Making Sense of "Chemical Recycling"

Criteria for Assessing Plastics-to-Plastics and Plastics-to-Fuel Technologies

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Prepared by the Product Stewardship Institute, Inc.

1 Beacon Street
Boston, MA 02108
productstewardship.us

The Product Stewardship Institute

The Product Stewardship Institute (PSI) is a policy advocate and consulting nonprofit that powers the emerging circular economy to ensure products are responsibly managed from design to end of life. In 2000, PSI pioneered product stewardship in the United States by convening diverse stakeholders to build extended producer responsibility (EPR) policies, programs, and laws. Our Members include state, local, and tribal governments in 48 states, and we partner with businesses, academic institutions, environmental nonprofits, and international governments. Together, we advance scalable solutions that protect people and the planet.

Since 2000, PSI has helped enact 130 EPR laws across 16 product categories in 33 states — and all of them began with a background paper, which established the foundation for dialogue. As such, the purpose of this report is to provide baseline information for a robust multi-stakeholder dialogue that PSI intends to facilitate with governments, NGOs, and companies running or planning chemical recycling facilities. We feel that a dialogue on this issue is desperately needed so that all stakeholders can present their interests and perspectives. It is through such a dialogue that PSI plans to develop specific recommendations for how EPR can be applied to emerging chemical recycling technologies.

The purpose of this report is to provide baseline information as a precursor to a robust multi-stakeholder dialogue that PSI intends to facilitate with governments, NGOs, and companies running or planning chemical recycling facilities.

Context

Concerns about chemical recycling are increasingly high-profile. In July 2022, U.S. Senator Cory Booker of New Jersey, along with U.S. Representatives Jared Huffman and Alan Lowenthal of California, published a letter to the Environmental Protection Agency (EPA)[1] requesting that pyrolysis and gasification continue to be regulated as "municipal waste combustion units" under the Clean Air Act. The letter was signed by 35 other members of Congress and endorsed by over 45 environmental organizations.

Critics of chemical recycling projects point out that they are typically situated in low-income communities of color and that they do not yet operate "at scale," i.e., at the required size to solve the problem. Both criticisms are true. However, waste management facilities, including

[1] "Booker, Huffman, Lowenthal Lead 35 Colleagues in Letter Raising Concerns Over Climate & Environmental Justice Risks of Chemical Recycling of Plastics" *CoryBooker.com* July 14, 2022. https://www.booker.senate.gov/news/press/booker-huffman-lowenthal-lead-35-colleagues-in-letter-raising-concerns-over-climate-and-environmental-justice-risks-of-chemical-recycling-of-plastics

mechanical recycling plants,[2] are also typically situated in low-income communities of color and are also not operating at a scale to solve the problem: In the United States, only about 30% of the nearly 300 million tons of municipal solid waste generated each year is mechanically recycled.[3] PSI and our Members agree that the siting of any facility that produces emissions and pollutants is a priority environmental justice concern. It is critical that we reduce – and ultimately eliminate – disproportionate harm to historically oppressed and overburdened communities.

Circular Economy

America has failed to address the plastic pollution crisis: The majority is currently landfilled, incinerated, exported, or leaked into the environment.[4] It is also evident that the best way to address this crisis – as well as the linked climate emergency – is to eliminate the overproduction of plastics, with strong emphasis on waste prevention systems such as reuse and refill. At the same time, we acknowledge that production is unlikely to stop in the near- or mid-term. While source reduction remains critical, strong recycling and waste management policies are also necessary to achieve a sustainable circular economy.

Also, we can't ignore the fact that chemical recycling increasingly dominates the discussion of waste management, especially for plastics. More than 40 companies are currently working to develop or manage chemical recycling projects in the United States, and 20 states — including, most recently, Missouri and New Hampshire[5] — have enacted laws that allow chemical recycling facilities to be permitted as manufacturing facilities, which reduces regulatory burdens and incentivizes companies to invest in these technologies[6] (see "Considerations for Public Entities" section).

This is antithetical to PSI's EPR model legislation for packaging, which informed laws enacted in California, Colorado, Maine, and Oregon and specifies that incineration and "waste to fuel" or "waste to energy" technologies, which burn material for energy, should be considered disposal.

The truth is: Government policy makers tasked with passing legislation or issuing permits lack criteria to assess their economic, environmental, and human health impacts. This report aims to begin to fill that gap.

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[2] EPA *National Recycling Strategy* November 15, 2021. https://www.epa.gov/system/files/documents/2021-11/final-national-recycling-strategy.pdf

[3] EPA *Frequent Questions Regarding EPA's Facts and Figures About Materials, Waste, and Recycling* July 9, 2022. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/frequent-questions-regarding-epas-facts-and

[4] Ibid.

[5] Megan Smalley, "Two states pass advanced recycling legislation" *Recycling Today* July 5, 2022. https://www.recyclingtoday.com/article/missouri-new-hampshire-pass-advanced-recycling-legislation/.

[6] Cheryl Hogue, "Chemical recycling of plastic gets a boost in 18 US states—but environmentalists question whether it really is recycling" *Chemical & Engineering News* May 15, 2022. https://cen.acs.org/environment/recycling/plastic-recycling-chemical-advanced-fuel-pyrolysis-state-laws/100/i17

Process

To develop the report, we first researched existing technology types. Then, we convened our Members to draft a set of criteria through which governments might assess chemical recycling technology permits and legislation. Finally, we solicited feedback.

The report is designed to provide guidance to government policy makers and is *not* an endorsement of any company or technology. All companies mentioned by name are used as examples to provide more clarity and were selected solely on the basis of readily available information. Our hope is that this report will inspire constructive dialogue among a range of stakeholders.

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*This report is designed to provide guidance to government policy makers considering chemical recycling technology permits and legislation and is **not** an endorsement of any company or technology. Our hope is that it will inspire constructive dialogue among a range of stakeholders.*

Acknowledgements

PSI works with state, local, and tribal government members in 48 states and we partner with businesses, academic institutions, international governments, and environmental nonprofits around the world. We reached out to stakeholders in all of these categories to provide feedback on this report and received a tremendous amount of valuable input.

Funding

This report was funded by PSI Members and Partners. Both groups are aligned with PSI's mission to ensure that products are responsibly managed from design to end of life; all are supportive of our principles of EPR. Our board of directors is made up of state and local government officials who helped to identify the need for the criteria presented in the report.

Report Contributors

Scott Cassel, PSI CEO and founder, and Sydney Harris, PSI policy and programs manager.

Project Contact

Scott Cassel: scott@productstewardship.us

Introduction

The Problem: We are facing a global plastics crisis,[7] with plastic production and related pollution continuing to increase.[8] In response, consumer brands, recyclers, governments, and environmentalists have sought solutions that will reduce waste, greenhouse gas emissions, and pollution. Plastics producers and other industry stakeholders have advocated for “advanced” or “chemical” recycling; however, these technologies have raised questions and concerns among environmental advocates and many government agencies.

Confusing Terms: The terms “advanced recycling,” “chemical recycling,” and even “molecular recycling,” are used interchangeably to refer to a wide range of technologies – not all of which are necessarily considered recycling. This report does refer to “chemical recycling” as it is the most commonly used term, but we prefer to identify technologies in more specific terms whenever possible.

Policy Questions: In trying to determine how to regulate these emerging technologies, policymakers and other stakeholders — including consumer brands, plastics production companies, recyclers, environmental advocacy organizations, government officials, and others — need a better understanding of them, especially as industry advocates seek investments into their development. Meanwhile, debates continue among policymakers and advocates who are crafting EPR legislation about whether resources should be invested into chemical recycling facilities under EPR programs. Some advocate for banning these technologies outright or prohibiting their use from being classified as recycling. In Europe, where EPR has been active for decades, there is still widespread skepticism about whether and how chemical recycling might be used to achieve program targets, but there are examples of producer responsibility organizations (PROs) investing in research and development of various chemical recycling technologies.[9]

Plastic vs. Fuel Outputs: From the perspective of PSI’s state and local government Members, the outputs of each technology type are key to their identity. If the final products are fuels, the process is often referred to as plastics-to-fuel and considered energy recovery rather than recycling. If marketable plastics are the final products, the process is referred to as plastics-to-plastics, or material-to-material, and typically seen as a type of recycling. Most U.S. governments and a growing number of international standards do not consider energy recovery technologies

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[7] UNEP, “What you need to know about the plastic pollution resolution” *UNEP.org* March 2, 2022. https://www.unep.org/news-and-stories/story/what-you-need-know-about-plastic-pollution-resolution

[8] UNEP *Drowning in Plastics: Marine Litter and Plastic Waste Vital Graphics* October 2021. https://www.unep.org/resources/report/drowning-plastics-marine-litter-and-plastic-waste-vital-graphics

[9] Federica Tiefenthaler, “Circular Resources’ Acquisition of Der Grüne Punkt” *Global Legal Chronicle* August 24, 2022. https://globallegalchronicle.com/circular-resources-acquisition-of-der-grune-punkt/
“Cross-industry consortium to study plastic chemical recycling in France” *Plastics News* December 10, 2019. https://www.plasticsnews.com/news/cross-industry-consortium-study-plastic-chemical-recycling-france.

(including plastics-to-fuel) to be recycling.[10] Therefore, the distinction between plastics-to-plastics and plastics-to-fuel technologies is seen by PSI's state and local government Members as critical to clear communication and policy design.

The distinction between plastics-to-plastics and plastics-to-fuel technologies is critical to clear communication and policy design.

Potential for Greater Plastics Circularity: One of the central questions facing policymakers is whether the investments, energy, and resources needed to scale up these technologies will result in a more sustainable economy with reduced environmental impacts. Brands and plastics production companies are investing millions of dollars into the development of these technologies, claiming that they expand end-of-life options for plastics and exceed the capabilities of traditional mechanical recycling. One of the arguments made for chemical recycling technologies is that they enable repeated processing without loss of quality.[11] By contrast, mechanical recycling of plastics results in approximately 10% material quality loss with each cycle of processing and degrades materials over their lifetime – with current mechanical recycling technologies, plastics can only be recycled up to seven times before the polymers are too degraded for further use.[12]

As demand for post-consumer recycled resins increases, especially in light of new policies enacting post-consumer recycled content requirements for certain types of plastics such as food-grade and bottle-grade packaging,[13] companies struggling to source recycled content see tremendous

[10] International Organization for Standardization (Europe) *ISO/TR 23891:2020 Plastics – Recycling and recovery – Necessity of standards* September 2020. https://www.iso.org/standard/77294.html
"Definitions – Material recycling" *The U.S. Plastics Pact Roadmap to 2025* 2022. https://usplasticspact.org/roadmap-reader/
"Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives" *The European Waste Directive* May 7, 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098
[11] Alexander H. Tullo, "Companies are placing big bets on plastics recycling. Are the odds in their favor?" *Chemical & Engineering News* October 11, 2020. https://cen.acs.org/environment/sustainability/Companies-placing-big-bets-plastics/98/i39
[12] Martyna Solis and Semida Silveria, "Technologies for chemical recycling of household plastics – a technical review and TRL assessment" *Waste Management Vol 105* March 15, 2020 https://doi.org/10.1016/j.wasman.2020.01.038
[13] There are three U.S. state laws establishing post-consumer recycled (PCR) content requirements for plastics – in California (AB 793, 2020), Washington (RCW Chapter 70A.245), and New Jersey (S 2515, 2022) – all of which include requirements for plastic beverage containers. In Europe, the Single-Use Plastics Directive (https://eur-lex.europa.eu/eli/dir/2019/904/oj), which sets minimum PCR content rates for PET beverage bottles by 2025 and expands to all beverage bottles by 2030, was enacted in 2019. Additionally, the European Commission enacted a *Circular Economy Action Plan* in 2020 (https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN), in which it states an intention to

potential in the reprocessing capacity of chemical recycling.[14] Many industry stakeholders argue that chemical recycling is the only way to meet both post-consumer recycled content requirements and state and federal health and safety requirements for food-grade applications.[15]

Brands and industry associations continue to seek investments into infrastructure — including public funding at the federal, state, and local levels — to accelerate the pace of these developments.[16]

Potential Greenwashing, Environmental Impacts: However, many environmentalists, recyclers, and others decry these technologies as distracting, greenwashing, and false solutions – a way for the plastics industry to continue expanding and to undermine arguments for eliminating single-use plastics.[17] These groups argue that investments into chemical recycling infrastructure — including purification, depolymerization, or conversion facilities and the expansion or alteration of infrastructure to collect feedstocks for such facilities — are a misuse of funds that could otherwise be spent on ready-to-implement improvements to mechanical recycling as well as upstream waste prevention (such as reuse systems) and product or packaging redesign.[18] They have also raised significant environmental justice concerns regarding the potential hazardous waste, hazardous air pollutants, and GHG emissions from these facilities, which are overwhelmingly sited (or proposed to be sited) in low-income communities, communities of color, and other marginalized communities.[19]

The Bottom Line: Caught in the middle between industry and environmentalists are federal, state, and local government officials who must work to support the public good but often lack sufficient information or resources to assess and regulate these emerging and rapidly evolving technologies. They know that to truly curb the global climate change and plastic pollution crises, a comprehensive suite of policies and voluntary actions is critical. PSI's state and local government Members agree that reduced material use and a robust reuse economy are central to any strategy – and must retain their place at the forefront of the classic materials-management hierarchy. But they also recognize that a circular economy will not function without recycling.

"propose mandatory requirements for recycled content and waste reduction measures for key products such as packaging, construction materials and vehicles." The Commission's requirements are expected to include PCR content mandates for food-grade plastic packaging.

[14] Megan Quinn, "Progress report: State waste and recycling policies gain notable traction this year" *Waste Dive* July 19, 2021. https://www.wastedive.com/news/2021-waste-recycling-state-policy-progress-epr-pcr-plastic/603457/

[15] Environment & Climate Change Canada/STINA, *Assessing the State of Food Grade Recycled Resin in Canada & the United States* 2021. https://www.plasticsmarkets.org/jsfcontent/ECCC_Food_Grade_Report_Oct_2021_jsf_1.pdf

[16] Plastics Industry Association *RECOVER ACT: Realizing the Economic Opportunities and Value of Expanding Recycling* 2019. https://www.plasticsindustry.org/sites/default/files/2019%20Recover%20Act%20Flyer.pdf

[17] Association of Mission Based Recyclers (AMBR), "'Chemical recycling' will not solve our plastics problem" September 15, 2022. https://ambr-recyclers.org/our_work/refuting-false-solutions/

[18] Natural Resources Defense Council (NRDC), *Recycling Lies: "Chemical Recycling" of Plastic is just Greenwashing Incineration* February 2022. https://www.nrdc.org/sites/default/files/chemical-recycling-greenwashing-incineration-ib.pdf

[19] Ibid.

Our Aim: This report provides a set of draft criteria by which policymakers can assess chemical recycling technologies to determine which, if any, can support a sustainable economy, prevent waste and pollution, and curb greenhouse gas emissions alongside other upstream solutions to prevent plastic pollution and waste. It is intended to provide basic clarification on the suite of emerging chemical recycling technology types, and our hope is that it can be used to inform a structured dialogue with key stakeholders on how to address these technologies through EPR or other types of policies, as well as how to regulate and permit them.

Existing & Emerging Technologies

Chemical recycling refers to a wide range of processes that use one of three technology types: purification, depolymerization, or conversion.

- **Purification** is a process by which plastics are dissolved in chemical solvents to recover virgin-grade plastic resins that are free from additives and dyes.
- **Depolymerization** processes break the molecular bonds of plastics to recover building blocks (monomers) that can be reconstructed into "like-new" resins.
- **Conversion** technologies (e.g., pyrolysis and gasification) convert plastics into refined hydrocarbons and petrochemicals. Pyrolysis and gasification technologies produce fuel or fuel intermediaries, but these outputs may be reprocessed into plastics.

Given the widespread confusion over the terms "chemical," "advanced," and "molecular" recycling, in this report we refer to each technology type (purification, depolymerization, conversion), plastics-to-plastics (recycling), and plastics-to-fuel (energy recovery) technologies, using these specific terms.

According to the investment firm Closed Loop Partners, at least 40 companies using one or more of these technologies are currently in either development or commercial stages in North America.[20] Closed Loop Partners outlines 10 levels of "technology readiness," from concept (level 0) to full commercial application (level 9).[21] Existing purification, depolymerization, and conversion companies fall across this spectrum, with some in the concept phase, conducting lab research, or undertaking pilot projects for proof of concept, and others in early commercial or full-growth stages (see Fig. 1).[22]

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[20] Closed Loop Partners, *Accelerating Circular Supply Chains for Plastics: A Landscape of Transformational Technologies that Stop Plastic Waste, Keep Materials in Play and Grow Markets* 2019. https://www.closedlooppartners.com/wp-content/uploads/2021/01/CLP_Circular_Supply_Chains_for_Plastics_Updated.pdf
[21] Closed Loop Partners, *Transitioning to a Circular System for Plastics* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/AR-report-V23_final7.pdf
[22] Ibid.

Closed Loop Partners states that the average time for chemical recycling facilities to reach full commercial operation is 17 years, and this timeline may be longer for plastics-to-plastics technologies that produce polymers rather than plastics-to-fuel techniques, which produce petrochemicals and other fuels.[23] In its 2021 report, the firm encouraged investors and policy makers to focus on scaling plastics-to-plastics technologies that meaningfully decarbonize the status-quo plastics supply chains to support a more rapid transition to a circular economy.[24] However, the significant time that it takes to scale to early commercial or full-growth stages, as well as the overall commercial viability of these companies, has been of major concern. The National Academies of Sciences recently characterized chemical recycling technologies as "unproven to handle the current plastic waste stream and existing high-production plastics."[25] Investigative reporters for Reuters have emphasized that "at least four high-profile projects have been dropped or indefinitely delayed over the last two years because they weren't commercially viable."[26] Opponents cite such examples of failed investments and a lack of fully operational, commercial-scale facilities as proof that the technologies are inherently flawed.[27]

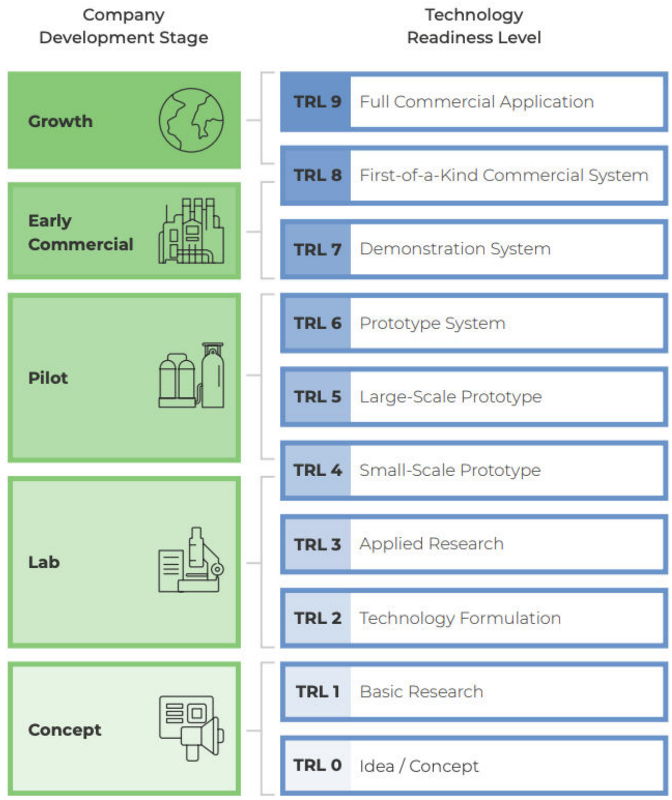

Figure 1: Technology Readiness Levels. Figure from Closed Loop Partners, Global Directory of Molecular Recycling Technologies – Supplemental Resource from Transitioning to a Circular System for Plastics: Assessing Molecular Recycling Technologies in the United States and Canada (2021).

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[23] Closed Loop Partners, *Accelerating Circular Supply Chains for Plastics* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/01/CLP_Circular_Supply_Chains_for_Plastics_Updated.pdf

[24] Closed Loop Partners, *Transitioning to a Circular System for Plastics* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/AR-report-V23_final7.pdf

[25] The National Academies of Sciences, Engineering, and Medicine, "Reckoning with the U.S. Role in Global Ocean Plastic Waste" *The National Academies Press* 2022. https://doi.org/10.17226/26132

[26] Joe Brock, Valerie Volcovici and John Geddie, "The Recycling Myth: Big Oil's Solution for Plastic Waste Littered with Failure" *Reuters* 2021. https://www.reuters.com/investigates/special-report/environment-plastic-oil-recycling

[27] Ivy Schlegel, "Deception by the Numbers" *Greenpeace* September 9, 2020. https://www.greenpeace.org/usa/wp-content/uploads/2020/09/GP_Deception-by-the-Numbers-3.pdf

Evaluation Criteria

Since the term chemical recycling is used to refer to such a wide variety of existing and emerging technologies, assessing which, if any, can support a more sustainable economy with reduced environmental impacts is challenging. To better define their goals, PSI's local and state government Members identified seven attributes of a sustainable circular economy with a minimal environmental footprint:

- Reduce, and ultimately eliminate, fossil fuel extraction.
- Reduce greenhouse gas (GHG) emissions.
- Reduce biodiversity loss and the loss of ecosystem services.
- Reduce emissions of toxic chemicals.
- Reduce the financial burden on taxpayers for materials management.
- Prevent disproportionate harm to overburdened communities domestically and globally.
- Prevent production of unnecessary and problematic materials.

The criteria are intended to serve as a starting point for further stakeholder dialogue, not as static guidelines.

The following criteria are proposed to assess which, if any, emerging technologies can help achieve these seven goals. The criteria are intended to serve as a starting point for further stakeholder dialogue, *not* as static guidelines. The objective of this report, as previously stated, is to elicit further discussion among stakeholders in the hope of reaching consensus on the best policy approach to chemical recycling.

- **Criteria #1: Proper Inputs.** The process should only source inputs that need to be disposed of, do not have reusable or mechanically recyclable alternatives, and have no less impactful end-of-life management options (e.g., plastics from medical waste, e-waste, textiles, and construction waste). By utilizing only non-mechanically recyclable inputs, the process should avoid competition for feedstocks with mechanical recycling operations. The technology should not be used to perpetuate unsustainable production of problematic or unnecessary materials, such as single-use cutlery and straws.

- **Criteria #2: Transparent Outputs.** The process should be publicly transparent about its outputs, including waste, emissions, and final products (except for proprietary information that would prevent fair competition among companies, which must still be disclosed as part

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Natural Resources Defense Council, *Recycling Lies: "Chemical Recycling" of Plastic is just Greenwashing Incineration* February 2022. https://www.nrdc.org/sites/default/files/chemical-recycling-greenwashing-incineration-ib.pdf.

of the permitting process). Only processes that produce plastics as their final output should be referred to and treated as recycling. Plastics-to-fuel technologies — whether the fuel is used for on-site or off-site combustion — should be referred to and treated as energy recovery, not recycling, as these technologies do not fit the U.S. Environmental Protection Agency (EPA) definition for recycling, which is "collecting and reprocessing a resource so it can be used again."[28] If a chemical recycling process produces some plastics and some fuels, these outputs should be transparently reported and only the portion of outputs that are plastics should be considered recycled. Third-party certification or other independent verification should be provided to support any claims regarding a technology's efficiency, outputs, environmental impacts, and other factors.

- **Criteria #3: Reduced Climate Impacts and Fossil Fuel Extraction.** The outputs of chemical recycling technologies must have lower life-cycle impacts, including GHG emissions, than the same outputs produced through traditional means. For example, polypropylene (PP) resins produced through purification must have a lower life-cycle impact than PP resins produced using virgin feedstocks derived from fossil fuels – accounting for the energy sources used to process the resins. In other words, the process of converting waste plastics into feedstocks must not use more non-renewable energy or resources than traditional plastic production processes and should support efforts to mitigate climate change.[29] Additionally, it is important to incorporate the full scope of each technology into assessments of impact, from collection and pre-processing through to end market.

- **Criteria #4: Minimal Harm.** The process should minimize emissions of harmful pollutants into the land, air, and water. Emissions must not exceed, at a minimum, federal Clean Air Act or Clean Water Act standards, or state standards if they are more stringent, and facilities should not add to any cumulative pollution impacts in overburdened communities.[30] The siting process for any facilities should include robust community engagement and transparency. Additionally, the process should prioritize the management of outputs and wastes within the United States over exporting them abroad. For any

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[28] EPA, *Recycling, Glossary of Climate Change Terms* September 9, 2013. https://sor.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do;jsessionid=Z2Wb-1xpDbgotz2v_jX3Ai4v_oT4YUUAkt6hQXAQEhkmhAix0bor!-1829608955?details=&vocabName=Glossary%20Climate%20Change%20Terms&filterTerm=recycling&checkedAcronym=false&checkedTerm=false&hasDefinitions=false&filterTerm=recycling&filterMatchCriteria=Contains.

[29] Lifecycle Assessment (LCA), the most common methodology for assessing the GHG and lifecycle impacts of a given product or material, is subject to significant variability depending upon the assumptions and parameters used. For example, Closed Loop Partners' own LCAs on chemical recycling technologies include a caveat that varying electrical grids across regions of the United States, among other factors, could significantly alter the results. Closed Loop Partners *Transitioning to a Circular System for Plastics: Assessing Molecular Recycling Technologies in the United States and Canada* https://www.closedlooppartners.com/appendix-molecular-recycling-technologies/#appendix40.

[30] Based on New Jersey's Environmental Justice Law, enacted September 2020. https://www.nj.gov/dep/ej/policy.html#ejlaw.

materials exported or proposed to be exported, the process should guarantee that all materials will be managed responsibly and without harm to receiving communities.[31]

- **Criteria #5: Widespread, Convenient Collection.** The process should have a convenient, equitable, and accessible means for waste generators to provide materials that do not increase contamination in mechanical recycling streams. For example, collection of flexible plastics for processing at chemical recycling facilities should not occur in such a way that mechanical recycling streams see increased contamination from flexibles due to consumer confusion.

- **Criteria #6: Operates at Scale Without Public Subsidy.** The process should be commercially viable within a realistic time frame. Technologies should ultimately result in a reduced financial burden on taxpayers for waste management and should not be dependent on public subsidies. Significant federal, state, and local government attention and funding have already been invested into chemical recycling technologies[32] and the petroleum industry has been heavily subsidized by taxpayers for decades.[33] PSI's government Members have emphasized that public subsidies should not be used to address a waste crisis that was caused by private industry. Public recycling programs may wish to consider whether selling materials from collection programs or MRFs to processors using plastics-to-fuel technologies also constitutes taxpayer support.

Considerations for Public Entities

Permitting

In 2021, the U.S. EPA opened a formal rulemaking process to consider whether any additional regulation of gasification, pyrolysis, and related technologies is needed at a national level. Currently, chemical recycling technologies and their associated facilities are regulated by existing federal and state permitting requirements. A full analysis of state laws and regulations regarding

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[31] Based on Oregon's EPR law for packaging and paper products, enacted August 2021. https://olis.oregonlegislature.gov/liz/2021R1/Downloads/MeasureDocument/SB582/Enrolled

[32] U.S. Department of Energy, *Department of Energy Launches Plastics Innovation Challenge* November 21, 2019. https://www.energy.gov/articles/department-energy-launches-plastics-innovation-challenge
U.S. Department of Energy, "Department of Energy Announces $25 Million for Plastics Recycling R&D, Launches Upcycling Consortium" March 16, 2020. https://www.energy.gov/articles/department-energy-announces-25-million-plastics-recycling-rd-launches-upcycling-consortium
Colin Staub, "Federal lawmakers launch plastics recycling task force," *Plastics Recycling Update* December 11, 2019. https://resource-recycling.com/plastics/2019/12/11/federal-lawmakers-launch-plastics-recycling-task-force
Colin Staub, "Plastics recovery efforts receive millions in state funding" *Resource Recycling* May 21, 2019. https://resource-recycling.com/recycling/2019/05/21/plastics-recovery-efforts-receive-millions-in-state-funding

[33] Yale School of the Environment, "Fossil Fuels Received $5.9 Trillion in Subsidies in 2020, Report Finds" *E360 Digest* October 6, 2021. https://e360.yale.edu/digest/fossil-fuels-received-5-9-trillion-in-subsidies-in-2020-report-finds

purification, depolymerization, and conversion technologies is beyond the scope of this report; however, an example can be found in the Oregon Administrative Rules Database (OARD).[34]

There is ongoing debate over whether to classify these technologies as forms of manufacturing or forms of waste management. The American Chemistry Council (ACC) and other industry groups seek to have all purification, depolymerization, and conversion technologies regulated as manufacturing processes because they consider waste plastics as feedstocks for manufacturing processes that produce either fuels or the building blocks for new plastics.[35]

In contrast, environmental groups and other advocates strongly support regulating these technologies as waste management processes,[36] because this would require more stringent restrictions on emissions and strong oversight over the handling of the primary inputs for each of the three technology types that use post-consumer or post-industrial wastes. Many of the existing facilities in the U.S. have been permitted as hazardous waste facilities due to the storage and release of chemicals and toxics.[37] Permitting for purification, depolymerization, or conversion facilities should address the following issues:

- Potential impacts on state and/or local GHG emissions reduction targets.
- Transparent and thorough environmental justice and environmental impact reviews, alongside robust community engagement and transparency.
- Financial assurance in the event of site failure(s), especially in the event that cleanups will be needed.

Extended Producer Responsibility (EPR) Legislation

EPR is a policy tool that requires producers of consumer goods to take responsibility for their products and packaging both upstream in the design phase and downstream in the post-consumer management phase. With government oversight, EPR policy shifts financial and sometimes management responsibility away from the public sector to producers and provides financial incentives for producers to incorporate environmental considerations into the design of their products and packaging. EPR intends to increase capacity for, and investments into, waste reduction and recycling infrastructure using producer – rather than taxpayer – funds.

There is growing consensus among governments, recyclers, and producers that EPR legislation should define “recycling” to include plastics-to-plastics technologies and never include energy recovery or plastics-to-fuel, but no national consensus on the terms has been established.

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[34] Oregon Administrative Rules Database *Solid Waste: Special Rules For Selected Solid Waste Disposal Sites* accessed September 2022. https://secure.sos.state.or.us/oard/displayDivisionRules.action?selectedDivision=1492
[35] Steve Toloken, “ACC pushes chemical recycling legislation” *Plastics News* April 22, 2019. https://www.plasticsnews.com/article/20190422/NEWS/190429997/acc-pushes-chemical-recycling-legislation
[36] GAIA, ”All Talk and No Recycling: An Investigation of the U.S. ’Chemical Recycling‘ Industry“ July 28, 2020. https://www.no-burn.org/wp-content/uploads/All-Talk-and-No-Recycling_July-28.pdf
[37] Ohio Environmental Protection Agency, “PureCycle RCRA Subtitle C Site Identification Form” March 15, 2019. http://edocpub.epa.ohio.gov/publicportal/ViewDocument.aspx?docid=1046080

Another critical topic is the need for transparency: EPR programs may require disclosure of inputs for each processing facility – including whether these are post-consumer, post-industrial, post-commercial, or a combination of these, and whether they are mixed with wastes not covered by the EPR program, such as automotive parts or medical waste – as well as outputs, such as whether or not a portion of the inputs is converted to fuel and how much is sold as plastic feedstock. They also may require reporting on the final destination of and/or the emissions from processing covered materials.

For now, the issue of whether and how to allow for purification, depolymerization, and conversion technologies in EPR programs tends to arise when defining "recycling," as well as in parameters defining PRO investments. Many producers view EPR systems – especially for packaging – as a means to invest in purification, depolymerization, and conversion technologies, among other upgrades to recycling infrastructure and waste reduction. But as states across the country introduce and pass EPR legislation covering packaging, electronics, carpet, textiles, and other products made from plastics, questions about how to treat plastics-to-plastics and plastics-to-fuel technologies in these systems continue to emerge. Some state EPR bills have sought to exclude certain chemical recycling technologies from the definition of "recycling," which has drawn opposition from consumer goods companies that would otherwise be supportive of EPR legislation.

For example, NY S1185-C (2021) included the following definition: "'Recycling' means reprocessing, by means of a manufacturing process, of a used material into a product, a component incorporated into a product, or a secondary (recycled) raw material. 'Recycling,' for purposes of this title, does not include energy recovery or energy generation by means of combustion, use as a fuel, or landfill disposal of discarded covered materials or products or discarded product component materials or chemical conversion processes, as determined by the department to not qualify in the state as recycling."[38]

The Sustainable Food Policy Alliance (SFPA) – a consortium of four major global consumer brands – wrote in testimony to State Senator Todd Kaminsky: "Our companies recognize the need for a suite of strategies, including innovative recycling technologies, to enable the recycling of both the rigid and flexible plastics that we use. We disagree that advanced recycling technologies that deliver feedstock to make new packaging are considered recovery, not recycling, under this bill. We agree that energy and fuel are considered recovery but advanced recycling technologies are a necessary part of the solution to not only recycle flexible plastic packaging but to also deliver food-safe recycled content."

The first two EPR laws for packaging in the U.S., both enacted in 2021, take distinct approaches to the management of packaging waste. While neither explicitly uses the terms "chemical" or "advanced" recycling, Oregon's new law prescribes an overall preference for EPR programs to

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[38] *New York Extended Producer Responsibility Act of 2021* S1185-C 2021. https://www.nysenate.gov/legislation/bills/2021/s1185/amendment/c

result in “reduction of net negative impacts on human well-being and environmental health” and requires program plans, submitted by producers to the state for approval, to include lifecycle assessments and additional information for any materials not managed through mechanical recycling.[39] Maine’s new law requires the state’s contracted stewardship organization to submit all proposals for infrastructure investments to the Department of Environmental Protection for approval and establishes criteria by which the state will assess such proposals on a case-by-case basis.[40]

In 2022, Colorado passed the nation’s third packaging EPR law, which emulates Oregon on the issue of recycling technologies – requiring producers to submit information on whether processing technologies will affect the ability for plastics-to-plastics recycling; details on the potential supply-chain impacts for food and pharmaceutical-grade plastic packaging; compliance with federal air, water and waste permitting requirements; and analysis of the environmental impacts of each technology as compared to incineration.[41] In both Oregon and Colorado, “mechanical recycling” is defined as “a form of recycling that does not change the basic molecular structure of the material being recycled,” which means purification technologies might fall under this umbrella. It remains to be seen whether this will be further clarified in regulations or how this definition could be applied to existing and emerging technologies.

On June 30, 2022, California became the fourth state in the nation to enact a packaging EPR law. California’s law leaves open the possibility for advanced plastics-to-plastics technologies but does not allow combustion, incineration, waste-to-energy, waste-to-fuel production (except for anaerobic digestion), or “other forms of disposal” to count as “recycling.”[42] The inclusion of chemical recycling technologies hinges on the word “disposal.” Existing California statute defines “disposal” to include pyrolysis, distillation, and “biological conversion other than composting,”[43] which calls into question whether certain chemical recycling technologies might be permissible under the new EPR program while others (like pyrolysis) are not. The new packaging EPR law also prohibits a producer responsibility organization (PRO) from investing program funds “to subsidize, incentivize, or otherwise support” any non-recycling operations, including any forms of “disposal.”[44] Under the law, CalRecycle will enact regulations that encourage less impactful recycling processes and will prohibit recycling technologies that produce “significant amounts of hazardous waste.”[45]

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[39] Oregon SB 582, Chapter 681, 2021 Laws” effective January 1, 2022.
https://olis.oregonlegislature.gov/liz/2021R1/Downloads/MeasureDocument/SB582/Enrolled

[40] ME LD 1541, Chapter 455 approved July 12, 2021.
https://legislature.maine.gov/legis/bills/getPDF.asp?paper=HP1146&item=11&snum=130

[41] CO HB 1355, as signed, Section 25-17-709. https://leg.colorado.gov/bills/hb22-1355

[42] CA SB 54 Chaptered, Section 42051.1(aa)(1). https://legiscan.com/CA/text/SB54/2021

[43] CA PRC Sec. 40192 defines “disposal” to include “transformation,” which is defined in Sec. 40201 June 6, 2016.
https://california.public.law/codes/ca_pub_res_code_section_40201

[44] CA SB 54, Chaptered, Section 42051.1(j)(2)(D) June 30, 2022. https://legiscan.com/CA/text/SB54/2021

[45] CA SB 54, Chaptered, Section 42042 Z(aa)(5) June 30, 2022. https://legiscan.com/CA/text/SB54/2021

All four new packaging EPR laws will incentivize increased use of post-consumer recycled (PCR) content in covered materials, which is likely to increase the drive, at least among some industry stakeholders, to achieve these targets through emerging chemical recycling technologies:

- Oregon's new law includes a requirement for producers to include consideration of PCR content use within the program's fee structure.
- Maine's requires the Department of Environmental Protection to specify program performance requirements through rulemaking that include increased use of PCR content.
- Colorado's law requires the PRO to set targets for PCR content for certain material types within its program plan that must increase over time, which the state will need to approve.
- California's law requires the PRO to describe in its program plan how PCR content will be incorporated into covered materials, and to include PCR content as a factor in the program's fee structure.

As demonstrated, the inclusion of plastics-to-plastics and plastics-to-fuel technologies in EPR systems is currently being addressed state-by-state. A more consistent evaluative approach should be developed, which could be applied not just to packaging but to all products containing plastics, including construction waste, electronic waste, textiles, and medical waste. Such an approach could be developed through a consensus-based process to harmonize criteria across states, or through the publication of a national standard. The draft criteria presented in this report are intended to support the development of a harmonized approach.

Chemical Recycling Technology Types

Technology Type #1: Purification

This technology uses solvents to dissolve plastics, removing additives, dyes, and other contaminants to obtain virgin-grade material. There is no change to the plastics at a molecular level. Purification includes processes such as dissolution and de-inking, which produce virgin-like resin pellets that can then be used to create new plastic items (see Fig. 2).[46] Because chemical solvents can reduce contamination (including resins that are not desired outputs), purification can accommodate slightly more contamination – including colorants, stabilizers, organic residues, and others – in post-consumer plastics than mechanical recycling.[47] However, purification technologies still require pre-processing as they are optimized for single-stream plastics and perform best when the inputs are clean.[48] Purification is the least energy-intensive of the three chemical recycling technology types and shows the highest plastic-to-plastic processing efficiency rate – i.e., the rate

[46] James Sherwood, "Closed Loop Recycling of Polymers Using Solvents" *Johnson Matthey* 2020. https://www.ingentaconnect.com/content/matthey/jmtr/2020/00000064/00000001/art00002;jsessionid=37mf8bcoou8jb.x-ic-live-03

[47] Eunomia, *Chemical Recycling: State of Play* December 8, 2020. https://www.eunomia.co.uk/reports-tools/final-report-chemical-recycling-state-of-play/

[48] Closed Loop Partners, *Transitioning to a Circular System for Plastics* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/AR-report-V23_final7.pdf

of plastics outputs vs. plastics inputs – 91% on average[49] - slightly higher than mechanical recycling (see Fig. 3 and Appendix A).

- **Inputs:** Purification is used for single-material plastics (also referred to as mono-material plastics), such as PE, PET, PS and PP. In theory, it could be used on any single resin type, provided a suitable solvent could be identified. But because purification relies on tailoring the specific solvent to the desired polymer, these processes perform best with source-separated, relatively clean inputs.[50]
- **Outputs:** The primary outputs of purification are virgin-like plastics of the same polymer type as the inputs. For example, when post-consumer PE is purified, virgin-like PE polymers are produced. Purification technologies are not always able to remove all contaminants from input materials, which means there can be residual toxics in the resulting resins.[51] Wastes from the process include spent solvents and other chemicals, which must be safely managed to avoid releasing environmental contaminants. **Level of commercialization**: Purification is a relatively new technology. Globally, there are approximately 11 pilot or early commercial-stage companies using purification – three with headquarters in the U.S. (one of which is a university conducting research).[52]

Plastic Polymers

This report refers to various plastic polymers as follows:

- PP = polypropylene
- PET = polyethylene terephthalate
- PE = polyethylene
- HDPE = high density polyethylene
- LDPE = low density polyethylene
- PS = polystyrene
- EPS = expanded polystyrene
- PLA = polylactic acid
- PVC = polyvinyl chloride
- PU = polyurethane

When preceded by "r," as in "rPP," the polymer are recycled (i.e., made from recycled resin).

EXAMPLE: PureCycle Tech, a U.S. company with headquarters in Orlando, Florida, uses a plastics-to-plastics purification technique patented by Procter & Gamble that separates color, odor, and other additives and contaminants from PP to "transform it into virgin-like resin." In 2019, PureCycle announced plans to open its first plant in Lawrence County, Ohio, in partnership with Milliken & Company and Nestlé[53] and the plant is expected to be completed by the end of 2022.[54] The company has since broken ground on another plant in Augusta,

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49 Ibid.

50 Eunomia, *Chemical Recycling: State of Play* December 8, 2020. https://www.eunomia.co.uk/reports-tools/final-report-chemical-recycling-state-of-play/

51 Ibid.

52 Closed Loop Partners, *Global Directory of Molecular Recycling Technologies* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/CLP_Molecular-Recycling-Directory-2021.pdf

53 "PureCycle Technologies partners with Milliken, Nestlé to accelerate revolutionary plastics recycling" March 13, 2019. https://purecycle.com/2019/03/purecycle-technologies-partners-with-milliken-nestle-to-accelerate-revolutionary-plastics-recycling

54 "PureCycle Technologies Provides Second Quarter 2022 Update" August 12, 2022. https://purecycle.com/2022/08/purecycle-technologies-provides-second-quarter-2022-update/.

Georgia.[55] In November of 2021, PureCycle announced the first consumer product manufactured using its recycled PP: A personal-care product dispenser made with post-consumer PP collected at stadiums.[56] PureCycle's Ohio-based plant will focus primarily on five inputs of PP: plastic tubs and lids, metallized films, supersacks (bulk bags made of woven PP), and waste carpet.[57] For its Georgia plant, the company aims to source residuals from materials recovery facilities (MRFs) and other materials bound for landfill, such as plastic billboards, fishing nets, PET films, and medical waste.[58] PureCycle states that it has tested a wide array of post-consumer products, including diapers and e-cigarettes,[59] and that its recycled PP (rPP) can be "infinitely" recycled.[60]

Technology Type #2: Depolymerization

Depolymerization, also referred to as decomposition, involves breaking the molecular bonds of plastics to recover simple molecules (monomers or oligomers), which can then be reconstructed ("repolymerized") into plastics. The molecular bonds can be broken through biological, chemical, or thermal means, or a combination of these (see Fig. 2). Depolymerization is one of the most rapidly evolving of the three technology types; most processes use chemical depolymerization, though thermal and biological methods are emerging as well. In some instances, depolymerization is more energy intensive than purification, but less energy intensive than conversion (see Technology Type #3). On average, it has a lower plastic-to-plastic processing efficiency than purification or mechanical recycling (75% - see Fig. 3)[61] but can process a wider variety of materials, including those with higher levels of additives and contaminants, because it includes more capabilities for removing them. Like purification, depolymerization also requires a degree of pre-processing as most technologies are optimized for clean, mono-material inputs.[62]

Chemical depolymerization: Chemical depolymerization uses chemical reagents to break down plastics into their building blocks (monomers or oligomers). The names of various chemical depolymerization technologies are derived from the chemical solution in which the plastics are deconstructed— e.g., hydrolysis (depolymerizing plastics in a water-based solution), methanolysis (depolymerizing plastics in methanol), glycolysis (depolymerizing plastics in glycol), etc.[63]

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[55] "PureCycle Breaks Ground on New Recycling Facility in Augusta, Georgia" March 23, 2022. https://purecycle.com/2022/03/purecycle-breaks-ground-on-new-recycling-facility-in-augusta-georgia/.
[56] "The Sustainable Plastic Revolution is Here" November 5, 2021. https://purecycle.com/2021/11/the-sustainable-plastic-revolution-is-here.
[57] Tamsin Ettefagh, CSO and VP of Industry, PureCycle Technologies, video call with author, February 2021.
[58] Ibid.
[59] Ibid.
[60] "The Sustainable Plastic Revolution is Here" November 2021. https://purecycle.com/2021/11/the-sustainable-plastic-revolution-is-here
[61] Closed Loop Partners, *Transitioning to a Circular System for Plastics* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/AR-report-V23_final7.pdf
[62] Ibid.
[63] Closed Loop Partners, *Accelerating Circular Supply Chains for Plastics* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/01/CLP_Circular_Supply_Chains_for_Plastics_Updated.pdf

- **Inputs:** Chemical depolymerization is used for certain mono-material polymers – specifically, a subset of plastics known as *condensation polymers,* which describes the molecular process through which they are formed – including PET, PU, polycarbonate, PLA, and some types of nylon.[64] Although chemical depolymerization can accommodate some contamination (additives, pigments/colorants, non-target polymers, etc.), these technologies perform best when the inputs are from source-separated, homogenous waste streams, necessitating sorting and pre-treatment.[65]

Plastic Building Blocks

The basic building blocks of plastics referred to in this report are as follows:

- **Monomers**: Molecules that can be bonded with other molecules to form polymers.
- **Oligomers**: Simple units consisting of few repeating monomers bonded together.
- **Polymers**: Substances (resins and plastics) consisting of many bonded monomers or oligomers.

- **Outputs:** The outputs of chemical depolymerization are the monomers or oligomers of the inputs. For instance, if post-consumer polyester is depolymerized, the monomers or oligomers of polyester will be the outputs. Monomers and oligomers are used to produce polymers, which are manufactured into new plastic items. Waste from the process includes spent reagents and other chemicals, which must be safely managed to avoid releasing environmental contaminants.
- **Level of commercialization:** Chemical depolymerization is one of the most rapidly evolving technology types. Globally, approximately 19 companies use chemical depolymerization techniques, with most still in research or pilot stages. Six of these are headquartered in the U.S.[66]

EXAMPLE: Eastman, a U.S. company with headquarters in Kingsport, Tennessee, has developed polyester renewal technologies that use chemical depolymerization by glycolysis and methanolysis to produce monomers of polyester, with a primary focus on methanolysis.[67] The monomers from this process can be used to create co-polyesters, specialty plastics, and other chemicals with 30% to 100% recycled content[68] for commercial products that are already being sold.[69] According to available LCA summaries commissioned

Closed Loop Partners, *Transitioning to a Circular System for Plastics* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/AR-report-V23_final7.pdf

[64] Eunomia, *Chemical Recycling: State of Play* 2020. https://www.eunomia.co.uk/reports-tools/final-report-chemical-recycling-state-of-play/

[65] Ibid.

[66] Closed Loop Partners, *Global Directory of Molecular Recycling Technologies* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/CLP_Molecular-Recycling-Directory-2021.pdf

[67] Eastman, *Polyester Renewal Technology* accessed January 4, 2022. https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Polyester-Renewal.aspx

[68] Eastman, "Polyester Renewal: A Big Step Toward a Small Footprint" 2021. https://www.eastman.com/Company/Circular-Economy/Resources/Documents/Polyester-Renewal-LCA-Infographic.pdf

[69] Eastman, "Success stories" March 17, 2022. https://www.eastman.com/Company/Circular-Economy/Success-Stories/Pages/Success-Stories.aspx

by Eastman, the company's polyester renewal technology will reduce greenhouse gas (GHG) emissions by 20-30% as compared to fossil-fuel based production of the same monomers.[70] Eastman is building a 100,000 metric ton methanolysis facility in Kingsport, which will process a variety of difficult-to-recycle polyester wastes including polyester textiles, carpet fiber, and byproducts from mechanical recycling processes.[71]

Thermal depolymerization: This technique breaks down plastics into their monomers or oligomers by heating the plastics along with catalysts. Thermal depolymerization is frequently used in combination with chemical processes.

- **Inputs:** Thermal depolymerization is used for polymers such as PP, PS, and acrylics.
- **Outputs:** The outputs of thermal depolymerization are the monomers or oligomers of the inputs. For instance, if post-consumer PS is an input, then the monomers or oligomers of PS (e.g., styrene) will be the output. Monomers and oligomers are used to produce polymers, which are manufactured into new plastic items.
- **Level of commercialization:** Thermal depolymerization is less developed than chemical depolymerization. Just two companies (Agilyx and Aquafil) currently use thermal depolymerization; both are headquartered in the U.S.[72]

EXAMPLE: Agilyx, a U.S. company with headquarters in Tigard, Oregon, processes post-consumer and post-industrial mixed plastics using several technology types. While the majority of Agilyx's outputs thus far have been a synthetic crude oil, its "single polymer pathway" includes a patented Polystyrene-to-Styrene Monomer (PSM) System, which uses post-consumer and post-industrial PS to produce styrene oil. Agilyx has operated a pilot facility, Regenyx, at its headquarters in Tigard in partnership with AmSty to recycle polystyrene since 2018.[73]

Biological depolymerization: This technique uses enzymes instead of chemical solvents or heat to break down plastics into their monomers or oligomers.

- **Inputs:** There are very limited biological (enzymatic) depolymerization technologies available today and those that are being researched or piloted are primarily focused on processing PET, mostly from textiles and beverage bottles.
- **Outputs:** The outputs of biological depolymerization are the monomers or oligomers of the inputs. For instance, if post-consumer PET is an input, then the monomers or oligomers of PET, such as PTA (terephthalic acid), will be the outputs. Monomers are used to produce polymers, which are manufactured into new plastic items.

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70 Eastman, "Building a better circle with less impact" March 2022. https://info.eastman.com/LCA

71 Eastman, "Eastman and Governor Lee Announce World-Scale Plastic-to-Plastic Molecular Recycling Facility to be Built in Kingsport, Tenn." January 29, 2021. https://www.eastman.com/Company/News_Center/2021/Pages/Eastman-and-Governor-Lee-Announce-Plastic-to-Plastic-Recycling-Facility.aspx

72 Closed Loop Partners, *Global Directory of Molecular Recycling Technologies* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/CLP_Molecular-Recycling-Directory-2021.pdf

73 Tim Stedman, CEO, Agilyx, presentation at Paper and Plastics Recycling Conference, November 5, 2021.

- **Level of commercialization:** Like thermal depolymerization, biological depolymerization is not yet widely adopted. Globally, two entities (Carbios and the University of Portsmouth, UK, in partnership with the U.S. National Renewable Energy Laboratory, NREL) are currently exploring biological depolymerization.[74]

EXAMPLE: Carbios, a European company with headquarters in France, claims to have developed the world's first enzymatic recycling technology for PET. The process, currently in the pilot stage, uses enzymatic hydrolysis to break down PET from rigid plastics of any color, along with textiles, into the monomers PTA and EG (ethylene glycol).[75]

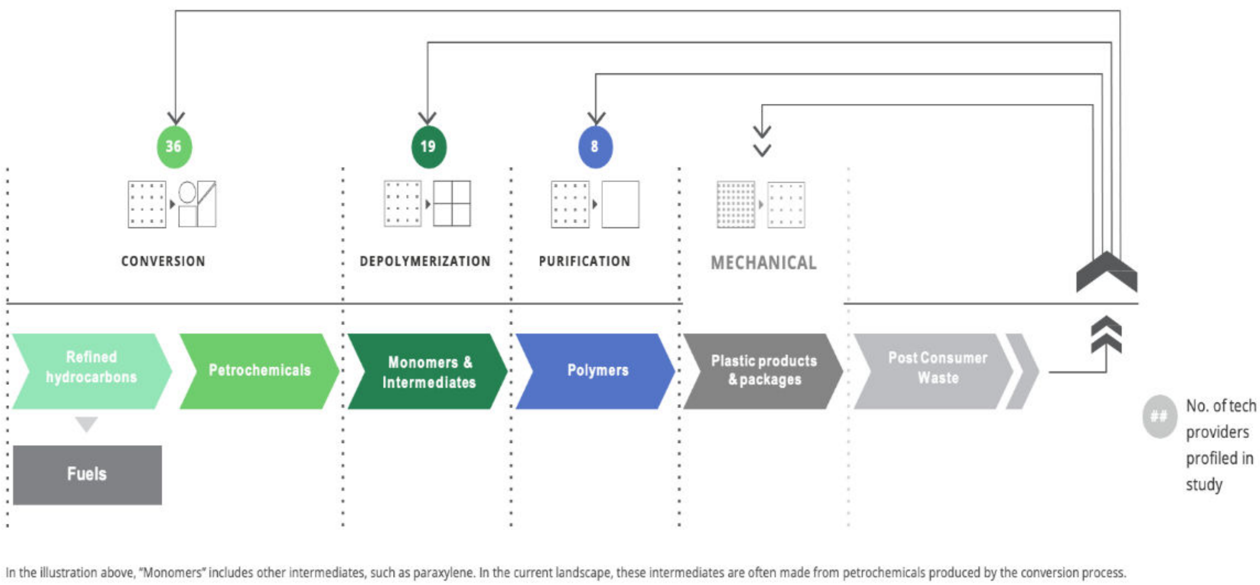

Figure 2: Schematic of Purification, Depolymerization and Conversion. Figure from Closed Loop Partners, Accelerating Circular Supply Chains for Plastics: A Landscape of Transformational Technologies That Stop Plastic Waste, Keep Materials in Play and Grow Markets (2019).

Technology Type #3: Conversion

The final technology type, conversion, includes — and is most widely known as — gasification and pyrolysis, which is sometimes classified as thermal depolymerization, rather than conversion. There are subtleties in the distinctions between different patented pyrolysis technologies and the distinct outputs from different companies' processes that lead to these different classifications, but pyrolysis is generally recognized by local and state government agencies as a form of conversion technology and has therefore been included in this section.

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[74] Closed Loop Partners*, Global Directory of Molecular Recycling Technologies* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/CLP_Molecular-Recycling-Directory-2021.pdf

[75] Carbios, "Enzymatic recycling: Removing the constraints of current processes" March 17, 2022. https://www.carbios.com/en/enzymatic-recycling

V. Tournier et al., "An engineered PET depolymerase to break down and recycle plastic bottles" *Nature No. 580* pages 216-219 April 2020. https://doi.org/10.1038/s41586-020-2149-4

Gasification and pyrolysis convert mixed and multilayer plastics into refined hydrocarbons and petrochemicals. The hydrocarbon outputs can either be used as fuels or reprocessed into feedstocks, from which monomers, then polymers, and, finally, plastic items can be produced (see Fig. 2). Like depolymerization technologies, conversion technologies break the molecular bonds of plastics — but the outputs distinguish conversion from depolymerization: Conversion produces liquid or gaseous hydrocarbons, whereas depolymerization produces plastic monomers. Today, conversion is the most widely adopted of the chemical recycling technologies, largely due to support and adoption by the petrochemicals sector. Conversion also requires less pre-processing than purification[76] Relative to the other technology types, conversion is the most energy intensive, and has the lowest average material processing efficiency (42% – see Fig. 3)[77]

- **Inputs:** Proponents of conversion technologies note that they accommodate the widest array of plastics, including highly contaminated mixed materials and durable, bulky plastics that would otherwise be landfilled. Some technologies specialize in processing items considered to be undesirable contaminants in other systems such as purification and depolymerization. While conversion technologies do perform best with heterogenous waste streams of simple polymers, they can accommodate more contamination than purification or depolymerization technologies.[78]
- **Outputs:** Conversion technologies are commonly criticized because they are often used to produce fuels (plastics-to-fuel) rather than recycled plastics (plastics-to-plastics). Outputs differ between pyrolysis and gasification technologies (see below). There is limited publicly available information documenting the percentage of outputs as fuels versus those used to produce recycled plastics. Because the end product depends on market demand, feedstock composition, local markets, and other factors, there is no guarantee that these technologies will produce only recycled plastics.
- **Level of commercialization:** Over 40 pilot or commercial-stage companies operating globally use conversion technologies that include pyrolysis and gasification; at least 25 are headquartered, operate, or have partnerships in the U.S.[79] Conversion facilities are the most developed of the three technology types.

Below is a brief comparison of pyrolysis and gasification, with emphasis on their distinct outputs.

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[76] Closed Loop Partners, "Transitioning to a Circular System for Plastics" 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/AR-report-V23_final7.pdf.
[77] Ibid.
[78] Eunomia, *Chemical Recycling: State of Play* December 9, 2020. https://www.eunomia.co.uk/reports-tools/final-report-chemical-recycling-state-of-play/. Note that this report characterizes conversion technologies as thermal depolymerization.
[79] Closed Loop Partners, *Global Directory of Molecular Recycling Technologies* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/CLP_Molecular-Recycling-Directory-2021.pdf

Pyrolysis: Pyrolysis converts plastics into oils and waxes by heating them in an oxygen-free environment so that they do not burn.[80] Pyrolysis is a lower-temperature process than gasification (see below), which is why it primarily results in longer-chain hydrocarbons (oils).

- **Outputs:** The outputs of pyrolysis include oils and waxes, gases, and char (a waste product). The oils and waxes can either e burned (on-site or off-site) as fuels, or post-processed into plastic monomers through a separate process. Monomers can be repolymerized to produce polymers, which can be manufactured into new plastic items. The gases created through pyrolysis are often used to generate electricity, sometimes directly powering the pyrolysis facility as a replacement for other energy sources. Char is an ash-like waste product that is typically landfilled but can be burned to capture energy. It often contains the contaminants (additives, pigments, etc.) that were removed from the plastics during the pyrolysis process.

Incineration vs. Pyrolysis and Gasification
Heat-based conversion processes such as pyrolysis and gasification are sometimes equivocated with incineration. Technically, incineration is a distinct process that uses different temperature ranges than either pyrolysis or gasification to heat plastics and other waste materials in a high-oxygen environment so that they combust. Temperatures for incineration range from 590°C to 1200°C, whereas temperatures for pyrolysis and gasification range from approximately 500°C to 850°C.

The outputs of each process are also distinct: incineration produces waste gases and ash that cannot be converted back into plastics of any form and is disposed of in landfills.

EXAMPLE: Nexus Circular, a U.S. company with headquarters in Atlanta, Georgia, uses pyrolysis to process primarily post-industrial and post-commercial plastics, with an emphasis on plastic film.[81] Of the plastic inputs that Nexus processes, as much as 85% result in saleable oils and waxes. Nexus claims that 100% of these oils and waxes are used by its partners to produce like-new polyethylene resin with minimal post-processing, which can then be converted into new plastic items.[82] The pyrolysis process used by Nexus also produces char as a waste product, and non-condensable gas, which Nexus uses to power its plant.[83]

[80] Pooja Ghosh et al., "Life cycle assessment of waste-to-bioenergy processes: a review" pages 105-122 *Bioreactors* 2020.
Muhammad Saad Qureshi et al., "Pyrolysis of plastic waste: Opportunities and challenges" *Journal of Analytical and Applied Pyrolysis,* vol. 152 November 2020. https://doi.org/10.1016/j.jaap.2020.104804
Prabir Basu, "Pyrolysis" *Biomass Gasification, Pyrolysis and Torrefaction (Third Edition): Practical Design and Theory* 2018 pages 155-187. https://doi.org/10.1016/B978-0-12-812992-0.00005-4
[81] Jeffrey Gold, Founder & CEO, Nexus, presentation at Paper and Plastics Recycling Conference, November 5, 2021.
[82] Ibid.
[83] Ibid.

Technology Type	Average Processing Efficiency (Plastics to Plastics)	Average Non-Pellet Outputs
Purification	**91%**	**N/A**
Mechanical Recycling	**83%**	**N/A**
Depolymerization	**75%**	**18%**
Conversion	**42%**	**17%**

Figure 3: Average processing efficiency of each technology type, based on Closed Loop Partners independent research, using a small sample size for each technology: purification (2), depolymerization (4), conversion (3).[84]

Gasification: Gasification heats plastics in a low-oxygen environment to produce gaseous hydrocarbons, which can be separately processed into oils and waxes.[85] Gasification uses higher temperatures than pyrolysis, which results in shorter-chain hydrocarbons (primarily gases).

- **Outputs:** Gasification outputs include syngas (a gaseous mixture of carbon monoxide and hydrogen known as synthetic gas, or syngas), as well as char and slag by-products that become waste. The syngas can be used to produce methanol, which is a building block of plastics.

  EXAMPLE: Eastman has developed a "carbon renewal technology" that is capable of using most types of plastic waste as feedstock.[86] This technology produces syngas, which Eastman

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[84] Closed Loop Partners, *Transitioning to a Circular System for Plastics*, 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/AR-report-V23_final7.pdf "We calculated how much plastic resin would be produced by each technology category if we were to put 1,000 kilograms of plastic feedstock into the technology reactor. Each technology category's feedstock corresponds to their specifications and is therefore different from one another" (p. 83). Calculations are from Figure 24 (p. 84). Processing efficiency is calculated by dividing pellet product outputs by material sorting & rejection inputs to account for the pre-processing stage of each technology type.

[85] Yaning Zhang et al., "Gasification Technologies and Their Energy Potentials" pages 193-206 *Sustainable Resource Recovery and Zero Waste Approaches* 2019. https://doi.org/10.1016/B978-0-444-64200-4.00014-1
Andrew N. Rollinson "Fire, explosion and chemical toxicity hazards of gasification energy from waste" pages 273-280 *Journal of Loss Prevention in the Process Industries*, vol. 54 July 2018. https://doi.org/10.1016/j.jlp.2018.04.010
Paola Lettieri and Sultan M. Al-Salem, "Thermochemical Treatment of Plastic Solid Waste" pages 233-242 *Waste: A Handbook for Management* 2011. https://doi.org/10.1016/B978-0-12-381475-3.10017-8

[86] Eastman, *Carbon Renewal Technology* accessed January 4, 2022. https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Carbon-Renewal.aspx

uses exclusively to replace coal-based syngas feedstocks for plastics, paint additives, and textile fibers.[87] According to available LCA summaries commissioned by the company, Eastman's carbon renewal technology reduces the GHG emissions for production of syngas by 20% to 50%, depending on the composition of the plastic waste feedstock.[88]

[87] Eastman, *Project Data on Eastman Chemical Company's Chemicals-from-Coal Complex in Kingsport, TN* March 2003. https://netl.doe.gov/sites/default/files/netl-file/Eastman-Chemicals-from-Coal-Complex_0.pdf

[88] Eastman, *LCA Carbon Footprint Summary Report for Eastman Carbon Renewal Technology* June 10, 2020. https://www.eastman.com/Company/Circular-Economy/Resources/Documents/CRT-Technical-LCA-report.pdf.

Next Steps

This report is the first step in a larger discussion. It is intended to clarify some of the basic facts and initial questions on purification, depolymerization, and conversion technologies. A shared understanding among stakeholders will be critical to inform future dialogue with those working across the plastics lifecycle on whether and how these technologies can be addressed through EPR and other legislation, regulations, and permitting procedures. Below is a brief outline of some topics that warrant further discussion. It is our hope to address these items through structured dialogue with key stakeholders including environmental organizations, consumer goods companies, and plastics reclaimers, and incorporate them into a complementary report.

Refinement of the proposed criteria:

- What is the threshold of "over-production" of unnecessary and problematic plastics?
- How should "unnecessary and problematic plastics" [89] be defined so as to assess whether a given technology type is perpetuating their production?
- What is a realistic timeframe for commercial viability of a given facility or company?
- What existing or new standards should be used to measure cumulative pollution impacts and responsible materials management?
- What is an effective model for "robust community engagement and transparency" during permitting and siting processes?
- What are potential economic impacts and benefits to state and local governments from new recycling technologies, including chemical recycling?

Application of the proposed criteria to emerging technologies:

- To what extent do specific emerging technologies meet the proposed criteria?
- Are there existing, credible, third-party certification or other independent verification processes to support claims regarding a technology's efficiency, outputs, environmental impacts, and other factors?
- Who should develop LCAs or other assessments to determine the climate impacts and fossil fuel usage for various technology types, and how can the assumptions and parameters be standardized across assessments?
- Should the characterization of plastics-to-plastics technologies be revised to capture plastics-to-*products* processes (for example, the use of post-consumer plastics as feedstock to create composite lumber)?

Further detail on EPR recommendations:

- What has each state proposed in EPR legislation for packaging and other plastics-containing products regarding plastics-to-plastics or plastics-to-fuel technologies? When should

[89] U.S. Plastics Pact, "Problematic and Unnecessary Materials List" January 25, 2022. https://usplasticspact.org/problematic-materials/. This list, which is exclusive to non-reusable plastics, includes cutlery, PFAS, non-detectable pigments such as carbon black, opaque or pigmented PET bottles, oxo-degradable additives, PETG in rigid packaging, problematic label constructions, PS, PVC, stirrers, and straws.

purification, depolymerization, or conversion technologies be considered across EPR systems for different types of consumer goods?
- How should EPR legislation and other policies address bio-based plastic, and how does this compare with recycled plastics when chemical recycling technologies are used?

The following technical details were beyond the scope of this initial report:

- Impacts of various technologies on plastics recycling rates, and percentages of plastics currently on the market that can be managed through mechanical recycling, purification, depolymerization, and conversion technologies.
- How mechanical recycling, purification, depolymerization, and conversion can contribute to emerging post-consumer recycled content requirements and mandates, and how post-consumer recycled content resulting from each technology type can be independently verified.
- An overview of *mass balance* – a set of techniques for assessing the quantity of inputs vs. outputs for a given process – and how mass balance might be used to verify the outputs of each technology type and further inform compliance with post-consumer recycled content mandates.
- Details on the pre-processing steps needed for post-consumer plastics by each technology type.
- Details on the post-processing steps needed for each technology type – especially depolymerization and conversion – to obtain plastics from the outputs.
- Specifics on the chemical solvents and reagents used for various technologies and their known or potential human and environmental health impacts.
- Environmental and human health impacts for each type of technology, including wastes produced, water usage, energy usage, toxic emissions, and other factors, and how these compare with existing mechanical recycling technologies and potential upgrades to mechanical recycling facilities.
- Cost considerations for each technology type.

Further details on enzymatic depolymerization and waste-to-energy technologies.

For more information on these and other technical topics, we encourage readers to review the many comprehensive technical resources referenced throughout this report.

Key Terms

- **Advanced Recycling:** This term is often used interchangeably with "chemical recycling."
- **Chemical Recycling:** This term refers to a wide range of technologies including but not limited to pyrolysis, gasification, depolymerization, solvolysis, catalysis, reforming,

purification, hydrogenation, dissolution, and dehydrochlorination that convert waste plastic into various forms of feedstocks or intermediaries for plastics or fuels. These technologies fall into three major categories: purification, depolymerization, and conversion, each of which is defined herein.

- **Conversion:** Technologies (most commonly pyrolysis and gasification) that convert plastics into refined hydrocarbons and petrochemicals using heat and pressure, which can be used as fuel or reprocessed into plastics.
- **Depolymerization:** A technique that breaks the molecular bonds of plastics to recover building blocks (monomers or oligomers) that can be reconstructed into “like-new” resins. Also referred to as decomposition. The process is most commonly chemical but can be thermal or biological as well.
- **Energy Recovery**: According to the U.S. EPA, “Energy recovery from waste is the conversion of non-recyclable waste materials into useable heat, electricity, or fuel through a variety of processes, including combustion, gasification, pyrolization, anaerobic digestion, and landfill gas (LFG) recovery. This process is often called waste-to-energy (WTE).”[90]
- **Mechanical Recycling:** Traditional recycling, also known as mechanical recycling, involves sorting, crushing, washing, shredding, and pelletizing post-consumer or post-industrial plastics. This process does not change the polymer structure of the plastics. Some consider all mechanical recycling of plastics to be downcycling, because there is a loss of quality each time an item is recycled, which limits the overall number of times that plastics can be mechanically recycled before they degrade too far to be reused.
- **Molecular Recycling:** Another term used interchangeably with “advanced” and sometimes “chemical” recycling. Some who use this term indicate that it refers to a wider array of technologies than chemical recycling because it includes nonchemical means of transforming plastic waste at the molecular level (e.g., technologies that use enzymes to break down polymers into monomers). In that case, chemical recycling could be considered a subset of molecular recycling. However, most continue to use these terms interchangeably as there are no universally accepted definitions of these technologies. This report uses “chemical recycling” for simplicity — see definition above.
- **Plastics-to-Fuel:** Technologies that convert waste plastics to fuels (rather than plastic feedstocks). This includes any processes that create poor-quality or contaminated feedstocks, which are ultimately incinerated. This is technically distinct from “waste-to-energy” (see below) because it does not directly produce energy but merely the fuel with which energy is then generated through combustion. However, both waste-to-energy and plastics-to-fuel technologies involve the destruction of plastics. Plastics-to-fuel technologies are considered energy recovery and not recycling by PSI and our state and local government Members.
- **Plastics-to-Plastics (or Material-to-Material):** Technologies that convert waste plastics into plastic pellets or new plastic items. These technologies may still have some residual (waste) outputs. Mechanical recycling is one form of plastics-to-plastics recycling.

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[90] U.S. *EPA Sustainable Materials Management: Non-Hazardous Materials and Waste Management Hierarchy* July 5, 2022. https://www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy

- **Processing Efficiency:** As used in this report, the "processing efficiency" of a certain technology refers to the proportion of plastic inputs that are successfully converted into plastic resin pellets. An analogy to mechanical recycling would be the proportion of municipal solid waste (MSW) successfully sorted, cleaned, and baled for resale at a Materials Recovery Facility (MRF).[91] Another way to think about processing efficiency is that it reflects the inverse of yield loss (i.e., processing efficiency = 1 – yield loss).
- **Purification:** A technique that uses chemical solvents to dissolve plastics in a pressurized environment, separating and removing additives, dyes, and contaminants to produce "pure" resins. There is no change to the plastics at a molecular level.
- **Recycling:** The U.S. EPA defines "recycling" as "collecting and reprocessing a resource so it can be used again." An example is collecting aluminum cans, melting them down, and using the aluminum to make new cans or other aluminum products."[92] Many U.S. states have introduced their own definitions of recycling, which can address considerations such as whether waste-to-fuel technologies are considered recycling, and where recycling fits within the state's waste management hierarchy and priorities. It is generally (though not always) agreed that recycling does *not* include conversion of waste plastics into fuels (plastics-to-fuel technologies) or waste-to-energy processes.
- **Waste-to-Energy:** The process of burning municipal solid waste (MSW) to produce steam that generates electricity or heat. Some landfills also generate electricity by capturing methane gas from decomposing biomass.[93] Waste-to-energy technologies are considered energy recovery and not recycling by PSI and our state and local government Members.

Plastics-to-fuel technologies are considered energy recovery and not recycling by PSI and our state and local government Members; similarly, waste-to-energy technologies are considered energy recovery and not recycling.

[91] Closed Loop Partners, *Transitioning to a Circular System for Plastics* 2021. https://www.closedlooppartners.com/wp-content/uploads/2021/11/AR-report-V23_final7.pdf.

[92] U.S. EPA *Glossary of Climate Change Terms* 2017. https://19january2017snapshot.epa.gov/climatechange/glossary-climate-change-terms_.html

[93] U.S. Energy Information Administration *Biomass explained: Waste-to-energy (Municipal Solid Waste)* November 26, 2021. https://www.eia.gov/energyexplained/biomass/waste-to-energy.php