Cleantech Group®

Spotlight

Waste & Recycling

Solvent Dissolution

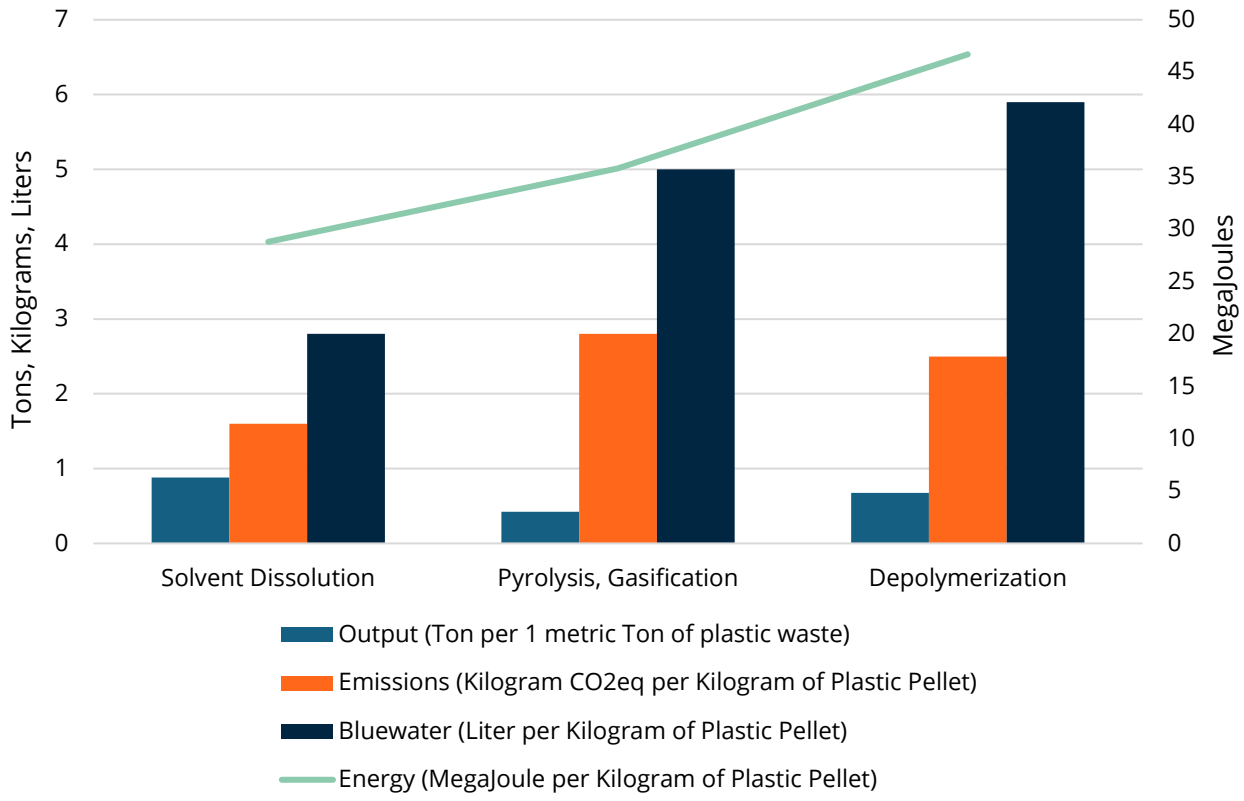
September 2024

Executive Summary: Solvent Dissolution Plastic Recycling

Solvent Dissolution broadens recyclable plastic, bolsters recycling efficiency

- Plastic waste is set to triple by 2060 (OECD), global recycling rate is 8%
- Incumbent recycling technologies have several limiting issues:
  - Mechanical recycling cannot recycle contaminated plastic or any multi-layer/composite, produces low quality recyclates
  - Pyrolysis & gasification are high volume but low yield, high emissions
  - Depolymerization accepts limited feedstocks and has high water use
- **Solvent dissolution efficiently recycles all plastic types**, valorizing low-value waste streams and reducing virgin plastic need
  - Compared to virgin plastic production: 59% decrease in energy use, 20% decrease in CO_2eq emissions, 43% decrease in water use (Figure 1)
  - Direct application in packaging recycling (31.2% of all plastic production)
- Solvents separate contaminants from polymers before an anti-solvent precipitates the polymer out of the solution, leaving pure polymers
- With several European and the U.S. commercial demonstration facilities standing up, the Technology Readiness Level stands at 5-7
- Large chemical and plastic manufacturers are financing commercial development, creating circular plastic manufacturing (**LYB, Braskem**)
  - **P&G**, **Dow** pursuing first-to-market innovation based on university research
  - First-to-market technologies consolidate large portions of waste streams though multi-year agreements, insulating feedstock from competition
  - Virgin-price parity without subsidies and high solvent recovery remain two core barometers of success

Figure 1: Advanced Plastic Recycling Performance & Environmental Impact



Source: Data collected from Closed Loop Partners' *Transitioning to a Circular System for Plastics* report. Accessed August 15, 2024.

Source: Cleantech Group

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Solvent Dissolution: Setting the Stage

Solvent innovation can provide first-to-market LDPE, PVC, PP, PS recycling

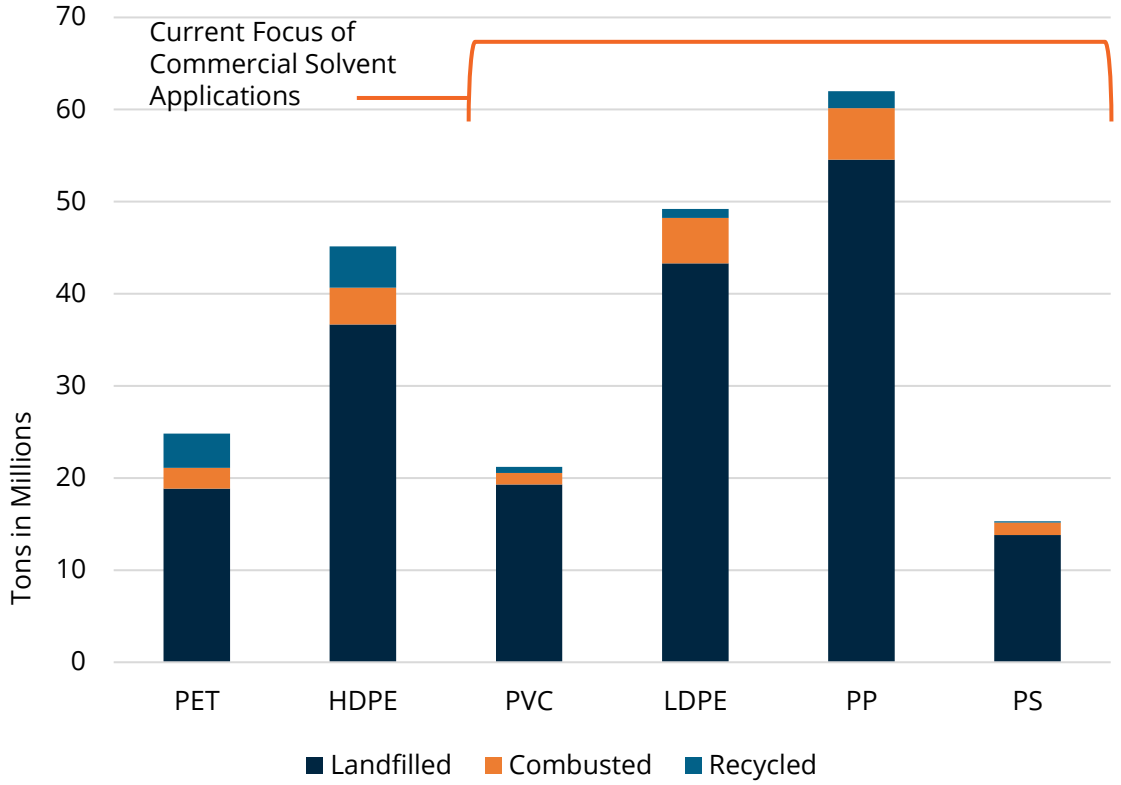
Waste Managers Ignore Difficult to Recycle Plastic

- The current global recycling rate is 8% and 6% in the U.S.
  - Approximately 3% of PP, 2% of LDPE, and 1% of PS was recycled last year (Figure 2)
  - Current plastic sorting infrastructure does not sort plastic 3-7, only PET and HDPE
- Mechanical recycling well suited for most plastic but severely degrades PP and PS, unable to process LDPE and other thin films
- Issues leading to low recycling rates (Figure 2):
  - PE, PP, PS, PVC are viewed as single use due to limited sorting infrastructure, low cost, degradation of material in recycling, and no specific recycling mandates
  - Poor sorting, labeling, education outside of the EU, Japan limits recycling efficiency

Impact

- Environmental metrics
  - Dissolution process for PP & PE uses 59% less energy, generates 20% fewer CO_2eq emissions, and 43% smaller bluewater footprint compared to virgin production (Closed Loop Partners)
  - PP recycled through supercritical butane dissolution has a 30% lower CO_2eq footprint, 60-85% lower energy use than virgin PP (UC Berkeley)
  - Annual plastic GHG emissions set to double by 2060 without recycling (NREL)
- Depolymerization, mechanical recycling also benefit from solvents
  - Glycolysis depolymerization lowers energy use, produces higher purity products
  - Mechanical recyclers dissolve adhesives, contaminants, or dyes to improve purity
- Reduced landfilling and incineration by recycling PP, PVC, LDPE, and PS
  - Commercial solvent dissolution could recycle 12.4M and 9.8M tons of recycled PP and HDPE by 2029, improving recycling rate by 16% and 17%, respectively
  - Reduced need for new fossil-based plastic or oil exploration

Figure 2: Disposal of Plastic Types



Source: Organisation for Economic Co-operation and Development (OCED).

Acronym list: PET - Polyethylene Terephthalate, HDPE - High Density Polyethylene, PVC - Polyvinyl Chloride, LDPE - Low Density Polyethylene, PP – Polypropylene, and PS - Polystyrene. Type 7 excluded due to difficulty in tracing and high variation in category of plastic.

Source: Cleantech Group

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Solvent Dissolution: Can New Solvents Find Market Fit, Reduce OPEX?

New solvents are redefining what is recyclable, but to scale, they must first optimize process inputs, energy use and applications

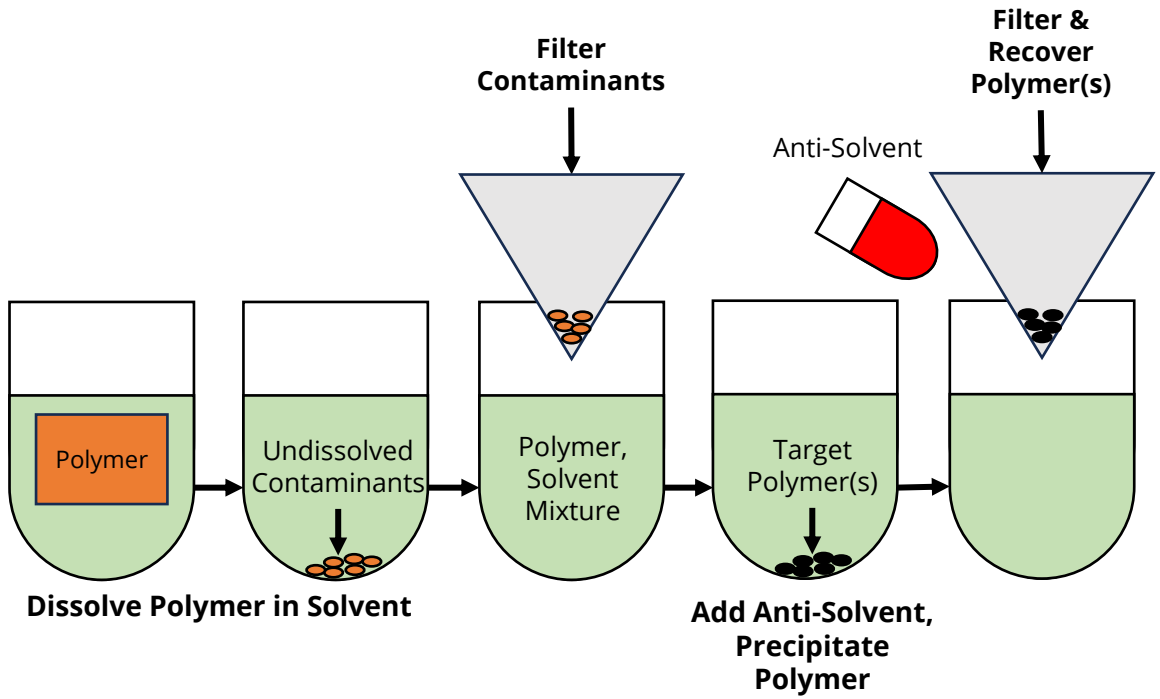
High CAPEX for Novel Technologies, Expensive Solvent Input

- Economic Issues:
  - Innovation must reduce volume of solvents/anti-solvents used/lost
  - Some novel solvents require extreme temperature/pressure controls, expensive specialized chambers
  - Material Recovery Facilities (MRFs) beginning to sort PP; PVC, LDPE, PS not sorted, still viewed as low-value contaminants
  - **Breakeven economics usually require ~70+% solvent recovery**
- Technical Limitations:
  - Incorrect solvent-polymer pairing damages polymer chains
  - **Fully renewable electricity would cut process emissions by 40%**

Delamination, Selective Dissolution

- Delamination: dissolves adhesives between polymers, metal (multilayer plastic, solar panels, battery casings, car panels, aluminum packages)
  - Switchable Hydrophilicity Solvents: Separates layers without antisolvents
  - Deep Eutectic Solvents (DES): Can separate PVC, PE from metals and adhesives, be used in depolymerization, reduce process toxicity
- Selective Dissolution: separates plastic, textiles from contaminants
  - Supercritical Butane, CO_2, Propane: **Purecycle**, **Cescco2** use solvents to separate contaminants from PP, PVC, and PE polymers
  - Organic Solvents: Several solvents dissolving PS, cellulose, PET, PP
  - Solvent-Targeted Recovery And Precipitation (**STRAP**): Dissolves individual layers in multilayer plastic to recover nearly all total material (PE, PET)
- **New solvents may eliminate use of antisolvents, cleaning costs**
- **Solvent selection software can identify solvent pairings to dissolve all polymers** from multilayer plastic without damaging any layer

Figure 3: Standard Dissolution Process



Source: Cleantech Group

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Solvent Dissolution: Value Chain

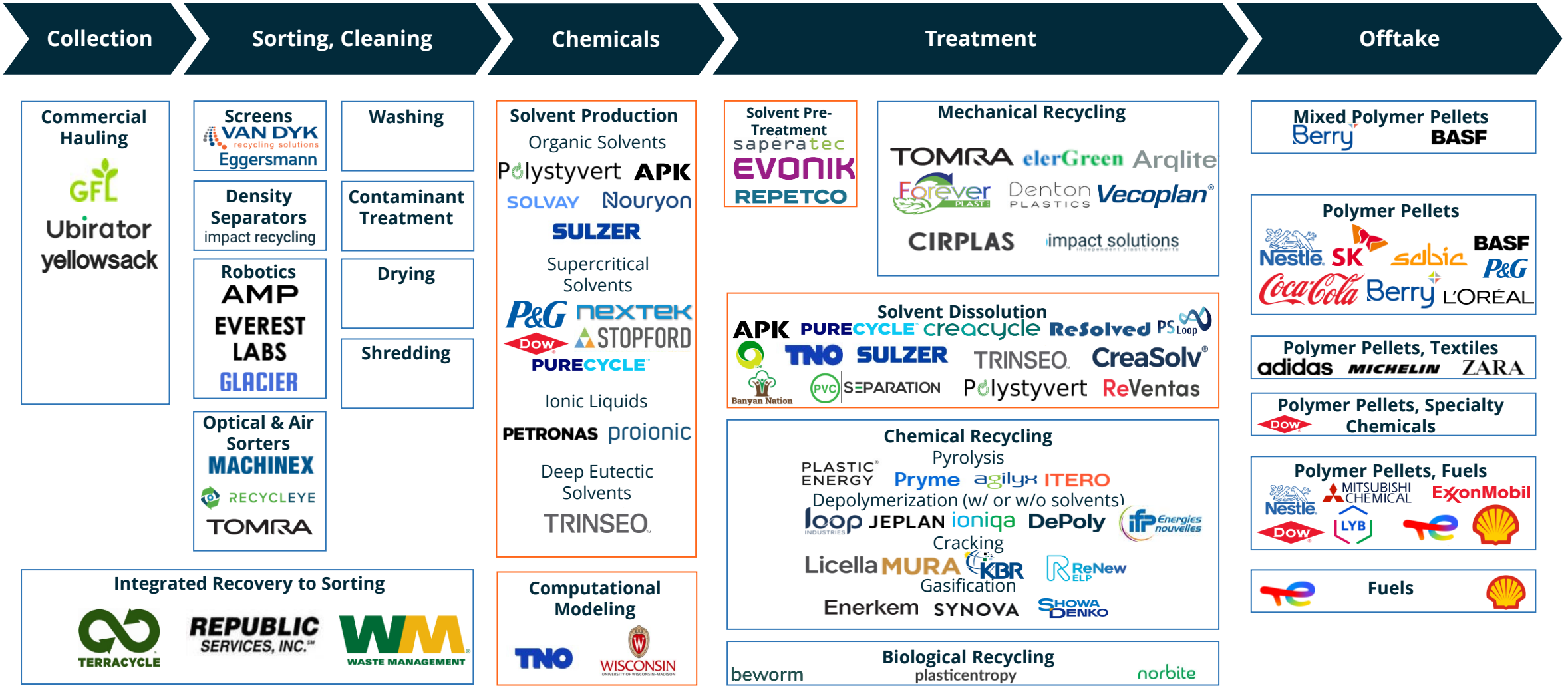

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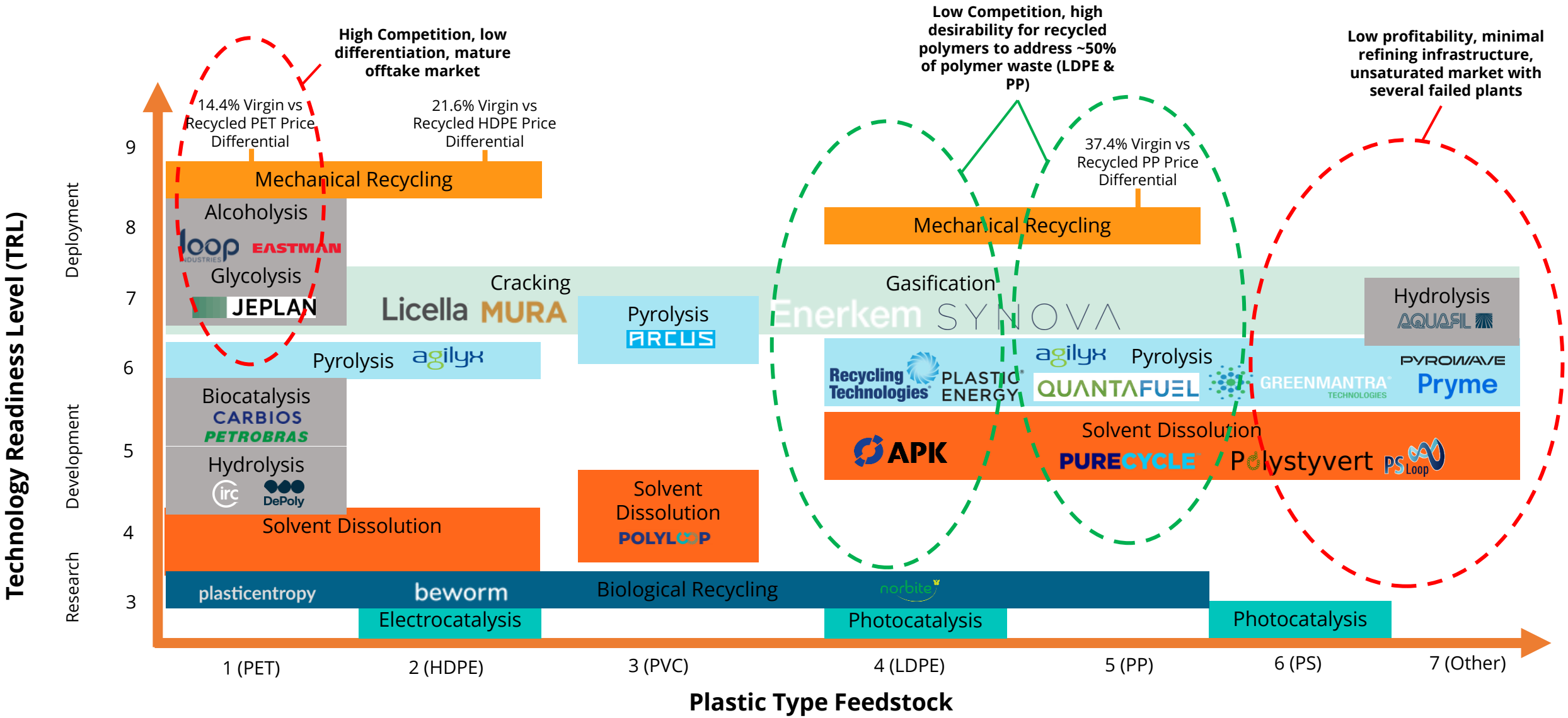
Figure 4: Recycling Process Maturity

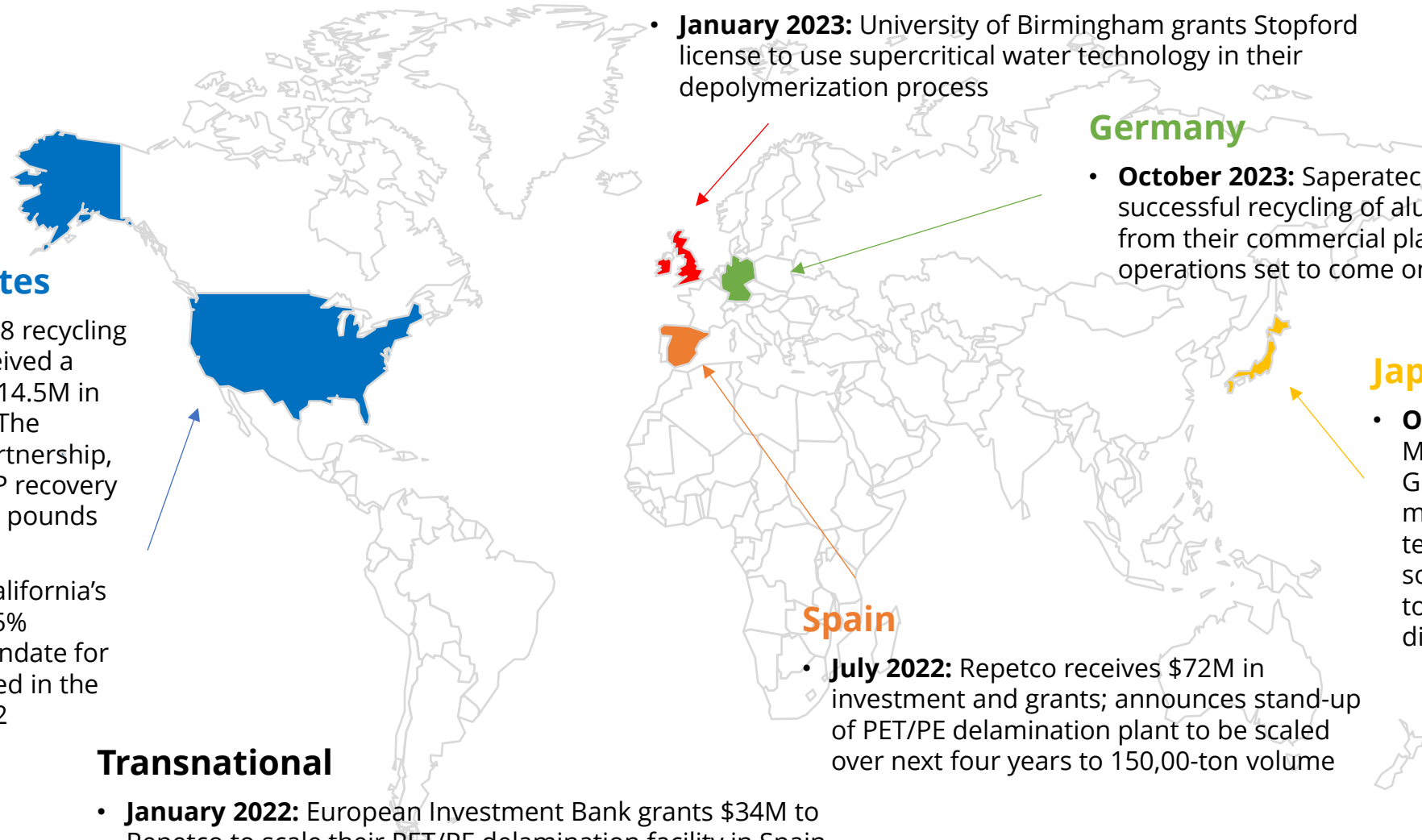
Solvent Dissolution has ample market opportunity across plastics, specifically in LDPE and PP



Source: S&P, Cleantech Group

Solvent Dissolution: Regional Drivers, Sources of Innovation, Pilots

Innovation in software, sortation, and commercial pilots is validating solvent dissolution recycling



United States

- **June 2024:** 58 recycling facilities received a combined $14.5M in grants from The Recycling Partnership, increasing PP recovery by 57 million pounds annually
- **July 2022:** California's SB 54 sets 65% recycling mandate for all plastic used in the state by 2032

United Kingdom

- **January 2023:** University of Birmingham grants Stopford license to use supercritical water technology in their depolymerization process

Germany

- **October 2023:** Saperatec announces successful recycling of aluminum and LDPE from their commercial plant; full commercial operations set to come online by end of 2024

Japan

- **October 2023:** Mitsubishi Chemical Group announces machine learning technology matching solvents with polymers to create new solvent dissolution pathways

Spain

- **July 2022:** Repetco receives $72M in investment and grants; announces stand-up of PET/PE delamination plant to be scaled over next four years to 150,00-ton volume

Transnational

- **January 2022:** European Investment Bank grants $34M to Repetco to scale their PET/PE delamination facility in Spain

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Solvent Dissolution: The ABCs

New technology has created high demand, recyclers carving out early niches defined by volume or flexibility

Discussion

Attractiveness

- The polypropylene (PP) market is expected to grow from $124.4B in 2024 to $200.4B by 2030, with a CAGR of 10.00%
- Specific interest in recycled PP to meet government or company-enforced sustainable packaging goals (**L'Oréal**, **Berry**, **SK**) in European/Asian fast moving consumer goods (FMCGs); slower growth in LDPE, PVC, and PS markets
- Recycled PP supply supplies less than 2% of total annual PP production, room for many producers to enter market
- Solvent dissolution offers an opportunity to recycle ignored feedstocks without downstream refining or repolymerization
- Nascent market allows for fast-moving innovators to establish regional dominance (**Purecycle**, **Polystyveryt**)

Business Models

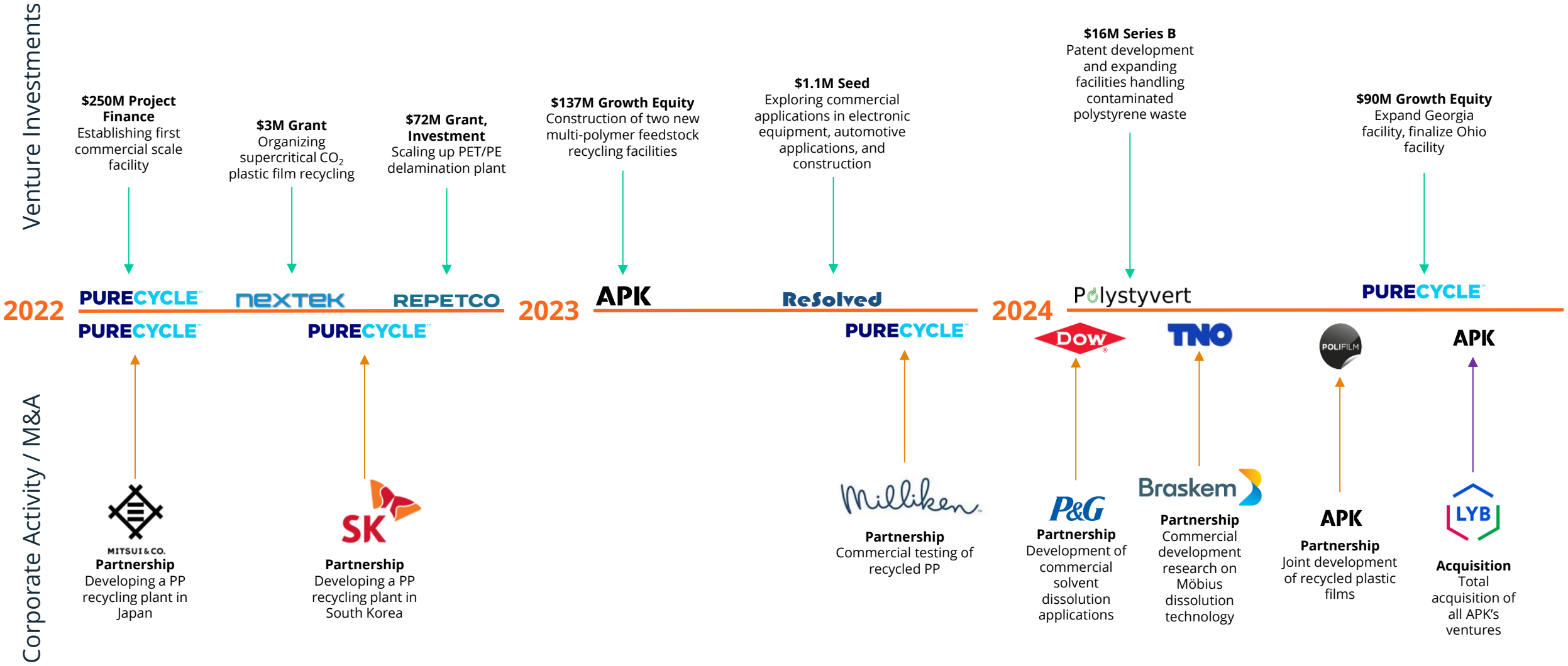
- Delamination companies like **Saperatec** run MRFs specializing in flexibility over several waste streams (lithium-ion batteries, solar panels, multilayer plastic packaging)
- Selective dissolution targets homogenous waste streams, strict use of one solvent to target one polymer from a homogenous feedstock (**Purecycle**)
- Solvent use in plastic recycling is highly sensitive to process malfunctions, disincentivizing any process alterations
- Leasing patented technologies to aggregators with large facilities (**P&G** leasing supercritical butane PP recycling to **Purecycle**)
- **Computational modeling** is a future intermediary to connect feedstock aggregators with MRFs

Competitive Trends

- Demand for recycled LDPE, PP high as it is largely unprecedented on the market and already near virgin plastic cost
- Commercial-scale emerging from demonstration plants, mostly concentrated in Europe as feedstocks are higher quality
- Corporates are increasingly convinced of economic viability for PP, lab work ongoing to validate PE economics (**Dow**, **P&G**)
- **LyondellBasell's** acquisition of **APK** is the first high-profile acquisition in the space, signaling incumbent acceptance and desire to scale emerging, stand-alone solvent projects
- Successful commercial plants target low competition feedstocks (LDPE, PP), partner with sortation companies, scale slowly to react to new technology applications/research, have high solvent recovery rates, low solvent cleaning/replacement needs
- Delamination of adhesives already being incorporated by commercial recyclers, makes multi-layer packaging recyclable

Solvent Dissolution: Investment/Corporate Activity

Small Seed through Series B rounds culminate in massive project financing for validated, innovative technologies



Solvent Dissolution: Innovator Examples

Commercial ventures targeting multi-layer films are first of their kind

APK

Positioning: LDPE, PP, and PA recycler using a range of organic solvents on multilayer packaging

Market insight

- Multilayer packaging recycling has yet to be fully commercialized as it requires stacking several dissolution technologies seamlessly
- Flexible, low-cost solvents can be applied to mixed waste streams

Company insight

- Only solvent dissolution start-up capable of recycling mixed waste at a commercial scale (multilayer packaging)
- Integrated air-jet sortation as a pretreatment step to separate feedstock by weight/blend
- Company's LDPE recyclates reduces GHG emissions by 50% compared to virgin plastic

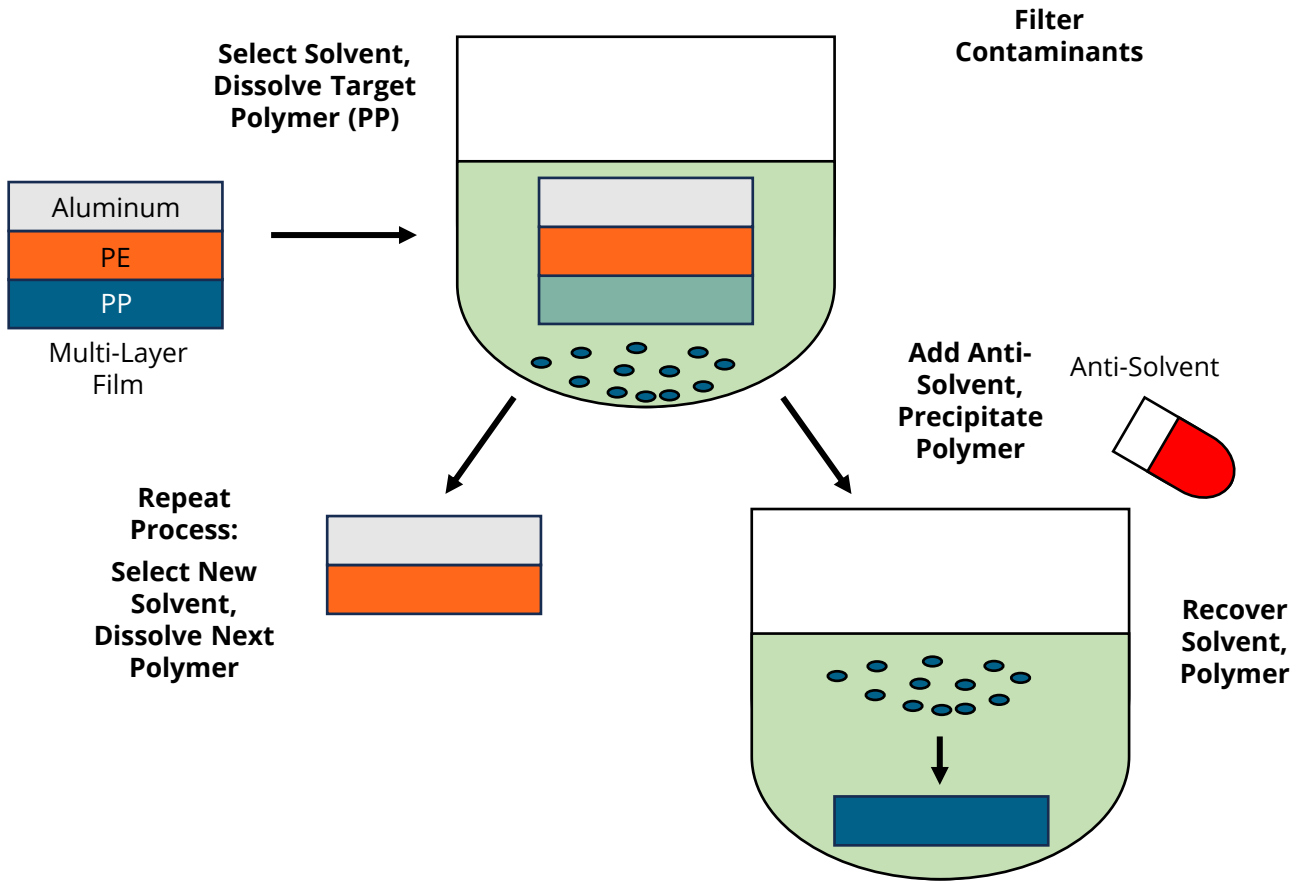
Milestones:

- Acquired by LyondellBasell (LYB) in August 2024
- Company opened its first full commercial facility operating at 13,000 pounds output per year in 2024
- Exploring Israeli market alongside Modiplast

Capital: $140M

Contact: Robert Marx, CTO

Figure 5: Multi-Layer Dissolution Approach



Source: Cleantech Group

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Solvent Dissolution: Innovator Examples

First-to-market innovators generated high demand, now scaling for global offtake

Polystyvert

Positioning: ABS and PS recycler utilizing cymene oil as a solvent

Market insight

- Recycling economics remain unfavorable in non-European markets
- Half of polystyrene market is in food grade plastic, requiring intense and frequent purity testing
- PS prone to degradation and contamination, ABS not recycled

Company insight

- Good offtake demand for first-to-market materials
- Core technology is protected by over 40 patents across 17 countries
- Remain open to licensing as a business model moving forward in order to maximize capital
- Recycled resins reduce GHG emissions by over 90% compared to virgin plastic thanks to low process temperature, low solvent toxicity

Milestones:

- Offtake partnership with longtime investor and polystyrene manufacturer, BEWi; additional partnerships with INEOS
- Constructing 9,000-ton polystyrene recycling plant; pilot ABS recycling plant in Montreal
- Recycling technology patented in over 20 countries

Capital: $36M

Contact: Roland Côté, CTO

PURECYCLE™

Positioning: Recycler using supercritical butane on polypropylene (PP)

Market insight

- Contaminants, plastic degradation limit will keep mechanical recycling from supplying full purity recycled PP
- Legislation mandating recycled content and Extended Producer Responsibility (EPR) will expedite growth
- PET is the major success story in plastic recycling, now lower competition and higher price paid for recycled types 2-7

Company insight

- Capitalized on cheap PP feedstock, low competition, increasing demand for recycled PP by being first to market; now looking to consolidate
- Difficulty in OPEX sizing due to high interest rates, feedstock sorting/purity expenses
- International expansion in Belgium, exploring Asia

Milestones:

- Facility development for SK in South Korea, Mitsui in Japan, TotalEnergies in Europe
- Flagship facility in Ironton, Ohio has an annual output of 49,00 tons
- Developed patents for recycling processes with Proctor & Gamble

Capital: $149M

Contact: Dustin Olson, CEO

Solvent Dissolution: Innovator Examples

Innovators approaching varied feedstocks to carve out larger market shares

worn again technologies

Positioning: Textile recycler primarily extracting PET and cotton using organic solvents DMSO, DMI, and Propyl benzoate

Market insight

- High contamination rates limit effectiveness of depolymerization on textile recycling, circularity requires contaminant-resistant processes
- Textile waste will always consist of blended fabrics, process must be able to handle this

Company insight

- Investment not a necessity now; required once commercial-scale validated, offtake partners secured
- Aiming to launch demonstration commercial plant in 2027 to recycle 1,000 tons per year, plant would be about 50-100x smaller than average commercial textile plant

Milestones:

- Working with Sulzer and IWK to incorporate recycled PET into foam solutions
- Opened first demonstration plant this year validating operational output up to a ton per year
- Offtake agreements with H&M, Kering

Capital: $48M

Contact: Mike Schwarz, Director of Operations

saperatec back to value

Positioning: Recycler utilizing water-based solvent to delaminate multi-layer waste including plastic, aluminum, glass, semiconductors, and batteries

Market insight

- Market currently has no means to recycle multilayer waste commercially
- Water-based solvent dissolution not commercially viable today, too expensive and too slow

Company insight

- Technological applications are open-ended, searching for best market fit; may end up licensing
- Produce several high value products (pure resins, aluminum, glass) from low-temperature delamination
- High degree of technology transfer from battery recycling/disassembly to multi-layer plastic, potential for partnership

Milestones:

- Commercial plant handles 18,000 tons of multi-layered packaging and other materials
- Products have passed EU food-safe chemical tests

Capital: $5.6M

Contact: Thorsten Hornung, CEO

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Solvent Dissolution: Incumbents

Joint research, licensing, and commercial partnership guiding solvent discovery

	Positioning	Engaging Innovation
P&G	▪ Cosmetics and hygiene products company with goals of waste reduction ▪ Set 50% virgin plastic use reduction, 100% recyclability targets for 2030 ▪ Encountered difficulty in securing adequate feedstocks for recycling facilities	▪ Established joint agreement with Dow Chemicals to develop and commercialize new solvent dissolution technology targeting polyethylene ▪ Leased solvent dissolution technology to **Purecycle** Technologies to develop several American recycling facilities for packaging recycling ▪ Developed HolyGrail 2.0, a digital sortation code embedded on all products to expedite sorting processes in Europe
Braskem	▪ Material manufacturer focusing on thermoplastic resins, rubber, and chemicals ▪ Pursuing new applications of solvents in recycling	▪ Solvent Application Laboratory researches novel solvents and improving existing formulations for new applications in commercial products and recycling ▪ Joint development with **TNO** on Möbius dissolution-based recycling technology for polyolefin plastic residue waste streams ▪ Researching biobased oxygenated solvents with lower GHG footprint than hydrocarbon solvents
SULZER	▪ Global chemical manufacturing and processing company ▪ Supporting bioplastics, pyrolysis, depolymerization, and solvent dissolution innovators looking to enhance processes with Sulzer chemicals	▪ Investment into **Worn Again Technologies**, a solvent dissolution textile recycler, including support for their commercial and demonstration plant rollout ▪ Launched DEVO, a solvent recovery technology for all plastic types to improve unit economics for solvent dissolution recyclers

Solvent Dissolution: Other Ecosystem Members

Academic institutions, investment funds, and non-profits advancing solvent dissolution technologies

	Role	Points of View
CUWP Chemical Upcycling of Waste Plastics	▪ Chemical Upcycling of Waste Plastics is the preeminent collaborative research organization working on plastic recycling ▪ Members include: 6 Universities, 1 National Laboratory, 23 Companies	▪ Partner university research created both **STRAP** and **COSMO-RS**, now aiming to commercialize both technologies on PE and PET polymers from LDPE for use in recycled food-grade packaging ▪ Planning first commercial STRAP facility at Convergen Energy in Green Bay, WI ▪ Simultaneous development of pyrolysis and depolymerization technologies for lower-value plastic
INFINITY RECYCLING	▪ Impact investment fund focused on increasing plastic recycling and plastic circularity generally ▪ Investing primarily in advanced recyclers focusing on chemical recycling: Itero, Ioniqa, Clariter, Pryme, Depoly	▪ Invested in **Polystyvert**'s $16M Series B focused on opening start-up's first commercial plant in Montréal processing Polystyrene using essential oils ▪ Firm has close relationship with ongoing plastic recycling research at Eindhoven University of Technology, Unilever, and Indorama Ventures ▪ Investment in **Ioniqa** focused on their use of glycol-based solvents
The Recycling Partnership	▪ Non-profit organization partnering with local waste organizations and recyclers to improve general plastic recycling, sortation, and management ▪ Mixed approach of grants and partnerships	▪ Raised and distributed $14.5M in grants to 58 different recycling facilities to bolster sortation infrastructure of polypropylene ▪ Sort 57 million new pounds of polypropylene annually at partner facilities ▪ Partnered with McDonald's, Braskem, P&G, Berry, PureCycle, Closed Loop Partners, Walmart, and TotalEnergies to identify supply chain shortcomings

Solvent Dissolution: Keep an Eye Out For…

Academic-industry collaboration brought this technology to market; policy support lags far behind

Market Milestones

- Large commercial facilities will follow the Purecycle model targeting a single polymer; economics only work with high offtake demand and solvent recovery (70+%)
- Solvent recovery, low-cost cleaning will remain the critical metric for scale-up regardless of facility size
- Renewable energy reduces process emissions up to 40%, a 50,000-ton PP facility would require 13GWh annually
- Sortation will improve availability of high purity LDPE, PVC, PP, and PS but expect investment from recyclers to sort mixed waste in-house
- Depolymerization, mechanical recycling using solvents as catalysts or pretreatments to improve reactivity, not to replace processes
- Delamination is being commercialized at scale in Europe and Japan, limited efforts in the U.S. outside of batteries, solar panels
- Price competition with virgin plastic closest with PP; PVC, PS far away but improving

Innovator Milestones

- Computational modelling still limited to organic solvents and some ionic liquids; improving this technology will redefine optimal solvent choices, approaches
- Strength of academic-industry partnership:
  - University of Wisconsin, Madison, Chemical Upcycling of Waste Plastics (CUWP) created both computational modeling and STRAP
  - CUWP now commercializing first facility in the world using COSMO-RS-informed STRAP as core recycling technology
  - Accelerated development thanks to industrial partners DOW, Sabic, and Braskem
- Specialized equipment needed for switchable hydrophilicity solvents, supercritical solvents; lowering CAPEX will attract investors
- Pilot-to-commercial plants are often first-of-their-kind and untested at scale, expect delays to stand up timelines as technologies are validated at scale and sortation infrastructure increases availability of homogenous feedstocks

Regulatory/Policy Milestones

- Intergovernmental Negotiating Committee 5 is set to finalize a global treaty to reduce plastic pollution by end of 2024 with below goals:
  - Elimination of chemical variation in standardized plastic types improves all plastic recycling but specifically reduces solvent dissolution research costs
  - Ongoing discussion over incentivization, regulatory support for advanced recycling
- Solvent-based recycling technologies are not well understood by policymakers, are often left out of advanced recycling definitions/subsidy programs (New Hampshire, Missouri)
- Japan's Plastic Resource Circulation Strategy and the European Union's Circular Economy Action Plan drastically modernized sortation
- Potential for regulation is high due to toxic nature of many solvents; some activity so far covering **Purecycle's** use of supercritical butane and escaped emissions

On the Radar – New Spin-Outs and Pre-Commercial Innovation

Academic institutions are driving innovation in solvent applications and discovery

Ecosystem	Source		Innovation
Private Research	TNO	▪ Private, not-for-profit research organization working on contract research, consulting, patents, and specialist software ▪ Work across corporates and start-ups	▪ Developed TNO Möbius process to simultaneously recover polymers and additives using solvent dissolution, plan to unveil demo plant in Q4 2024 ▪ Completed two joint development agreements to research commercial viability alongside **Braskem** and **ELIX Polymers** ▪ Developing computational analysis tools to optimize solvent reactivity
National Labs	BERKELEY LAB	▪ Lawrence Berkeley National Laboratory is a joint research laboratory run by the University of California and the U.S. Department of Energy's Office of Science	▪ Research PET solvent-assisted depolymerization using ethylenediamine and pure solvent dissolution using N,N-bis(2-aminopropyl)terephthalamide ▪ PET has been the focus for depolymerization; PET and PC for dissolution ▪ Lab has patents pending on both dissolution and depolymerization reactions
University Research	UNIVERSITY OF BIRMINGHAM	▪ Public research university; chemical engineering department develops polymer recycling research under Dr. Bushra Al-Duri	▪ In tandem with the engineering firm Stopford, developed depolymerization tool using supercritical water to expedite and lower reaction temperature of PET depolymerization ▪ Won a $370K grant from Innovate UK to commercially develop the technology for PET and PP recycling at Tyseley Energy Park ▪ Licensed technology to Stopford under their CircuPlast project
	WISCONSIN UNIVERSITY OF WISCONSIN–MADISON	▪ Public research university in Wisconsin specializing in computer science and chemical engineering ▪ Transferred previous research on solvent-based reactions converting biomass into useful chemicals or fuel precursors	▪ Created Solvent-Targeted Recovery and Precipitation (STRAP), a recycling analysis that applies various solvents to mixed plastic waste thereby isolating and recycling specific polymers including PE, PET, and PVC over time ▪ Conductor-like Screening Model for Realistic Solvents (COSMO-RS) is the computational model that calculates the solubility of target polymers

Waste & Recycling Sector Research

Recent Published Research

Spotlights

- Grid Flexibility (Q1 2024)
- Residential Heat Pumps (Q4 2023)
- Cultivated Protein (Q4 2024)
- Plant Protein (Q3 2023)
- eJet (Q2 2023)
- Cathode Manufacturing (Q2 2023)
- Flood Resilient Infrastructure (Q1 2023)

Insights

- Battery Recycling (Q2 2024)
- Plastic Recycling (Q1 2024)

Upcoming Topics

Insights

- Textile Recycling (Q4 2024)

Upcoming Events

- **Cleantech Forum Europe** – Chantilly, France – November 5-7, 2024
- **Cleantech Forum North America** – San Diego, CA – January 27-29, 2025
- **Cleantech Forum Asia** – Singapore – May 6th-7th, 2025

Associate – Parker J. Bovée

- Focused on emerging innovation & trends across cleantech sectors, including water management systems and recycling technology.
- Prior to joining Cleantech Group, Parker developed wildfire prevention technologies with VegaMX and researched wildfire management at Duke University and the University of California, Berkeley.
- Parker earned a Bachelor's degree in History and Public Policy from the University of California, Berkeley, where he specialized in the history of American environmental entrepreneurship.

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