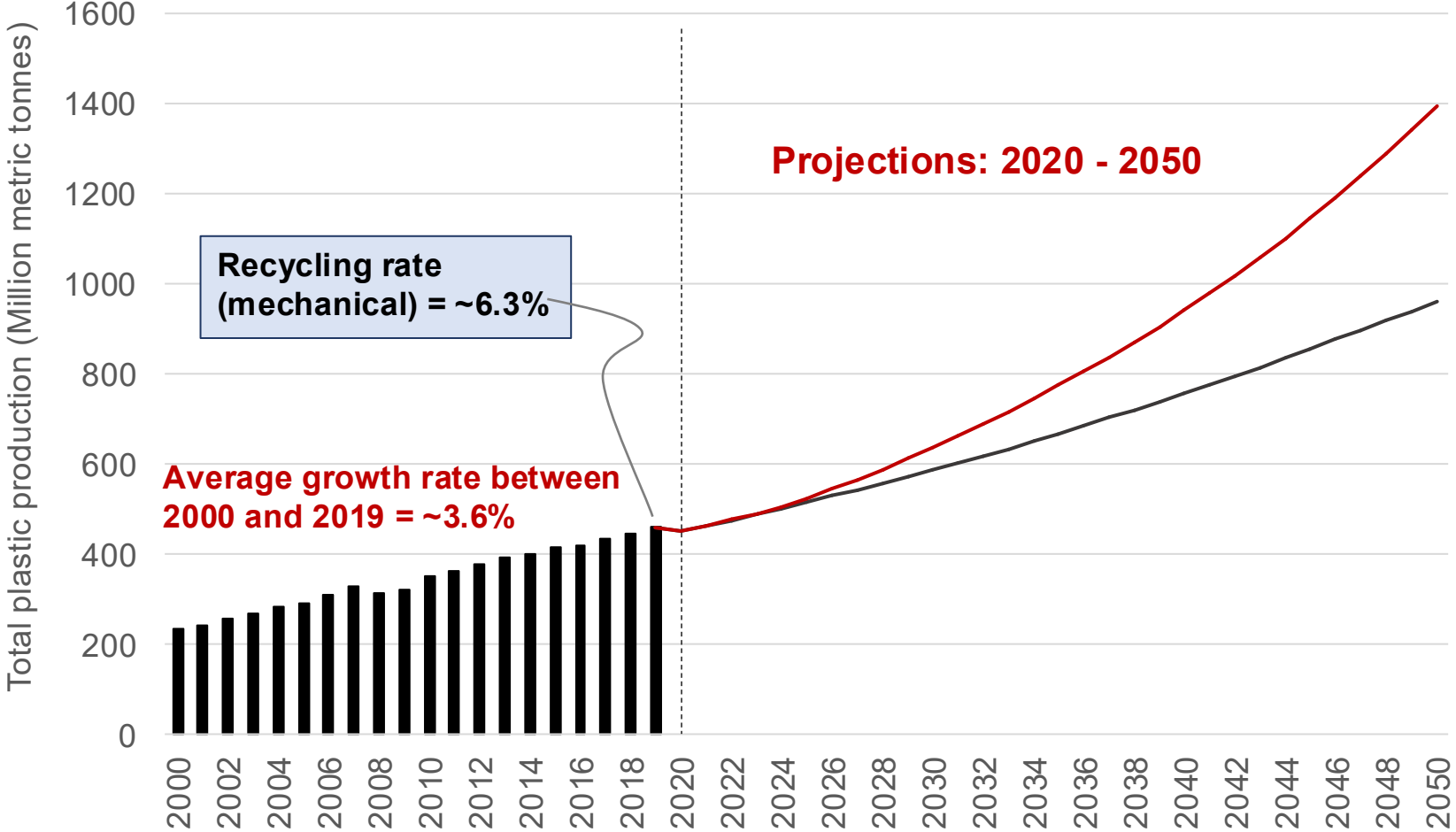
The Technical Limits of Chemical Recycling

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Plastic Production Growth



Source: Historical data is based on OECD (2022). 2.5% and 4% annual growth projections are based on OECD (2022) and NASEM (2022), respectively, and represent the total global plastic demand growth.

Circular Economy Policies: Global Ambitions

Governments worldwide have enacted ambitious **recycled content mandates and EPR schemes**— yet targets often outpace what recycling technologies can physically deliver.

- **EU:** 25-30% recycled content in plastic packaging by 2025-2030 (PPWR 2025/40)
- **California SB 54:** 65% recycling of single-use plastic packaging by 2032 (SB 54 2022)
- **Japan's 3R + Renewable initiative:** 60% reuse/recycling target by 2030
- **China:** National targets for recycling rates and resource efficiency



CHEMICAL RECYCLING PROMOTED AS SOLUTION TO MECHANICAL RECYCLING'S LIMITATIONS.

⚠ High contamination sensitivity

Requires clean, sorted, single-polymer streams

⚠ Material quality loss

Processing degrades molecular weight significantly — limited to ~1 cycle before quality fails

⚠ Downcycling, not circularity

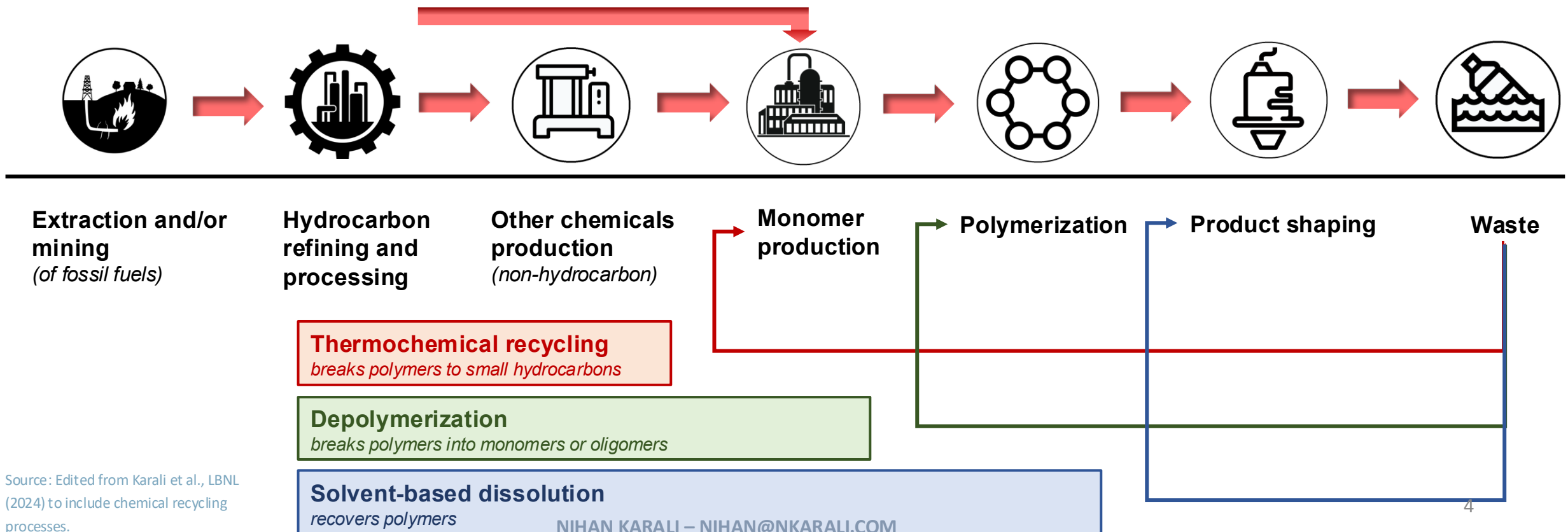
Recovered materials cannot substitute for virgin plastic in high-value applications

What is Chemical Recycling – And Why Does It Matter?

DEFINITION

Chemical recycling uses chemical processes to break down plastics into constituent parts—hydrocarbons, monomers, or oligomers— or to separate additives from polymers. Products can be used to manufacture new plastics (**closed-loop**), or serve as alternative chemicals or fuels (**open-loop**).

Plastic production chain and closed-loop chemical recycling



Source: Edited from Karali et al., LBNL (2024) to include chemical recycling processes.

Each Technology Targets Only Specific Polymer Types

Most chemical recycling processes are designed for specific polymers due to differences in polymer chemistry and process requirements.

Technology Type	Recovered product	Applicable Common Polymers	Challenging
Solvent-based Dissolution	Polymer	LDPE, LLDPE, HDPE, PP, PET, PS, ABS, PVC	PU
Depolymerization	Monomer	PET	LDPE, LLDPE, HDPE, PP, PS, ABS, PVC, PU ^φ
Enzymatic Hydrolysis	PTA, EG		
Methanolysis	DMT, EG		
Glycolysis	BHET		
Thermochemical Recycling			
Pyrolysis	Pyrolysis oil, gases, monomers, aromatics, char	LDPE, LLDPE, HDPE, PP, PS	PET, PVC, ABS, PU
Gasification	Syngas (Synthesis gas)	LDPE, LLDPE, HDPE, PP, PET, PS	PVC, ABS, PU

^φ PU: Although glycolysis of PU is possible and discussed in the literature, commercial applications do not yet exist.

Contamination Limits Process Efficiency, Safety, and Substitution Rates

CONTAMINATION

- (1) reduces **process efficiency** and creates **direct safety hazards**,
- (2) determines the **maximum share of recycled material** that can be incorporated into new products while meeting quality or safety specifications—the substitution rate.

Sources of Contamination

- Food residues & detergents
- Labels, adhesives & dyes
- Mixed polymer types
- 16,000+ chemical additives in plastic products (*Monclús et al. 2025*)
- Heteroatoms (Cl, N, S, O) in thermochemical feedstocks (pyrolysis and gasification)

Process Efficiency & Safety Impacts

- Efficiency: heteroatoms suppress catalyst activity & lower hydrocarbon yields in pyrolysis
- Safety: residual oxygen in pyrolysis feedstock creates fire and explosion risk
- Safety: chlorine contamination releases HCl gas, corroding reactors and downstream equipment

Substitution Rate Constraints

- Pyrolysis oil: only 5-20% replaces virgin naphtha in steam crackers
- Solvent dissolution & depolymerization: up to 30% recycled blend
- Food-contact applications: residual contaminants force deep dilution

Material Degradation Across Recycling Cycles

MECHANISM

Each recycling pass causes chain scission, thermal oxidation, molecular weight reduction, and discoloration—even without contamination. These cumulative changes progressively degrade polymer performance.

Mechanical Recycling

1–2

cycles max

Chain scission & oxidation degrade molecular weight rapidly

Solvent-Based Dissolution

3–4

cycles max

Polymer chains intact, but heat and solvent stress cause gradual degradation

Enzymatic Hydrolysis

3–4

cycles max

Biological catalysts still cause cumulative structural weakening with each pass

Glycolysis

3–4

cycles max

EG-based cleavage preserves monomer structure, but heat stress and BHET contaminants accumulate with each pass

Source: Uekert et al., ACS SCE (2023)

⚠ Pyrolysis & gasification bypass degradation by breaking polymers to basic hydrocarbons—but introduce severe contamination constraints instead (see Slide 6).

Process Inefficiencies Compound Across the Value Chain

Material losses accumulate at every stage: pretreatment, the recycling process itself, and final product formation— each step eroding the fraction of waste that reaches new plastic products.



MRF PRE-PROCESSING

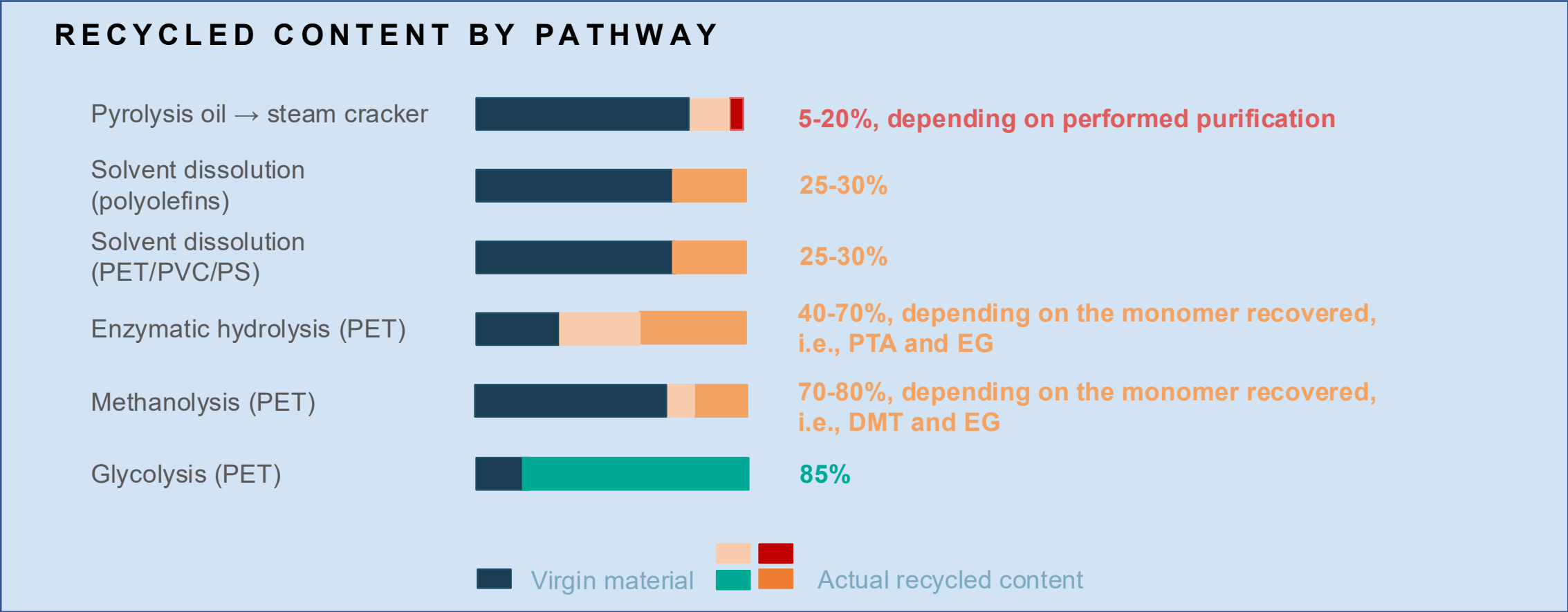
Single-stream collection + rigorous MRF sorting is a prerequisite for all pathways. Even with dedicated sorting, washing, drying, and cleaning, **pre-processing losses may range from 5–30%** of incoming mass—before any conversion begins.

BLENDING / PURIFICATION

Purification is highly process-specific—each method targets contaminants for a specific polymer. With **16,000+ chemical additives** present in plastics—most additives are untracked and no universal purification process exists.

The Mass Balance Gap: What's Actually Recycled

To meet product performance and safety specifications, recovered materials must be diluted or blended with virgin plastic—creating a gap between waste for recycling and actual recycled content.



Sources: Uekert et al., ACS SCE (2023); Gracida-Alvarez et al., J. Clean. Prod. (2023); Karali et al. (under review)

Chemical Recycling Pathways Are Inherently Energy-Intensive

Energy burdens differ by technology but share a common feature: they are **intrinsic to the underlying chemistry**—driven by chemical production, thermal conversion, or multi-step processes.

Solvent-Based Dissolution

⚡ Dominant: solvent & antisolvent production

- Production of most solvent pairs are very energy intensive. PET, PVC, and PS require especially energy-intensive solvent pairs.
- Alternative low-energy solvent pairs (e.g., bio-based solvents, supercritical fluids) remain at experimental stage with no commercially proven low-energy option at scale.

Pyrolysis

⚡ Dominant: thermal process + substitution paradox

- Operates at 400–800°C in the absence of oxygen, requiring large, sustained heat inputs.
- The pyrolysis process including purification accounts for significant amount of energy.
- A purification paradox: achieving higher substitution rates demands more intensive purification, which itself increases energy consumption. Increasing the substitution rate without breakthroughs increases rather than decreases total energy burden.

Gasification (F-T & MTO)

⚡ Highest energy burden of all closed-loop recycling pathways

- Gasification at 700–1500°C produces syngas.
- Fischer-Tropsch (F-T) synthesis accounts with—F-T catalytic conversion alone is highly energy-intensive.
- The Methanol-to-Olefin (MTO) route carries an even heavier burden: primary methanol production is extremely energy intensive.

Chemical Recycling Pathways Are Inherently Energy-Intensive (cont.)

Energy burdens differ by technology but share a common feature: they are **intrinsic to the underlying chemistry**—driven by chemical production, thermal conversion, or multi-step processes.

Enzymatic Hydrolysis

PET only

⚡ Dominant: hydrolysis process & chemicals

- The enzymatic hydrolysis reaction plus all associated chemical production is the largest energy component. Enzyme production and temperature maintenance add to this load.
- Pretreatment is a significant secondary load. Contamination in feedstock directly amplifies pretreatment energy demand.

Methanolysis

PET only

⚡ Dominant: primary methanol production (coal/gas-based)

- Uses superheated methanol vapor under high temperature and pressure—the most energy-intensive PET depolymerization route.
- Primary methanol production is the critical energy driver.

Glycolysis

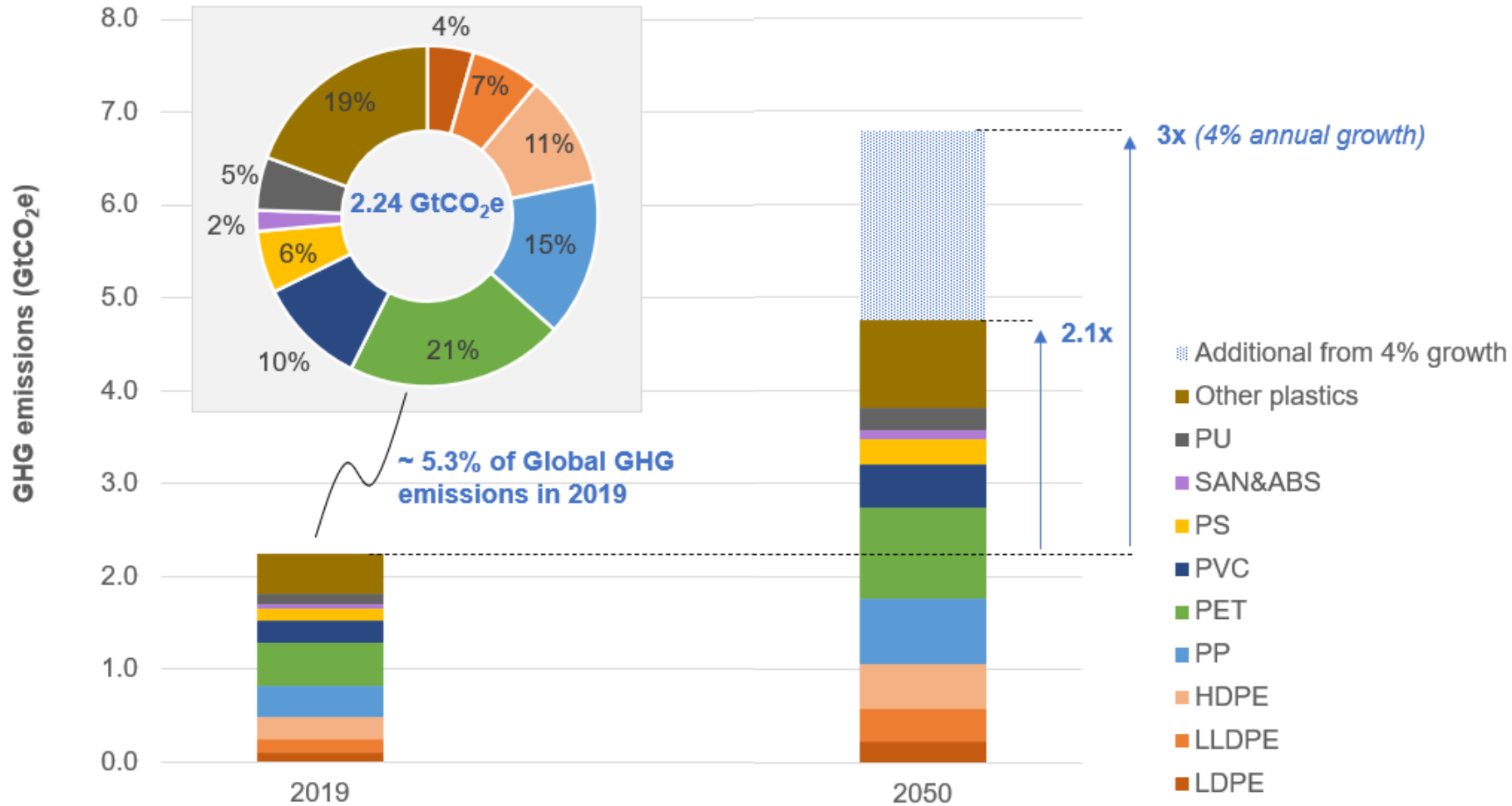
PET only

⚡ Lowest burden among depolymerization routes

- Uses ethylene glycol (EG) at moderate temperature and pressure to produce BHET—the least energy-intensive PET depolymerization pathway.
- BHET often has lower molecular weight and contaminants from thermal degradation. Additional purification to meet product quality requirements carries energy costs that partially offset the process advantage.

Global GHG Emissions from Primary Plastics Production

Already Set to Grow



Source: Karali et al., LBNL (2024)

Conclusions

- Chemical recycling in its current form could not be a viable technological path.
- Current technologies **struggle with** substantial energy and chemical demands, high contamination sensitivity, material degradation, and process losses that prevent them from delivering true technological, environmental, economic, or societal benefits.
- Four compounding technical barriers drive this result:
 - (1) **contamination sensitivity** limits substitution rates;
 - (2) **material degradation** caps most pathways at 3–4 recycling cycles before quality fails;
 - (3) **substantial energy and chemical demands** are intrinsic to the chemistry; and
 - (4) **cascading process losses** at MRF, recycling, and purification stages further erode yields.
- Incremental optimization could not overcome inherent limitations.

Thank you!