What Is Happening in Chemical Recycling?

Overview of the Various Processes and Suppliers

For a long time, chemical recycling was considered an unfinished addition to established material processes. In the meantime, however, some technologies are making the leap into large-scale industrial use: an overview of the various processes and providers.

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In the European Union (EU), 30 million t of plastic waste are generated annually, of which about 29 million t are collected again. Overall, 32 % of the collected post-consumer plastics are recycled. The significantly larger share, however, ends up in waste incineration plants or landfills. With the "Green Deal", the EU has presented an ambitious industrial strategy – the EU is to be climate neutral by 2050 – which, among other things, provides for the establishment of a clean circular economy. Among other things, all packaging on the EU market is to become reusable or recyclable. A recycling rate of 70 % for all packaging materials is already planned for the year 2030. In order to achieve these new targets, far-reaching measures and considerable investments are required. In addition to conventional mechanical recycling, a wide range of chemical recycling technologies are also coming into focus (**Fig. 1**).

As the collection and recycling system is not yet cost-efficient and the quality of recyclates is often not yet sufficient to replace new plastics on a large scale, current mechanical recycling has clear limitations. Chemical recycling technologies represent alternative ways of dealing with end-use waste. They are able to process waste streams that cannot be mechanically recycled (**Fig. 2**) and thus offer the possibility of recycling plastic waste that previously was sent to energy recovery or landfilling. This applies, for example, to mixed waste streams and heavily contaminated or multi-layered materials. As the technologies are still at an early stage of development, suppliers face the challenge of proving their potential.

Waiting for a Start Signal

Many companies have already developed and partly implemented chemical recycling technologies at small-scale. The changed political framework conditions and voluntary commitments of the large polymer and product manufacturers are

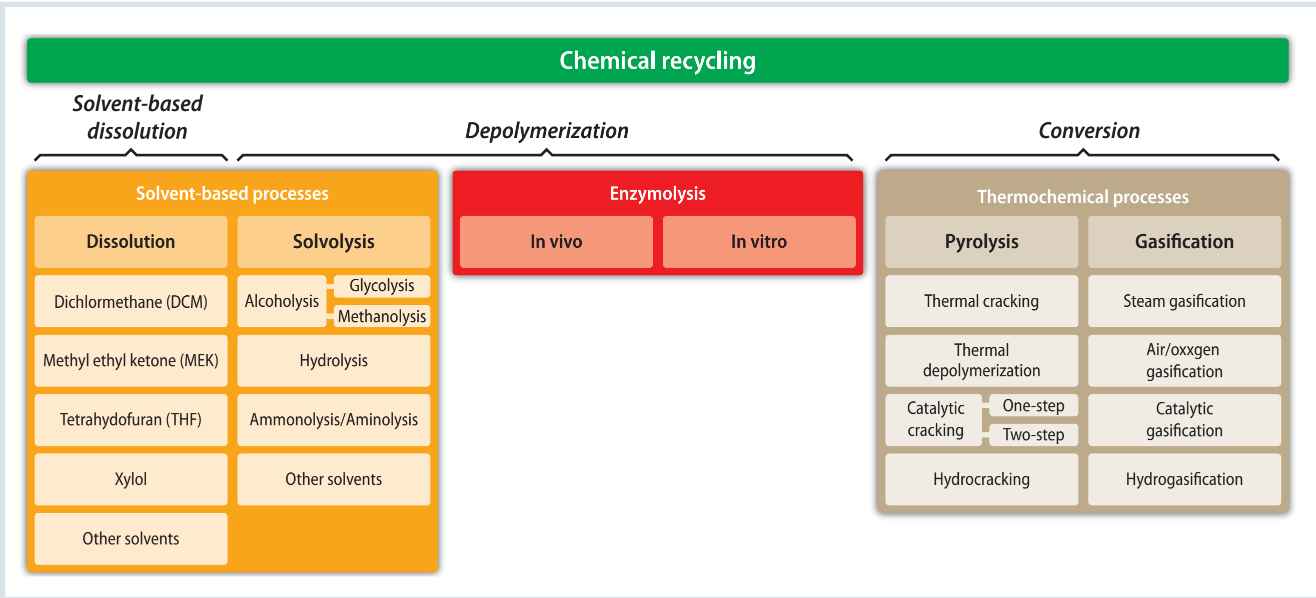

Fig. 1. Overview of the different methods for chemical recycling of plastic waste: different processes are available for all approaches Source: nova-Institut; graphic: © Hanser

encouraging faster development. Several companies have recently announced the construction of large-scale plants, some of which are expected to be operational as early as 2021. A number of these projects are based on collaborations and joint ventures, e.g. between plastics producers and waste management companies, from which technology and supply chain synergies are expected to emerge. While the entire sector is characterized by great innovation dynamics and considerable investment interest, there is great uncertainty due to the lack of legal regulations. In Europe, the chemical recycling sector is waiting for clear political framework conditions as a starting signal. The next decisive steps in this direction are expected from politicians, which will significantly increase the dynamics in the recycling sector. Accordingly, more clarity is to be created at the European level on the crediting of recycling quotas for the different processes. According to information from Brussels so far, a corresponding assessment is to be made on the basis of life cycle assessments. The greenhouse gas reduction compared to fossil polymers must then reach a minimum value that has not yet been defined.

The Available Technologies,

In a market report, the nova-Institute has investigated which chemical recycling processes are currently being developed and how far they have come. This also breaks down which companies are working on the various technologies [1]. The chemical recycling processes developed so far are based on three fundamentally different mechanisms: solvent-based dissolution, depolymerization, and conversion. »

Technology		Input (feedstock)
Solvent-based	Dissolution	PE, PP, PS, PVC, **PLA**
	Solvolysis	PA, PC, PET, POM, PU, **CA, PBAT, PBS, PHA, PLA**
Thermochemical	Pyrolysis	Broad spectrum of polymers such as PE, PP, PET, PU, PS, PMMA, **PHA, PLA**, rubber and biowaste
	Gasification	Potentially all kind of plastic wastes, rubber, biowaste
Biochemical	Enzymolysis	PET, PU, (PA, PE, PS), **CA, PHA, PLA**

Table 1. Summary of available recycling technologies and their inputs: bio-based polymers are marked in bold, bio-based drop-in polymers are not specifically highlighted. They can be treated in the same way as their fossil counterparts. Polymers in brackets indicate certain limitations for the process Source: nova-Institut

Company Profil

The **nova-Institute** is a private and independent research institute founded in 1994. It provides research and consultancy focusing on the transformation process of the chemical and material industries to renewable carbon through the substitution of fossil carbon with biomass, direct CO_2 use and recycling. The institute's more than 40 staff members deal with the topics of renewable raw materials, technologies and markets, economics and politics, sustainability, communication and strategy development. A special focus is on life cycle assessments for renewable chemicals and plastics and for chemical recycling.

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Dissolution: Selective Separation of Thermoplastics

Dissolution allows the removal of contaminants from plastics without changing the molecular structure of the polymer. Depending on the underlying definition or classification system, it is therefore debatable whether this is a chemical, physical or mechanical recycling process. The method is based on the selective dissolution and separation of a target polymer from plastics in a suitable solvent. Subsequently, non-dissolved components, e.g. additives or coloring substances, are removed and the target polymer is precipitated from the solvent. The mechanism of dissolution is limited to thermoplastics and can be applied to both fossil and bio-based polymers (**Table 1**). The nova-Institute has identified six companies worldwide (**Table 2**) that offer technologies with capacities of up to 8000 t/a [1]. Higher capacities are expected in the near future. The company PureCycle Technologies, for example, plans to start up a commercial plant in Ohio in the USA with a capacity of 48,000 t/a this year. The technology used can process polypropylene (PP) waste and includes decontamination and deodorization processes. They are developed by the Procter & Gamble Company and further developed through the partnership with PureCycle.

Depolymerization: Breakdown and Resynthesis

In contrast to dissolution, the **depolymerization** involves the breakdown of the polymer into its building blocks, i.e. monomers, dimers or oligomers. After the breakdown, the obtained building blocks often have to be separated from the remaining polymer components such as additives, coloring substances or other non-target polymers before new polymers can be synthesized by polymerization. In general, depolymerization can be initiated by heat energy, referred to as thermal depolymerization, or by a combination of heat energy and chemicals (solvolysis), or enzymes (enzymolysis).

Solvolysis can be used to process a whole range of fossil-based and bio-based polymers (**Table 1**). For this process, the nova-Institute identified 14 companies worldwide (**Table 2**) that offer corresponding technologies with capacities of up to 10,800 t/a [1]. Of particular note is a European consortium with the project name PUReSmart, which is made up of international partners. Among them are Ayming, Covestro, Ecoinnovazione, Ghent University, KU Leuven, Recticel, Redwave, the University of Castilla-La Mancha (UCLM) and WeylChem InnoTec. The project seeks ways to transition from the linear life cycle of polyurethane (PU) products to a circular economic model that spans the entire value chain of PU reprocessing. For the chemolysis technology part, Covestro, KU Leuven and UCLM are involved. The process has so far achieved a yield of 98 % polyether polyol with a purity of 97 %.

Compared to all the other processes mentioned here, **enzymolysis** is still at a very early stage of development, which is also reflected in the still small number of companies offering corresponding technologies (**Table 2**). Theoretically, a range of fossil-based and bio-based polymers are suitable for the process. However, for cer-

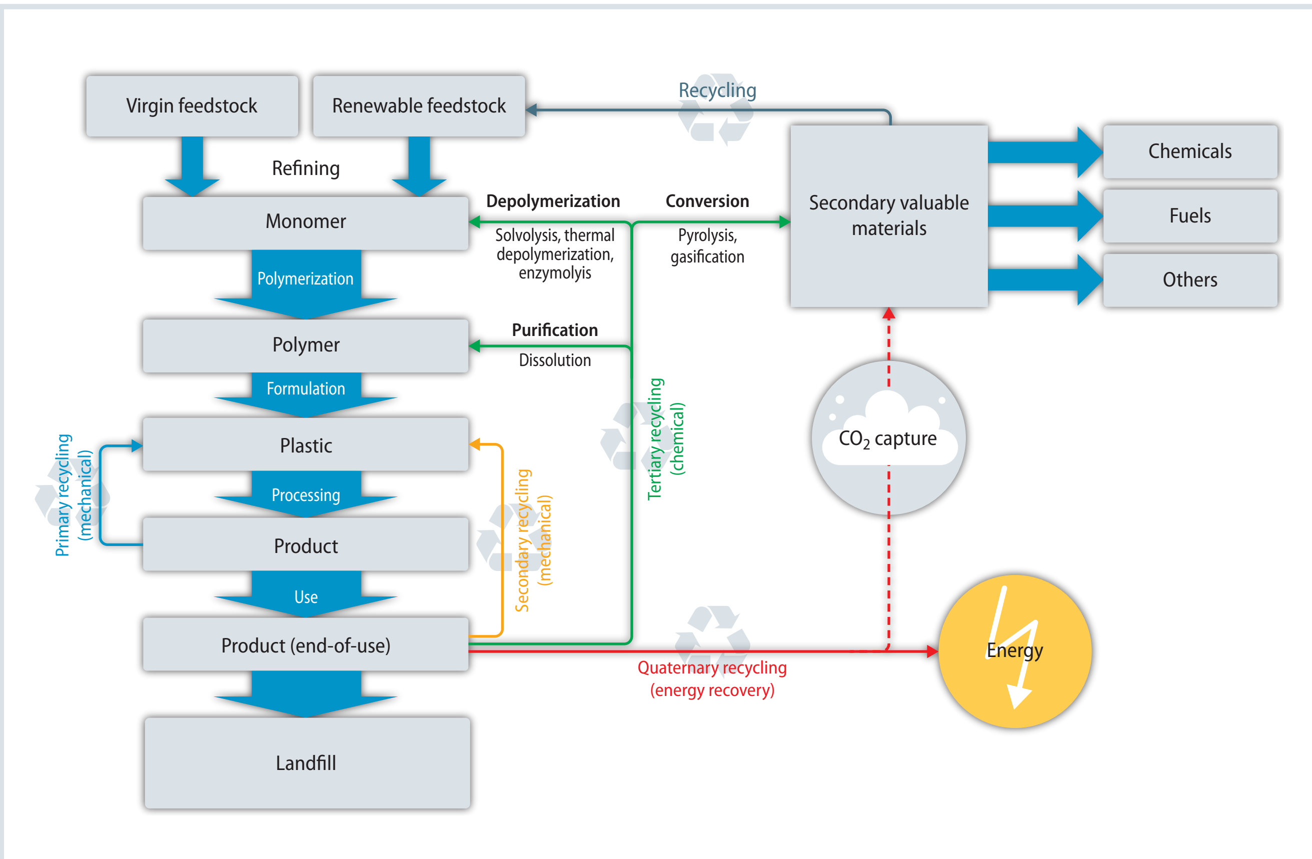

Fig. 2. Different recycling processes exist for the treatment of plastics. The products of the processes can be used as raw materials at different levels of plastics production Source: nova-Institut; graphic: © Hanser

Country	Technology					
	Dissolution	Solvolysis	Pyrolysis	Gasification	Enzymolysis	All
Australia	-	-	3	-	-	3
Austria	-	-	1	-	-	1
Belgium	-	1	-	-	-	1
Canada	1	1	3	2	-	7
Czech Republic	-	-	1	-	-	1
Europe (consortium)	-	1	1	-	-	2
Finland	-	-	3	-	-	3
France	-	1	-	-	1	2
Germany	2	-	3	-	-	5
Hungary	-	-	1	-	-	1
India	-	-	2	-	-	2
Italy	-	2	1	-	-	3
Japan	-	-	1	-	-	1
Luxembourg	-	-	1	-	-	1
Netherlands	1	2	4	-	-	7
Norway	-	-	1	-	-	1
Poland	-	-	1	-	-	1
Spain	-	-	1	1	-	2
Sweden	-	-	1	-	-	1
Switzerland	-	2	-	-	-	2
Thailand	-	-	1	-	-	1
United Kingdom	1	-	3	1	-	5
USA	1	4	11	4	-	20
All	6	14	44	8	1	73

Table 2. Number of chemical recycling technology providers by country: especially in North America and Europe, many companies are working on chemical recycling Source: nova-Institut

tain polymers such as polyamide, polyethylene, and polystyrene, certain limitations are to be expected in terms of feasibility (**Table 1**). The French company Carbios is currently planning the construction of a demonstration plant with a capacity of 50,000 to 100,000 t/a. Advantages of enzymolysis are relatively mild reaction conditions (e.g. atmospheric pressure, room temperature) and the potential for fine-tuning through enzyme and metabolic engineering.

Conversion: Raw Materials for Plastics, Chemicals and Fuels

Plastic waste is converted by thermochemical processes such as pyrolysis or gasification. In these methods, polymers are broken down and converted into simpler molecules. The resulting molecules are chemically different from the polymer building blocks that result from depolymerization. The substances obtained are often liquids or gases that can be used as feedstock for the production of plastics, chemicals and fuels [2], although further upstream processing steps (refining) may be required.

Pyrolysis can be applied to a whole range of fossil- and bio-based polymers (**Table 1**). Compared to the solvent-based processes, increased heterogeneity of the waste, including contamination through bio-waste, is less problematic. The nova-Institute was able to identify 44 companies worldwide (**Table 2**) that offer corresponding technologies with capacities of up to 38,000 t/a [1]. The pyrolysis oil obtained in the process requires further processing steps to be able to use it for the production of polymers. Such efforts are being made, for example, in the ChemCycling project, in which BASF and pyrolysis start-up Quantafuel plan to produce commercial products from chemically recycled plastics.

Compared to pyrolysis, **gasification** can process an even wider range of plastic waste, including increased contamination from biowaste (**Table 1**). Worldwide, the nova-Institute has identified eight companies (**Table 2**) that offer these technologies with capacities of up to 100,000 t/a [1]. In addition to the production of syngas, technologies are also available that couple gasification to a gas fermentation process to synthesize ethanol or other chemicals from the syngas produced.

Neither mechanical nor chemical recycling alone can build a circular economy. However, the combination of methods has the potential to transform the entire plastics industry, including waste management, towards a full circular economy. The available technologies offer a wide range of possibilities to process all waste streams. The targets set in the EU Plastics Strategy are not achievable without the introduction of further recycling technologies. Therefore, a modern, sustainable plastics industry that fits into a circular economy cannot do without chemical recycling. ■

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Michael Carus founded the nova-Institut in 1994 with other scientists and has been Managing Director since then. In 2020, Carus initiated the Renewable Carbon Initiative (RCI; renewable-carbon-initiative.com). It is dedicated to replacing fossil carbon sources with renewable ones.

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