Status, potentials and risks of Chemical recycling of waste plastics

Study on the evaluation of approaches for the feedstock recycling of plastic waste

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Abstract

Chemical recycling aims to convert plastic waste into chemicals or raw materials for the chemical industry using different technologies. Process approaches for chemical recycling of plastics include solvolysis, liquefaction, pyrolysis and gasification. With solvolysis, polymers are processed into monomers or secondary raw materials using solvents. Liquefaction is the thermal conversion of polymers into smaller molecules at higher temperatures. Products are mainly oil and a solid residue. Pyrolysis is the thermal conversion of polymers into smaller molecules in the absence of oxygen. Products from pyrolysis are mainly gas, oil and a solid residue. The conversion of polymers into a gas at high temperatures with a limited amount of oxygen is called gasification. The gas (also called syngas) can be used as a raw material for further processing in the chemical industry. However, an internationally recognized or legal definition of chemical recycling is not yet established, but necessary in order to ensure compatibility of different legal regulations and planning security for businesses.

Not only is a legal definition missing, chemical recycling of plastics as a whole cannot yet be described as a state-of-the-art technology. Particularly in the case of contaminated input material, problems occur in practice. Consequently, many attempts to implement a process fail at the development stage or during commissioning. Due to the complexity of the processes in connection with the demanding feedstocks, it is not to be expected that chemical recycling can reach similar availability and operational times as waste incineration in the near future.

For those waste streams for which mechanical recycling is an option, it generally performs better than any other recycling or recovery option in terms of CO_2 emissions. However, LCA studies consistently postulate an ecological benefit of chemical recycling on global warming potential (CO_2 emissions) in comparison to waste incineration, but it should be noted that many studies do not consider the treatment or disposal of by-products and residual materials of chemical recycling. Since the amounts of generated residues can be quite relevant (depending on the quality of the waste feed), this simplifying assumption may distort the assessment significantly. A general problem with life cycle assessments of new technologies is the lack of experience and the often unrealistic underlying assumptions.

Besides the reduction of climate-affecting emissions, another main reason for the development of chemical recycling processes is the option for a detoxification of the recycled material flow. This statement is correct from a chemical-physical point of view, but in practice it is strongly dependent on the specific conditions. Particularly in the case of heavily contaminated waste fractions, the further processing of the products generated is very difficult. It has yet to be proven that the postulated detoxification potential of chemical recycling processes can actually be realized and that contamination is not merely shifted to other products or residues. This appears to be a challenge,

particularly in the case of small-scale processes that can be implemented on a decentralized basis (e.g. solvolysis or pyrolysis).

Furthermore, the operation of chemical recycling equipment is technically very demanding. Therefore, the established rules of engineering should be applied with foresight and accuracy, and only suitable and appropriately processed feedstocks should be used.

It has been shown that the operation of such plants ideally takes place in conjunction with refinery or chemical sites, in order to ensure high-quality recovery of all products (especially gases) and to be able to dispose of residual materials in the existing facilities as well. This increases the achievable yields and minimizes costs and effort for residue disposal. Operation at sites of MSWI plants could have advantages for smaller chemical recycling installations for the same reason.

Due to the high expenditure for the preparation of the input materials and the cleaning of the generated products, together with continuously occurring operating problems, high economic burdens are constantly created, which cannot be eliminated even in the long term. In addition, suitable input materials for the chemical recycling processes are limited. Nevertheless, due to the socio-political situation and the available financial resources, a large number of processes is currently under development and corresponding pilot plants are realized. The opportunities and risks that arise are dependent on the specific environment and the general conditions of the respective countries. While direct negative impacts of chemical recycling process operation on the environment are unlikely, provided that the usual plant and emission standards are respected, the establishment of structures for chemical recycling of plastics in countries with insufficient infrastructures and governmental controls to ensure environmentally sound operation is viewed with particular concern. It could result in uncontrollable environmental risks from the plant operation and could also encourage the export of plastic waste for recycling, with the risk of ending up in the environment.

Regarding the approach for quantifying recycled content in products from chemical recycling, the need to use a mass balance approach is undeniable as a physical tracing of recycled material is next to impossible in common production processes of the chemical industry. The use of the "rolling average" or "polymers only" approach is recommended in order to reflect the physical conditions as closely as possible. As a general rule, accounting across company sites or even national borders should be rejected in order to prevent dubious practices.

Additionally, a general definition of end-of-waste criteria for products from chemical recycling is necessary in order to ensure equal opportunities for all chemical recycling plants as well as planning security for companies. This also would help administrations in the authorization issuing process.

Currently, the technical feasibility and economic viability is not proven and the environmental assessment is ambiguous. No excessive subsidies should be provided for chemical recycling of plastics, as there is a risk to lock in on disadvantageous processes and infrastructure.

Under favorable general conditions and assuming the operation of chemical recycling plants follows established rules of engineering and principles of environmental and emissions legislation, chemical recycling processes may contribute to the recycling of plastic waste.

Kurzfassung

Das Chemische Recycling zielt darauf ab, Kunststoffabfälle mit Hilfe verschiedener Technologien in Chemikalien oder Rohstoffe für die chemische Industrie umzuwandeln. Zu den Verfahrensansätzen für das chemische Recycling von Kunststoffen gehören Solvolyse, Verölung, Pyrolyse und Gasifizierung. Bei der Solvolyse werden die Polymere mit Hilfe von Lösungsmitteln zu Monomeren oder Sekundärrohstoffen verarbeitet. Verölung ist die thermische Zerlegung von Polymeren bei hohen Temperaturen zu Polymerbruchstücken. Die Produkte der Verölung sind hauptsächlich Öl und ein fester Rückstand. Pyrolyse bezeichnet die thermische Umwandlung von Polymeren in Polymerbruchstücke unter Ausschluss von Sauerstoff. Die entstehenden Produkte sind hauptsächlich Gas, Öl und ein fester Rückstand. Die Umwandlung von Polymeren in ein Gas bei hohen Temperaturen und einer begrenzten Menge an Sauerstoff wird als Gasifizierung bezeichnet. Das Gas (auch Synthesegas genannt) kann als Rohstoff für die Weiterverarbeitung in der chemischen Industrie verwendet werden. Eine international anerkannte oder Legaldefinition des Chemischen Recyclings ist jedoch noch nicht etabliert, aber notwendig, um die Übereinstimmung verschiedener gesetzlicher Regelungen und die Planungssicherheit für Unternehmen zu gewährleisten.

Es fehlt jedoch nicht nur eine anerkannte Definition, chemisches Recycling von Kunststoffen kann insgesamt auch noch nicht als Stand der Technik bezeichnet werden. Insbesondere bei verunreinigtem Ausgangsmaterial treten in der Praxis Probleme auf. Viele Umsetzungsversuche scheitern bereits in der Entwicklungsphase oder bei der Inbetriebnahme. Aufgrund der Komplexität der Prozesse in Verbindung mit anspruchsvollen Einsatzstoffen ist nicht zu erwarten, dass das chemische Recycling in naher Zukunft ähnliche Verfügbarkeiten und Betriebszeiten wie die Müllverbrennung erreichen kann.

Das werkstoffliche Recycling schneidet für Abfallströme, für die es technisch einsetzbar ist, in Bezug auf die CO_2-Emissionen im Allgemeinen besser ab als alle anderen Recycling- oder Verwertungsoptionen. Im Vergleich zur Abfallverbrennung wird in Ökobilanzstudien in Bezug auf das Treibhausgaspotenzial (CO_2-Emissionen) durchweg ein ökologischer Vorteil des chemischen Recyclings prognostiziert, wobei anzumerken ist, dass viele Studien die Behandlung oder Entsorgung von Nebenprodukten und Reststoffen des chemischen Recyclings nicht berücksichtigen. Da die Menge der anfallenden Rückstände (je nach Qualität des Abfallinputs) durchaus relevant sein kann, führt diese vereinfachende Annahme zu teilweise erheblichen Verzerrungen der Bewertung. Ein allgemeines Problem bei der Ökobilanzierung von neuen Technologien ist, dass Erfahrungswerte fehlen und oft unrealistische Annahmen getroffen werden

Neben der Verringerung klimawirksamer Emissionen ist die Möglichkeit Schadstoffe aus dem recycelten Stoffstrom auszuschleusen ein weiterer Hauptgrund für die Entwicklung chemischer Recyclingverfahren. Aus chemisch-physikalischer Sicht ist dies sicher möglich, in der Praxis ist die Möglichkeit der Schadstoffentfrachtung aber stark von den spezifischen Bedingungen abhängig. Insbesondere bei stark kontaminierten Abfallfraktionen ist die Weiterverarbeitung der anfallenden Produkte sehr aufwendig. Es muss erst noch ein Nachweis erbracht werden, dass das postulierte Schadstoffentfrachtungspotenzial chemischer Recyclingverfahren tatsächlich realisiert werden kann und die Kontaminationen nicht lediglich auf andere Produkte oder Rückstände verlagert werden. Dies könnte insbesondere bei dezentralen Verfahren auf Kleinanlagen (z.B. Solvolyse oder Pyrolyse) eine Herausforderung darstellen.

Zudem ist der Betrieb von chemischen Recyclinganlagen technisch sehr anspruchsvoll. Daher sollten die allgemein anerkannten Regeln der Technik sorgfältig angewandt und nur geeignete und entsprechend aufbereitete Einsatzstoffe verwendet werden.

Der Betrieb chemischer Recyclinganlagen sollte idealerweise im Verbund mit Raffinerie- oder Chemiestandorten erfolgen, um eine qualitativ hochwertige Rückgewinnung aller Produkte (insbesondere Gase) zu gewährleisten und Reststoffe auch in den bestehenden Anlagen entsorgen zu können. Dies erhöht die erzielbaren Ausbeuten und minimiert die Kosten sowie den Aufwand für die Reststoffentsorgung. Der Betrieb an Standorten von Müllverbrennungsanlagen könnte aus dem gleichen Grund Vorteile für kleinere chemische Recyclinganlagen bieten.

Aufgrund des hohen Aufwands für die Aufbereitung der Einsatzstoffe und die Aufbereitung der erzeugten Produkte, verbunden mit häufig auftretenden Betriebsproblemen, entstehen hohe Kosten, die auch langfristig voraussichtlich nicht zu vermeiden sind. Hinzu kommt, dass geeignete Einsatzstoffe für die chemischen Recyclingverfahren begrenzt sind. Dennoch werden aufgrund der gesellschaftspolitischen Situation und der gegebenen finanziellen Möglichkeiten derzeit eine Vielzahl von Verfahren entwickelt und entsprechende Pilotanlagen realisiert. Die sich daraus ergebenden Chancen und Risiken sind abhängig vom spezifischen Umfeld und den Rahmenbedingungen der jeweiligen Länder. Während direkte negative Auswirkungen des Betriebs von chemischen Recyclingverfahren auf die Umwelt unwahrscheinlich sind, sofern die üblichen Anlagen- und Emissionsstandards eingehalten werden, ist die Einrichtung von Strukturen für das chemische Recycling von Kunststoffen in Ländern mit unzureichender Infrastruktur und fehlenden staatlichen Kontrollen zur Gewährleistung eines umweltverträglichen Betriebs besonders kritisch zu beobachten. Solche Entwicklungen könnten zu unkontrollierbaren Umweltrisiken durch den Betrieb der Anlagen führen und auch die Ausfuhr von Kunststoffabfällen zur Wiederverwertung begünstigen, mit dem Risiko, dass diese letztendlich doch unkontrolliert in die Umwelt gelangen.

Zur Quantifizierung des Rezyklatanteils in Produkten aus dem chemischen Recycling ist die Verwendung eines Massenbilanzansatzes notwendig, da eine physische Rückverfolgung des Rezyklats in den üblichen Produktionsprozessen der chemischen Industrie nahezu unmöglich ist. Es wird empfohlen, den Ansatz des "rolling average" oder "polymers only" zu verwenden, um die physischen Bedingungen so gut wie möglich widerzuspiegeln. Eine standort- oder gar länderübergreifende Bilanzierung sollte generell abgelehnt werden, um unseriöse Praktiken zu verhindern.

Darüber hinaus ist eine generelle Definition von Kriterien für das Abfallende von Produkten aus dem chemischen Recycling notwendig, um Chancengleichheit für alle chemischen Recyclinganlagen sowie Planungssicherheit für Unternehmen zu gewährleisten. Dies würde auch den Behörden in Genehmigungsverfahren helfen.

Derzeit sind die technische Machbarkeit und die wirtschaftliche Tragfähigkeit nicht erwiesen, und die Umweltbewertung ist unklar. Für das chemische Recycling von Kunststoffen sollten keine übermäßigen Subventionen gewährt werden, da die Gefahr besteht, dass nachteilige Verfahren und Infrastrukturen festgeschrieben werden.

Unter günstigen Rahmenbedingungen und unter der Voraussetzung, dass chemische Recyclinganlagen nach dem Stand der Technik betrieben werden und Umweltstandards eingehalten werden, können chemische Recyclingverfahren zum Kunststoffrecycling beitragen.

Résumé

Le recyclage chimique vise à transformer les déchets plastiques en produits chimiques ou en matières premières pour l'industrie chimique au moyen de diverses technologies. Les procédés pour le recyclage chimique des plastiques comprennent la solvolyse, la liquéfaction, la pyrolyse et la gazéification. Dans le cas de la solvolyse, les polymères sont transformés en monomères ou en matières premières secondaires à l'aide de solvants. La liquéfaction est la conversion thermique des polymères en molécules plus petites dans une cuve d'agitation à haute température. Les produits sont principalement de l'huile et un résidu solide. La pyrolyse est la conversion thermique de polymères en molécules plus petites dans un réacteur de pyrolyse, en l'absence d'oxygène. Les produits issus de la pyrolyse sont principalement du gaz, de l'huile et un résidu solide. La conversion des polymères en gaz à des températures élevées et avec une quantité limitée d'oxygène est appelée gazéification. Le gaz (également appelé syngas) peut être utilisé comme matière première pour un traitement ultérieur dans l'industrie chimique. Une définition juridique ou reconnue au niveau international du recyclace chimique n'a pas encore été établie, mais elle est nécessaire pour assurer la compatibilité des différentes réglementations juridiques et la planification de la sécurité pour les entreprises.

Non seulement il n'existe pas de définition juridique, mais le recyclage chimique des plastiques dans son ensemble ne peut pas encore être qualifié d’état de l’art. Des problèmes se posent dans la pratique, en particulier dans le cas de matériaux d'entrée contaminés. Par conséquent, de nombreuses tentatives de mettre en œuvre un processus échouent au stade du développement ou lors de la mise en service. En raison de la complexité des processus liés aux matières premières exigeantes, il ne faut pas s'attendre à ce que le recyclage chimique atteigne une disponibilité et des durées d'exploitation similaires à celles de l'incinération des déchets dans un avenir proche.

Pour les flux de déchets pour lesquels le recyclage mécanique est une option, il est généralement plus performant que toute autre option de recyclage ou de valorisation en termes d'émissions de CO2. Toutefois, les études ACV affirment de manière systématique que le recyclage chimique présente un avantage écologique sur le potentiel de réchauffement planétaire (émissions de CO2) en comparaison avec l'incinération des déchets, mais il convient de noter que de nombreuses études ne tiennent pas compte du traitement ou de l'élimination des sous-produits et des matières résiduelles du recyclage chimique. Étant donné que les quantités de résidus générés peuvent être très importantes (en fonction de la qualité des déchets), cette hypothèse simplificatrice peut fausser l'évaluation de manière significative. L'un des problèmes généraux de l’ACV des nouvelles technologies est le manque de données empiriques et que souvent des hypothèses irréalistes sont faites.

Outre la réduction des émissions ayant une incidence sur le climat, la possibilité de détoxifier le flux de matières recyclées est une autre raison majeure du développement des processus de recyclage chimique. Cette affirmation est correcte d'un point de vue physico-chimique, mais dans la pratique, elle dépend fortement des conditions spécifiques. En particulier dans le cas de fractions très contaminées, le traitement ultérieur des produits générés est très difficile. Il reste à prouver que le potentiel de détoxification postulé des processus de recyclage chimique peut réellement être réalisé et que la contamination n'est pas simplement déplacée vers d'autres produits ou résidus. Cela semble être un défi, en particulier dans le cas des processus à petite échelle qui peuvent être mis en œuvre de manière décentralisée (par exemple, la solvolyse ou la pyrolyse).

En outre, le fonctionnement des équipements de recyclage chimique est techniquement très exigeant. Il convient donc d'appliquer les règles d'ingénierie établies avec prévoyance et précision, et de n'utiliser que des matières premières appropriées et transformées de manière convenable.

Il a été démontré que l'exploitation de telles installations se fait idéalement en conjonction avec des sites de raffinage ou de transformation chimique, afin de garantir une récupération de haute qualité de tous les produits (en particulier les gaz) et de pouvoir également éliminer les matières résiduelles dans les installations existantes. Cela permet d'augmenter les rendements réalisables et de minimiser les coûts et les efforts liés à l'élimination des résidus. Pour la même raison, l'exploitation sur des sites d'incinération des déchets solides municipaux pourrait présenter des avantages pour les installations de recyclage chimique plus petites.

Les dépenses élevées liées à la préparation des matières premières et au nettoyage des produits générés, ainsi que les problèmes d'exploitation qui surviennent en permanence, entraînent constamment des charges économiques importantes qui ne peuvent être éliminées, même à long terme. En outre, les matières premières appropriées pour les processus de recyclage chimique sont limitées. Néanmoins, en raison de la situation socio-politique et des ressources financières disponibles, un grand nombre de processus sont actuellement en cours de développement et les installations pilotes correspondantes sont mises en place. Les opportunités et les risques qui se présentent dépendent de l'environnement spécifique et des conditions générales des pays respectifs. Bien qu'il soit peu probable que l'exploitation des procédés de recyclage chimique ait des incidences négatives directes sur l'environnement, à condition que les normes habituelles en matière d'installations et d'émissions soient respectées, la mise en place de structures de recyclage chimique des matières plastiques dans des pays où les infrastructures et les contrôles gouvernementaux sont insuffisants pour garantir une exploitation respectueuse de l'environnement, est considérée comme particulièrement préoccupante. Elle pourrait entraîner des risques environnementaux incontrôlables liés à l'exploitation des installations et encourager l'exportation de déchets plastiques à des fins de recyclage, avec le risque qu'ils se retrouvent dans l'environnement.

En ce qui concerne la méthode de quantification du contenu recyclé dans les produits issus du recyclage chimique, il est indéniable qu'il est nécessaire d'utiliser une approche par bilan de mass, car le traçage physique des matériaux recyclés est pratiquement impossible dans les processus de production courants de l'industrie chimique. L'utilisation de l'approche "rolling average" ou "polymers only" est recommandée afin de refléter les conditions physiques le plus fidèlement possible. En règle générale, une comptabilité qui couvre plusieurs sites d'une entreprise, voire plusieurs pays, doit être rejetée afin d'éviter les pratiques douteuses.

En outre, une définition générale des critères de fin de la propriété de déchet pour les produits issus du recyclage chimique est nécessaire afin de garantir l'égalité des chances pour toutes les usines de recyclage chimique ainsi que la sécurité de la planification pour les entreprises. Cela serait également utile aux administrations dans le cadre de leurs procédures pour la délivrance d'autorisations.

Actuellement, la faisabilité technique et la viabilité économique ne sont pas prouvées et l'évaluation environnementale est ambiguë. Le recyclage chimique des plastiques ne doit pas faire l'objet de subventions excessives, car il existe un risque d'enfermement dans des processus et des infrastructures désavantageux.

Dans des conditions générales favorables et en supposant que les usines de recyclage chimique respectent les règles d'ingénierie et les principes de la législation en matière d'environnement et d'émissions établies, les processus de recyclage chimique peuvent contribuer au recyclage des déchets plastiques.

List of abbreviations

ABS	Acrylonitrile butadiene styrene
AC	Activated carbon
AP	Acidification potential
ASA	Acrylonitrile styrene acrylate
AS	Acid scrubber
ARD	Abiotic resource depletion
BASF	Badische Anilin- & Sodafabrik
BAT	Best Available Techniques
BGL	British Gas/Lurgi
BREF	Best Available Techniques Reference Documents
CED	Cumulative energy demand
CCU	Carbon capture and utilization
CCS	Carbon capture and storage
Cefic	Conseil Européen des Fédérations de l'Industrie Chimique (European Chemical Industry Council)
CR	Chemical recycling
CK	Cement kiln
DECHEMA	Gesellschaft für Chemische Technik und Biotechnologie e.V. (Society for Chemical Engineering and Biotechnology)
DKR360	Specific plastic waste fraction
EN	Energy use
EOL	End of live
EP	Eutrophication potential
EPS	Expanded polystyrene
ESP	Electrostatic precipitator
ET	Ecotoxicity
FFP	Fossil fuel potential
FRD	Fossil resource depletion
GWP	Global warming potential
HDPE	High-density polyethylene (auch PE-HD)
HIPS	High impact polystyrene
HM	Heavy metals
HT	Human toxicity
HTP	High temperature pyrolysis
HVC	High value chemicals (ethylene, propylene, butene, butadiene, aromates)
ICCA	International Council of Chemical Associations
INC	Intergovernmental Negotiating Committee on Plastic Pollution
ISCC	International sustainability & carbon certification
ISO	International Organization for Standardization
JRC	Joint Research Centre
LCA	Life cycle assessment
LDPE	Low-density polyethylene (auch PE-LD)
LF	Landfill
LPG	Liquefied petroleum gas

LTP	Low temperature pyrolysis
LWP	Light-weight packing
MBT	Mechanical-biological treatment
MEG	Monoethylene glycol
Mg	Mega grams (means 1000 kg = 1 ton)
MR	Mechanical recycling
MSW	Municipal solid waste
MSWI	Municipal solid waste incineration
MTP	Middle temperature pyrolysis
NGO	Non-governmental organization
NS	Neutral scrubber
PA	Polyamide
PAH	Polyaromatic hydrocarbons
PE	Polyethylen
PET	Polyethylene terephthalate
PLA	Polylactic acid
PMF	Particulate matter formation
POF	Photochemical oxidant formation
PP	Polypropylene
PS	Polystyrene
PMMA	Polymethyl methacrylate
PUR	Polyurethane
PVC	Polyvinylchloride
RDF	Refuse derived fuel
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RTO	Regenerative thermal oxidizer
SAN	Styrene-acrylonitrile resin
SCR	Selective catalytic reduction
SLF	Shredder light fraction
SOD	Stratospheric ozone depletion
SUPD	Single Use Plastic Directive
SWG	Solid waste generation
TPA	Terephthalic acid
TRL	Technology Readiness Level
UNEP	The United Nations Environment Programme
VCI	Verband der chemischen Industrie (Association of the Chemical Industry)
VDI	Verein Deutscher Ingenieure e.V. (Society of German Engineers)
VOC	Volatile organic carbon emissions to air
WEEE	Waste of electrical and electronic Equipment
WC	Water consumption
WWG	Waste water generation

Glossary

Within the frame of this study the following definitions are only applied to the field of plastic waste recycling. In general, these terms could be applied to recycling or treatment of different waste types.

Physical recycling

Generic term that includes those types of recycling in which the polymers are preserved, such as mechanical and solvent-based recycling.

Mechanical recycling

Polymers are processed into secondary raw materials using mechanical technologies. The chemical structure of the polymers is not significantly changed in the process.

Solvent based recycling (solution-precipitation)

Polymers are processed into secondary raw materials using solvents. The chemical structure of the polymers is not significantly changed in the process.

Solvolysis

Polymers are processed into secondary raw materials using solvents. The polymers are broken down into monomers. The technique is also called chemolysis or depolymerization by some authors.

Liquefaction

Thermal conversion of polymers into smaller molecules in a so-called starter oil. Products are mainly oil and a solid residue. The technique is also referred to as depolymerization.

Pyrolysis (thermolysis)

Thermal conversion of polymers into smaller molecules in a pyrolysis reactor in the absence of oxygen. Products are mainly oil, gas and a solid residue. The technique is also called dry distillation.

Gasification

Conversion of polymers into a gas at high temperatures by reaction with oxygen and/or water steam. The gas (also called syngas) can be used as a raw material for further processing in the chemical industry.

1 Introduction and background

Uncontrolled input of plastics into the environment, for example as marine litter or microplastics, is a global problem of increasing severity. Reasonable measures to combat this challenge can only be developed and implemented on an international level. Against this background, the resolution (5/14) has been adopted by the UN Environment Assembly (UNEA) requesting the UN Environment Programme (UNEP) to convene an Intergovernmental Negotiating Committee to end plastic pollution (INC) to develop an international legally binding instrument to tackle plastic pollution.

The committee started its work in November 2022 in a first meeting in Punta del Este, Uruguay (INC-1). The second round of negotiations (INC-2) took place in Paris in May 2023 and the third round (INC-3) was carried out in Nairobi in November 2023.

According to the resolution (5/14), “the instrument" is to be based on a comprehensive approach that addresses the full life cycle of plastic, including its production, design, and disposal. Accordingly, measures for the treatment of plastic waste, such as recycling and energy recovery, need to be included in the considerations.

Chemical recycling of plastic waste streams is currently being intensively pursued and investigated by many companies and research institutes. This raises the question if or to what extent the chemical recycling of plastics can contribute to the management of these waste streams in the future and what the advantages and disadvantages of the individual technological approaches are. However, the **chemical recycling of plastic waste is discussed very controversially**. Due to the **lack of practical, industrial-scale and long-time experience**, it is currently difficult to evaluate the multitude of different approaches scientifically and technically on the basis of the available and published data.

In order to provide a solid data basis for the treaty negotiations, the Swiss Federal Office for the Environment commissioned the present study. The aim was to summarize in a compact form the state of knowledge on the technologies and possible impacts of chemical recycling. The study focuses on the three aspects **technologies – environmental impacts – governance** and also includes recommendations on the basis of the current state of knowledge.

Due to limited availability of data, the discussed technology examples, studies and legal frameworks mostly concern Europe. Nevertheless, globally valid recommendations are expressed.

2 Technologies of chemical recycling

This chapter presents the various approaches applied for the chemical recycling of plastic waste. All technological variants are illustrated by practical examples. Initially, various definitions for chemical recycling are presented.

2.1 Definition of chemical recycling

Currently, there are no legal definitions for chemical recycling. However, some suggestions have already been elaborated and published. Some of these definitions, proposed by various stakeholders, mainly from associations or representatives related to the chemical and plastics industries, are presented below.

Plastics Europe (European plastics manufacturer association)

"Chemical recycling is the process of converting polymeric waste by changing its chemical structure and turning it back into substances that can be used as raw materials for the manufacturing of plastics or other products. There are different chemical recycling technologies, e. g. pyrolysis, gasification, hydro-cracking and depolymerisation." [46]

European Chemical Industry Council (Cefic)

"Feedstock recycling, also known as chemical recycling, aims to convert plastic waste into chemicals. It is a process where the chemical structure of the polymer is changed and converted into chemical building blocks including monomers that are then used again as a raw material in chemical processes. Feedstock recycling includes processes such as gasification, pyrolysis, solvolysis, and depolymerisation, which break down plastic waste into chemical building blocks including monomers for the production of plastics." [7]

Chemical Recycling Europe (European manufacturers association for CR technologies)

"Chemical Recycling is defined as any reprocessing technology that directly affects either the formulation of the polymeric waste or the polymer itself and converts them into chemical substances and/or products whether for the original or other purposes, excluding energy recovery." [8]

European Coalition for Chemical Recycling (initiative by Cefic and PlasticsEurope)

"Chemical Recycling converts polymeric waste by changing its chemical structure to produce substances that are used as products or as raw materials for the manufacturing of products. Products exclude those used as fuels or means to generate energy." [21]

German Federal Environmental Agency (study in preparation)

"Chemical recycling of plastics refers to process chains in which polymers are completely or partially broken down into their components and subsequently used as a feedstock, to produce new polymers or other substances, and – apart from by-products or residual materials – are not used for energy recovery." [5]

The definitions show a broad consensus. Mainly the **material use is addressed**, and, in most cases, an **energetic utilization of the products is explicitly excluded**. Some definitions specify concrete processes for the realization of chemical recycling, although there are certain differences in the terminology and technologies addressed.

2.2 Variants of chemical recycling

Due to the polymer structure of plastics, they can be recycled not only with mechanical processes but in principle also with chemical and thermochemical processes. There are huge differences with regard to the required composition and purity of the input materials as well as with respect to the product spectra and qualities that can be produced. Figure 1 shows the general recovery options for plastic waste.

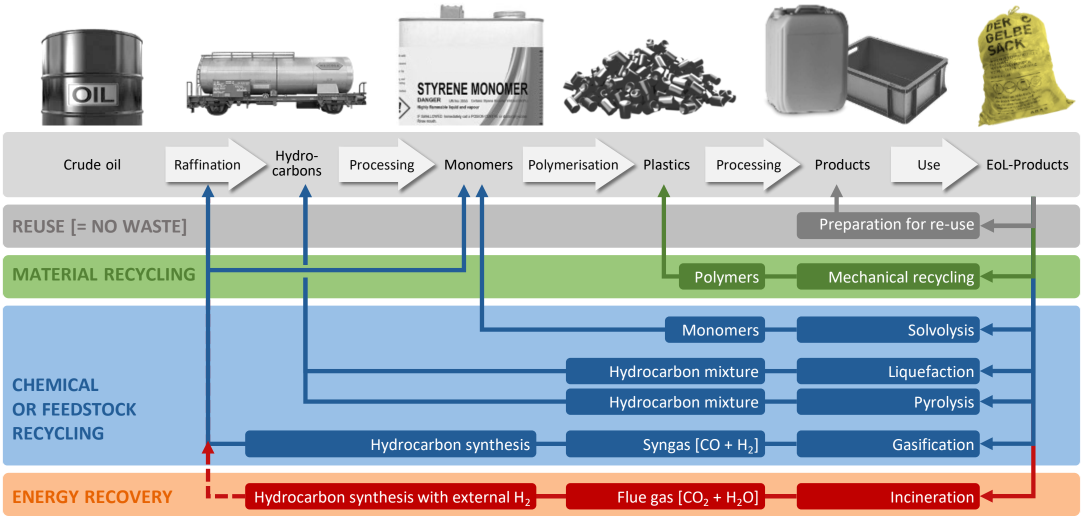

Figure 1: *Options for recycling and material recovery processes during the polymer life cycle (figure: P. Quicker)*

Direct reuse or preparation for reuse is of minor importance in the commercial sector and therefore not addressed here any further.

The two currently dominating methods for the controlled management of plastic waste are recycling by mechanical processes and the incineration of those fractions that are found to be unsuitable for mechanical recycling.

The processes highlighted in blue in Figure 1 are currently being pursued as approaches for chemical recycling of plastic waste. In the following subsections, these different approaches are outlined briefly, and process-specific characteristics, advantages and disadvantages are discussed. In addition, at least two commercial processes are presented as examples. The selection of the processes discussed is not intended as a statement on the quality of the process but was mainly based on the availability of information.

Figure 2 shows the thermochemical processes that can be used for the chemical recycling of plastic waste and that have already been addressed in commercial approaches. Also indicated are typical reactants and the temperature range in which the processes can be operated. Particularly in the case of gasification processes, the upper reaction temperatures are usually only limited by the material properties of the apparatus. “Allothermal” means that a process needs an external heat supply, “autothermal” means that the process generates enough heat to keep itself running, by oxidizing a part of the organic content of the fuel. λ “lambda” is the air-fuel ratio. A value of 1 means that there is just enough oxygen present to burn all the fuel. Values higher than 1 mean that there is a surplus of oxygen, values lower than 1 mean that there is not enough oxygen for total combustion of the fuel.

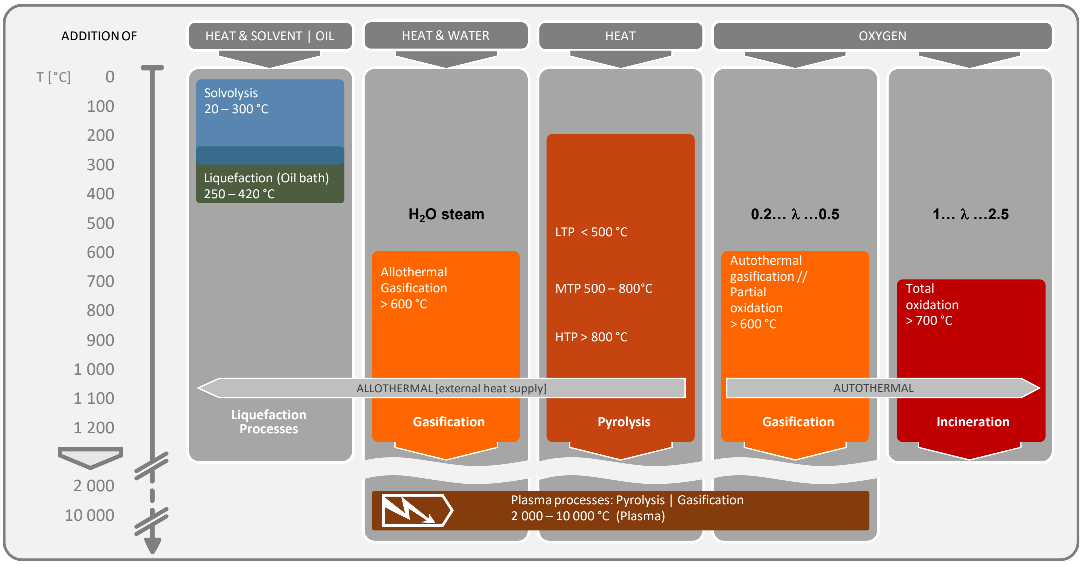

Figure 2: (Thermo-)Chemical processes (figure: P. Quicker)

The depicted processes are briefly described in the following subsections. Merely the plasma processes are not further discussed in this study as it is not expected that these processes will gain technological importance for plastics recycling, due to the high effort necessary for their operation and the availability of simpler methods for the conversion of polymers.

The following subsections are illustrated with pictures of typical plastic waste input materials. However, as operators do not disclose details of their processes, the composition of those depicted plastic waste fractions is unknown.

2.2.1 Solvolysis

Solvolysis, also called chemolysis or depolymerization by some authors, includes processes in which the plastic fractions are specifically broken down into their monomers (and partly oligomers) by reaction with a solvent. This is not possible for all types of plastics. Therefore, the polymer must be chemically decomposable by solvents, e.g. by acidic or alkaline hydrolysis, glycolysis, alcoholysis etc. Polycondensates like polyester or polyamides are typical examples which can be addressed with these approaches.

The selective dissolution of the bonds (e.g. ether or ester bonds) requires highly specific solvents, particularly because foreign plastics should not be transferred into the solution, but remain in the solid residue. The temperatures of such solvolytic processes for the chemical recycling of plastic waste range from room temperature to about 300 °C, the operating pressures from ambient pressure to 40 bar. The residual material is separated from the liquid after dissolution of the addressed plastic type by filtration and the solution with the monomers is returned to polymerization after purification. [5][52]

Solution-precipitation processes are very similar to the solvolytic approach. However, the operators of such processes emphasize that in these approaches the polymer structures in the plastic are (completely) retained and no cleavage into monomers takes place. The background of this claim is the desire to be recognized as a physical recycling process, which may have advantages in countries which explicitly demand mechanical processes in their legislation, e.g. to fulfill recycling quotas [52].

Solvolysis and solution-precipitation processes both allow the relatively gentle removal of contaminants, fillers and foreign plastics from the fractions containing the addressed monomers and/or polymer chains, due to the liquefaction of the desired products with specific solvents at moderate conditions.

The **major challenge of the processes is the operation with genuine plastic waste fractions**, which usually contain non-negligible proportions of impurities, contaminants and foreign plastics. This leads to high levels of solids in the solution, which makes filtration, i.e. recovery of the desired fraction, extremely difficult.

Another point to consider is related to the challenges of a solvent-based process. It is essential to **ensure that no harmful or toxic solvents are used**, as these could be transferred with the product or the residual materials into the environment.

2.2.1.1 Example revolPET

The revolPET® process (cf. Figure 3 and Annex 2.1: Solvolysis – revolPET) is applying an alkaline hydrolysis for the selective depolymerization of polyethylene terephthalate (PET) into its monomers monoethylene glycol (MEG) and terephthalic acid (TPA). The process is currently operated on a pilot scale level. Input materials are shredded plastic waste fractions which are containing PET and (preferentially) are not useable for mechanical recycling processes. The process is based on the application of solid sodium hydroxide NaOH to depolymerize the PET into monoethylene glycol and disodium terephthalate. The process uses an extruder which operates at temperatures of 120–160 °C.

The recovery of monoethylene glycol is realized via condensation of the vapor in a first step or later stage in the process by distillation. The remaining sludge is dissolved in water and impurities like polypropylene (PP), polyethylene (PE) and other plastics are removed by consecutively course and fine filtration steps. Finally, terephthalic acid is recovered by applying an acid (e.g. H_2SO_4) and purified.

The operator quantifies the yield of recovered terephthalic acid from PET with 97%. Waste plastic factions with a PET content down to 30% can be processed, but economics can be improved by applying input material with higher PET content. High amounts of chemicals, especially NaOH and H_2SO_4, are used in the process.

Figure 3: revolPET pilot laboratory plant and typical input material.

2.2.1.2 Example Rampf

Rampf Eco Solutions (Pirmasens, Germany) produces polyols from residual materials from the production of polyurethane (PUR). No high-quality mechanical processes are available for PUR waste (e.g. furniture, car seats, mattresses, insulating foams); energy recovery is common practice.

As part of a funded project, a demonstration plant for recycling PUR plastic waste is being built. Two different routes, adjusted to rigid and flexible foam PUR respectively, will be implemented. In the solvolysis of polyurethane, the material is cracked with glycol or an acid. The end product is a recycled polyol that is to be used again directly as a raw material in PUR production. [63] The approach is particularly interesting because it addresses PUR materials that are highly relevant for the circular economy, because these materials are mechanically hardly recyclable.

2.2.2 Liquefaction

Compared to solvolysis, liquefaction in an oil bath (also referred to in the literature as depolymerization) leads to a much more unspecific decomposition of plastic fractions, at temperatures between 250 and 420 °C, under ambient pressure, relatively short residence times and, depending on the process, with the addition of various additives such as catalysts or neutralizers.

The **products of such processes are hydrocarbon mixtures** (product oil) with a large number of different chemical compounds, which also contain a relevant part of the impurities of the feedstocks and have to be treated (purified, hydrogenated, possibly distilled) before they can be can be considered a valuable recycling product. Liquid yields between 70 % and 90 %, depending on the purity of the input material, can be reached on industrial scale [49][57]. Since plastic waste is a very heterogeneous material with a multitude of substances and elements, which are also transferred into the liquid product, an **extensive purification of the product oils**, especially to get rid of heteroatoms (e.g. N, S, Cl, O), has to be applied before the further processing of the oil, e.g. in the chemical industry or refineries.

The remaining solid (or slurry) residue contains coke, fillers, aluminum flakes, dust, eventually used additives and all other solid contaminants introduced with the plastic waste. Amount and characteristics of the residue is strongly related to the quality of the feedstock. Typically, potentially hazardous components, like heavy metals and polyaromatic hydrocarbons (PAH) accumulate in this stream. Due to these characteristics and the normally high organic content, the **thermal treatment of the solid residue in a waste incineration plant** or similar facility is inevitable. Another byproduct is a **permanent gas** (which stays gaseous at normal temperature and pressure), arising from the liquefaction reactor, which **has also to be treated thermally**, due to burnable and potentially toxic constituents.

The use of the side products – gas and e.g. produced waxes – also in the downstream production of new polymers (e.g. at an integrated site of a refinery) enhances the efficiency of the whole process chain and the yield of the HVC products.

2.2.2.1 Example ReOil

The mineral oil company OMV operates pilot plants for the liquefaction of plastic waste at the refinery site Schwechat, near Vienna (Austria) according to a technology based on a tubular reactor (cf. Figure 4 and Annex 2.2: Liquefaction – ReOil). Feedstocks are various polyolefin fractions, like polypropylene or -ethylene, with a low level of contamination.

The tubular reactor is operated at 450 °C and fed with the plastic flakes by an extruder. The melted material is mixed with a solvent and then cracked in the reactor. The rising volatile components are extracted, cooled, condensed and gained as hydrocarbon fractions. The liquid phase remains as oil in the process and is recycled to the reactor. A side stream is extracted from the cycle, to remove contaminants and impurities, and can be energetically utilized. The remaining permanent gases can be supplied to the steam cracker of the site. The product oil is also directly utilized in the Schwechat refinery, without any upgrading, due to the high dilution with fossil naphtha. The oil has a share of up to 20 wt.-% olefins and 10 wt.-% aromatics. [60]

The company OMV has several thousand hours experience in operation and scaled up the process from laboratory level in 2009 to a pilot plant facility size of currently 16 000 Mg/a (Mega grams per year). The next scale-up step to a commercial size of 200 000 Mg/a is already in implementation. Planning started and start-up is scheduled for 2027. [42]

Figure 4: Pilot plant of OMV reoil-process and typical input material.

2.2.2.2 Example CARBOLIQ

In Ennigerloh, Germany, the company CARBOLIQ operates a pilot plant (input capacity of 6000 Mg/a) for the liquefaction of different plastic waste fractions (cf. Figure 5 and Annex 2.3: Liquefaction – Carboliq).

Before the feed is supplied to the stirred tank reactor, it is screened, freed from remaining ferrous and non-ferrous metals and mixed with catalyst (zeolites, approx. 20 kg/Mg Feed) and 2 wt.-% quicklime (neutralizer, pH increase, binding of Cl and F). Subsequently, the material is dried in heated screws (water content reduction from about 10-15% to less than 2%) and at the same time preheated to 100 °C and compacted.

Figure 5: Pilot plant of Carboliq in Ennigerloh and typical input material (RDF).

The liquefaction process is executed in an oil bath (waste oil as starting oil), which is heated to the reaction temperature of 320-360 °C purely mechanically (friction), using fast-running impellers (called turbines) that continuously mix the oil bath. The introduced plastics are melting and evaporate with further shortening of the chain length. The vapors are condensed in a spray cooler by direct contact with product oil of approx. 60 °C. The remaining permanent gas is cooled to 15 °C and has to be treated (e.g. RTO plant) due to about 200 mg/m³ of organic components (at normal conditions).

The additives, impurities and solids accumulating in the reactor are removed from the sump at regular intervals. The calorific value of these solid residues is about 30 MJ/kg [41].

2.2.3 Pyrolysis

Pyrolysis (also called thermolysis, dry distillation) is a process in which substances are decomposed by the impact of heat only, without any reaction partner, which demands the strict absence of (ambient) oxygen in the reactor. The thermal treatment initiates a cleavage of different bonds and results in the decomposition of polymers into smaller molecules. Typical treatment conditions are temperatures of 400-550 °C and atmospheric (sometimes also elevated) pressures and an inert reactor atmosphere, to avoid oxidation of the input material. Pyrolysis processes are robust against different consistencies and compositions of feedstock materials. Some operators use additives, like catalysts, to support the decomposition of the plastics.

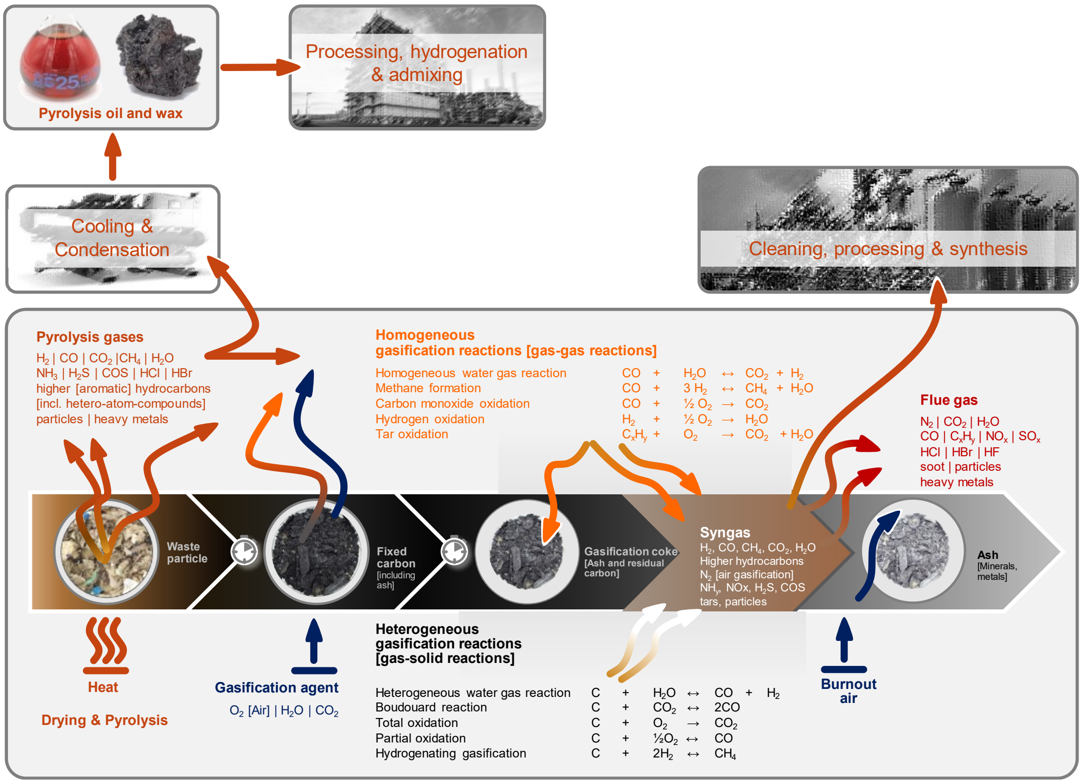

Figure 6: Thermochemical conversion of plastic waste with important gasification reactions and products obtained via gas cooling and condensation. The pyrolysis is shown on the very left side. When a gasification agent is added, further gasification reactions happen, as seen on the right side (cf. 2.2.4 Gasification) (figure: P. Quicker).

Figure 6 (left part) lists the potential products (pyrolysis gases) which typically arise from the pyrolysis of plastics. By (fast) cooling and condensing of these gases, the desired liquid products are obtained. Typically, **two or more fractions, with significant divergent consistency and viscosity are generated** during condensation (cf. pictures in Figure 6 and Figure 16). A (combustible) permanent gas remains after condensation, which can typically be used to heat the process. The **solid residue has to be treated thermally in a waste incineration facility**, since its quality is too low for material use.

Elevated process temperatures and longer residence times support the degradation of long-chain polymers to light fractions, such as gases, whereas moderate process temperatures and short dwell times promote the formation of heavy oil fractions with longer chain length.

Since the technical effort for the realization of pyrolysis technologies is rather low, there are many developments of various companies, which designed and followed their own approaches during the last years. Currently, about 100 different suppliers or developers of processes for pyrolytic chemical recycling of plastics are active on the market (cf. Annex 3 – List of CR-processes).

2.2.3.1 Example Arcus Greencycling Technologies

Arcus Greencycling Technologies GmbH was founded in 2019 and is developing a pyrolysis process for the chemical recycling of waste plastics on the basis of a screw reactor. Recently, the company erected a pilot plant with 500 kg/h feedstock capacity in the industrial park in Frankfurt Hoechst, Germany (cf. Figure 7 and Annex 2.4: Pyrolysis – Arcus). This is the standard size to be marketed in the future. Larger capacities will be realized by parallel operation of several modules.

Figure 7: Pyrolysis pilot plant of Arcus Greencycling Technologies in Frankfurt Hoechst, Germany and typical input materials [62].

The polyolefinic plastics such as polypropylene or polyethylene are shredded and agglomerated (by an external service provider) to achieve the desired bulk density of 250-300 kg/m^3 for proper transport and feeding of the materials into the reactor. The screw-reactor is continuously operated and electrically heated (500 kW), as far as possible by using electricity produced from the generated permanent gas and by additional electricity from the grid.

In addition to the plastic waste feedstock, an additive for adsorbing inorganic gases released during pyrolysis, and an inert material as heat carrier are fed together into the reactor. Heating this mixture results in the pyrolysis of the plastics, which are then transferred to the gas phase and cracked. The gases, still at reaction temperature, are freed from particles by a hot gas filter and afterwards cooled and condensed in two stages. The reaction water is separated and the product stored.

Remaining permanent gases are processed, purified and transformed into electricity in a gas engine to generate the power required for the process.

The solids discharged from the screw reactor are screened after cooling and the recovered inert carrier is returned to the process. The remaining fine dust is the main pollutant sink of the process and must be disposed of adequately.

2.2.3.2 Example Quantafuel

The Norwegian start-up Quantafuel ASA operates a pilot plant with 4 lines on industrial level, for the pyrolysis of mixed plastic waste in a rotating kiln reactor, in Skive, Denmark. The plant has an input capacity of 1000 Mg plastic waste per month and operates at a temperature level between 380 and 460 °C (cf. Annex 2.5: Pyrolysis – Quantafuel). The energy supply for the reactor heating is realized by burning the non-condensable gases remaining from the process.

The produced gas is cooled down in several steps and the condensed oil is distilled and separated into three fractions. The oil is sold to chemical facilities, to recycle it into the polymer production chain, e.g. to BASF in Germany [38].

Quantafuel claims that the process allows plastics from household waste to be used directly without a further cleaning step.

2.2.3.3 Example Recycling Technologies

The company Recycling Technologies developed a technology for the pyrolysis of waste plastic fractions on the basis of the fluidized bed technology between 2013 and 2022 (cf. Figure 8 and Annex 2.6: Pyrolysis – Recycling Technologies). The concept for the process was developed at the Warwick University, UK. Pilot facilities of the company were operated in Swindon, UK.

Pre-processed waste plastics are pyrolyzed in a fluidized bed reactor, equipped with an inert sand bed, at temperatures between 450 and 550 °C under slight overpressure. This pyrolysis reactor is coupled to another fluidized bed, which is operated as an incinerator. A part of the sand is continuously circulated between the two reactors, to get cleaned and heated up in the incinerator and transport the heat into the endothermically operated pyrolysis reactor.

The solid plastic waste is cracked in the pyrolysis reactor and transferred into the gas phase. From this gas the particles are separated by hot gas filtration. Following, the gases are cooled and condensed on specific temperature levels, to get products with desired chain lengths of the contained hydrocarbons.

Figure 8: Pyrolysis pilot plant of Recycling Technologies in Swindon, UK and typical input materials.

Recycling Technologies failed to get additional investments and had to file for insolvency in autumn 2022 [24]. The granted patents are part of the insolvency estate and available for interested investors.

2.2.4 Gasification

Gasification processes aim to produce a synthesis gas with the **main components hydrogen and carbon monoxide**, which can subsequently (after cleaning and upgrading) be used to produce basic chemicals again. Gasification can be considered as a continuation of pyrolysis by means of conversion of its degassing products with the controlled addition of a reactant. Oxygen, water vapor and carbon dioxide can be applied for this purpose. The solid and gaseous products from drying and pyrolysis of the plastic waste (and of other components in the feed) are further converted by reactions with the reactant in homogeneous (gas-gas) and heterogeneous (gas-solid) reactions (cf. Figure 6).

Depending on the selected gasification agent, two operational modes – **autothermal and allothermal gasification** – can be distinguished (cf. Figure 2). The presence of (sufficient) oxygen in the gasification reactor results in a partial oxidation of the solid and gaseous components. The heat from these exothermal (heat-releasing) reactions allows an autothermal operation of the process, meaning that no external heating of the reactor is necessary to supply the energy for the overall endothermal (heat-consuming) gasification reactions. If water steam (or CO_2) is used as gasification agent, no exothermal reactions take place, and the energy must be supplied from outside (allothermal gasification).

Besides the addressed main product constituents hydrogen and carbon monoxide, the gases produced by gasification usually contain methane, aliphatic and aromatic hydrocarbons and the other components depicted in Figure 6.

Independently of the feedstock**, gas production from solid fuels is associated with major challenges**. In particular, **high proportions of tars**, which condense in pipes and process equipment and can affect downstream plant components, create major difficulties. Waste-derived feedstocks, especially those of inferior quality, further aggravate these problems.

Presumably due to the high effort for erecting and operating gasification plants and the necessity to build larger facilities for economic reasons, the number of chemical recycling processes on the basis of gasification is limited.

2.2.4.1 Example Ebara | Showa Denko

The company Showa Denko in Kawasaki, Japan, operates an industrial scale gasification unit for plastic waste since 2003 (cf. Figure 9 and Annex 2.7: Gasification – Ebara). The plant produces hydrogen for the production of ammonia.

The gasification at the facility is carried out in two serially arranged gasification reactors at pressures of 5-16 bar and with a mixture of oxygen and steam as gasification agent. The plastic waste is pretreated and compacted with high effort (cf. Figure 9, pictures in the middle) and subsequently gasified in a rotating fluidized bed reactor (manufacturer Ebara) at temperatures of 600-800 °C. The product gas including the conveyed particles is treated in a second reactor at 1300-1500 °C. The particles melt and the slag is granulated below the reactor in a water bath.

The produced syngas is treated in gas cleaning system, equipped with a gas scrubber and a desulfurization unit. By CO-shift and CO_2-separation pure hydrogen is generated for the ammonia synthesis according to the Haber-Bosch process.

The arising residues from the process – metals, slags, sulfur etc. – have to be disposed of, according to their low quality. In spite of the years of operating experience, the operators are still facing operational challenges, like formation of slag in the reactor, problems with the gas purification and the pretreatment of the feedstock. Therefore, only about 7000-7500 hours of operation can be reached per year.

Figure 9: Gasification of plastic waste at Showa Denko, Kawasaki Japan (2017). Left: input material, middle: extruder for preparation of plastic waste and produced extrudates, right: gasification reactor according to Ebara UBE process.

2.2.4.2 Example SVZ

Another technical functioning industrial facility for the gasification of waste was operated at the SVZ Schwarze Pumpe near Cottbus, Germany from 2003 to 2007. At this site, lignite (brown coal) was gasified to produce city gas in several industrial-scale reactors until 1989. After reconstruction of the site, 7 fixed-bed gasifiers, 2 entrained-flow gasifiers and a BGL slag-bath gasifier were used for the gasification of different waste fractions, including plastic waste (cf. Figure 10).

Figure 10: Gasification infrastructure at SVZ Schwarze Pumpe, Germany (2003). Left: Oil-steam burner nozzle and reactor head of entrained flow gasification, middle: model of entrained flow gasifier, right: gasifier building with 6 fixed bed reactors.

All plants were operated at an elevated pressure level (20-40 bar) and high temperatures between 1200 and 1600 °C. Oxygen and steam were applied as reactants. Again, a large effort was invested to prepare the feedstock for the challenging processes. Figure 11 shows examples of agglomerated waste fractions from different origins of high quality and density. The quality of the produced gases required a sophisticated multi-step gas purification, followed by a CO-shift and Rectisol CO_2-separation, to reach the necessary purity for the utilization in the methanol production plant of the site.

Figure 11: Input materials at SVZ Schwarze Pumpe, Germany (2003). Left: Pellets made from processed residual waste, middle: extrudate from DSD plastic waste, right: briquettes from SLF.

The huge technical challenges could be controlled after several years of commissioning and all reactors in the facility were operated for several years. Nevertheless, due to the high effort for plant operation and maintenance as well as for pretreatment and handling of the feed materials, an economic operation could never be reached at any time.

The facility was closed down in 2007, after changes of the ownership and several insolvencies.

2.3 Other options for recovery of waste plastics

2.3.1 Mechanical recycling

Mechanical recycling means the sorting, cleaning, shredding and further processing of plastic waste. Typically, the cleaned and sorted product is further processed by extrusion, a process in which the plastic is heated up, and melted, typically in screw reactors, and pressed through special nozzles. The end product is a granulate that can be used in the production of plastic articles again.

This type of recycling is only applicable for thermoplastic materials, which can be melted during the extrusion process. The input material has to be of high quality, without impurities such as dirt, non-plastic materials or different plastic types. Separate collection is an aspired precondition, sorting by plastic type and color is crucial to ensure a high quality recyclate.

Due to these requirements, **mechanical recycling is hardly applicable for composite or multi-layer plastic materials and also not for thermoset and elastomer type polymers**.

The great **advantage of mechanical recycling is the preservation of the material**. The polymer is only melted but not chemically affected. Therefore, the energy and the corresponding CO_2-emissions that were spent during the plastic production can be saved by mechanical recycling, compared to the production of virgin material.

However, mechanical recycling cannot be applied infinitely to the same polymers, due to aging processes and the impurities and contaminations remaining in the material and being transferred to the new product.

2.3.2 Energy recovery

Energy recovery is state of the art for treating non-recyclable plastic waste fractions and carried out in different facilities for incineration and co-incineration of waste. **Cement kilns** demand relative high fuel qualities with low concentrations of contaminants and defined qualities, due to the lack of an adsorption step in the flue gas cleaning and the quality assurance of the clinker product. Similar, but less stringent are the requirements of **coal power plants**.

RDF power plants and **MSWI plants** accept the lowest quality of input material, but even these plants have problems with some fractions, like carbon fiber reinforced plastics (cf. Chapter 2.4 and Figure 14).

2.3.3 Incineration with carbon capture and utilization (CCU)

The processes of drying, pyrolysis and gasification, as depicted in Figure 6, finally lead to an incineration of the fuel (here the plastic particle), if the applied reactant consists of sufficient oxygen (e.g. as air). Main **products are CO_2 and H_2O** and, if air was the oxidizing agent, surplus nitrogen. Due to the impossibility of an ideal combustion of solid fuels, at least low concentrations of CO and hydrocarbons are always present. If heteroatoms – N, S, Cl, Br, F or heavy metals – are present in the incinerated plastic waste, corresponding reaction products like NO_x, SO_x, HBr, HBr, HF etc. will be created and found in the off-gas. Modern MSWI plants are equipped to clean these gases to an environmentally sound level.

Currently, **many MSWI plants are working on the concept of CO_2 capture**. Background is the increasingly stringent framework regarding the CO_2 emissions, which could lead to considerable financial burdens in the future.

First plants for CO_2 capture have already been installed. At the MSWI plant in Duiven, the Netherlands, a pilot plant on an industrial scale is operated to capture more than 100 000 Mg of carbon dioxide per year from the flue gas of the waste incineration plant (cf. Figure 12). After purification and liquefaction, the CO_2 is marketed through a distribution partner for the application in greenhouses, where it substitutes CO_2 from incinerated natural gas. It can be assumed that further plants of this kind will be built and that the captured CO_2 will be used for the synthesis of hydrocarbons in the near future.

Figure 12: Plant for CO_2-separation form the flue gas of the MSWI plant Duiven, Netherlands.

Figure 13 shows the concept of a resource optimized MSWI facility, operated with oxy-fuel combustion and CO_2 conversion with (preferably green) hydrogen to hydrocarbons. In the oxy-fuel mode, an operation without exhaust gas seems possible, since no nitrogen – the remaining species in the off-gas, after precipitation of pollutants, condensing water and capturing CO_2 – is introduced into the system.

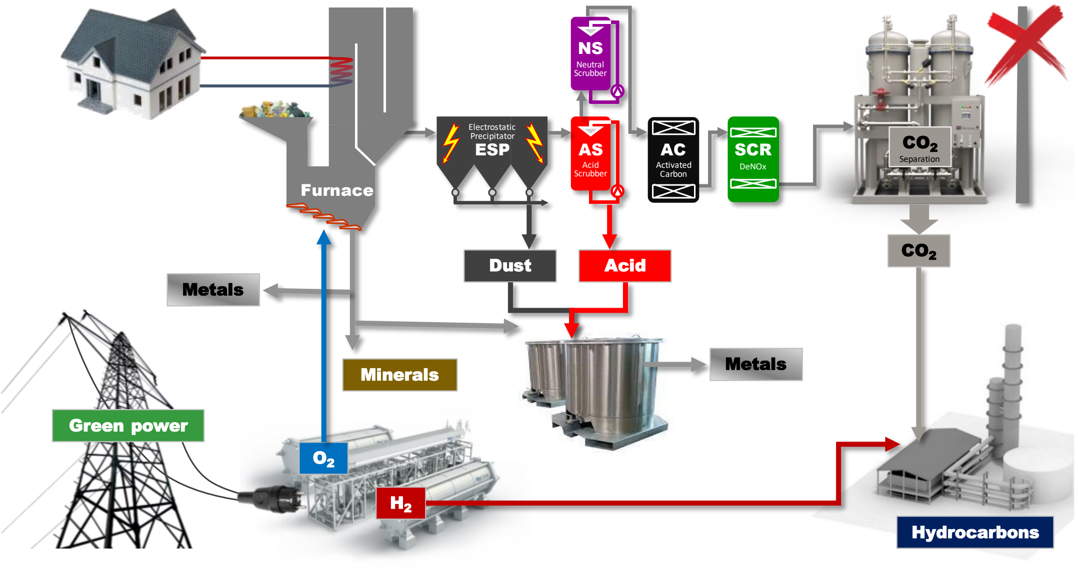

Figure 13: Concept layout for a resource optimized MSWI plant, with oxy-fuel combustion and CCU to hydrocarbons (figure: P. Quicker).

2.3.4 Landfilling

Some groups postulated in the last years that landfilling of (separated) plastic waste fractions could be a promising approach to tackle climate change. These groups argue that plastic landfilling is a cheap and easy option for a decentralized and local CCS.

Apparent disadvantages of this approach are the environmental impacts (e.g. land use, release of degradation products and pollution of the environment), the **loss of resources without any utilization** of the waste and last but not least the **violation of intergenerational justice by transferring contaminated sites** (plastic landfills) to future generations. The argument that such landfills may serve as sources of raw materials in the future is not valid since the technological challenges will increase significantly in the case of a later utilization (after decades of storage and degradation).

2.4 Potential plastic waste streams for CR

The selection in Figure 14 shows clearly that the waste fractions currently available on the market can be completely different in their composition. While polyolefins collected separately in the classical way can be fed directly into mechanical recycling, the only option left for shredder fractions (of various sources such as cars, home appliances or e-waste) is energy recovery in waste incineration. However, even this robust recovery route is unsuitable for carbon fiber-reinforced plastics, as the conditions in such waste incineration plants are not sufficient for the thermal conversion of carbon fibers [53]. For this reason, it is of great importance to critically reflect which of the available material streams are – presumably in many cases after additional pre-processing – generally suitable for chemical recycling, in order to conduct a serious market assessment.

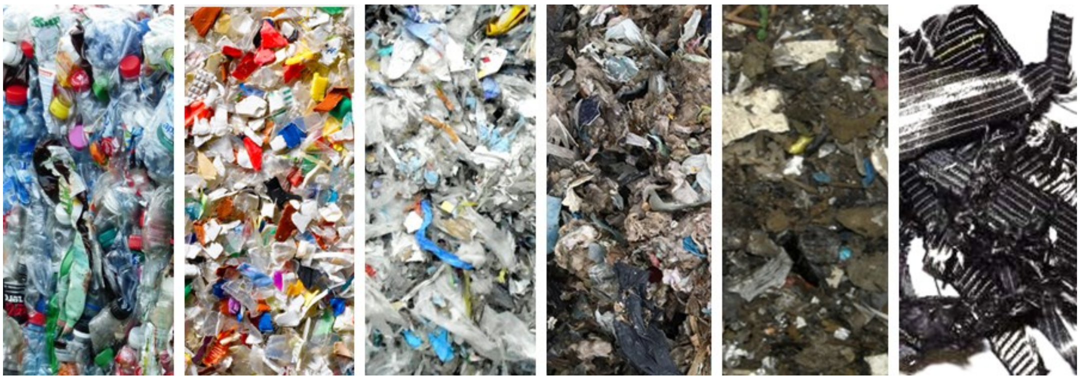

Figure 14: Illustrative examples of qualities of plastic waste streams.

The commonly declared goal of almost all stakeholders involved in the emerging chemical recycling business – in politics and science as well as industry – is the positioning of this new approach as a **supplement to mechanical recycling**, which has obvious ecological and energetic advantages because the plastic material and energy used in its production is preserved. This means, **all materials for CR have to be detracted from the currently incinerated** (or in some countries even landfilled) **plastic waste fractions**.

Despite this consensus, plastic waste streams directly suitable for chemical recycling are difficult to identify. The reason is that the current waste management system does not yet take this new recycling option into account. Instead, plastic waste sorting facilities are designed and optimized to maximize the mass flows for mechanical recycling. The remaining material flows are currently only processed to such an extent and also blended with other material flows so that the addressed incineration process works, be it in cement rotary kilns or on the grate of an MSWI plant. It is not unusual to additionally dispose of some contaminated materials in such fuel fractions, if the defined technical delivery conditions leave room for it, due to not yet exhausted limit values for certain parameters.

Consequently, it can be expected that, parallel to the development of industrial plants for the chemical recycling of plastics, the processing of potential feedstocks would also have to adjust to the new market conditions and, in the future, would provide tailor-made material flows for the CR route.

The waste flows that could be considered and the extent to which they could be recycled in CR processes were queried in a survey, based on the Delphi methodology (part of a research project on behalf of the German Federal Environment Agency on the chemical recycling of plastics [51]) among an interdisciplinary group of experts with many years of experience in the field of plastics recycling, including practical experience with CR. For this purpose, the plastic waste categories potentially eligible for chemical recycling were listed in the following three tables according to different criteria (origin, type, waste code number) and evaluated by the experts with regard to their suitability.

Table 1: Plastic waste streams according to origin and potential suitability for chemical recycling, according to the expert group opinion, inquired in a project for the evaluation of chemical recycling on behalf of the German Environmental Agency [51].

Plastic waste according to origin		
Expert opinion on Choice	Suitability for CR [0-10]	Potential share in CR [0-100%]
Packaging	7,8	30
Construction	5,8	25
Vehicles	5,3	32
Electro | Electronics	5,6	31
Household| Sport | Leisure	6,1	29
Agriculture	5,6	32
Other	3,9	21

With regard to the origin of the plastic waste, the **packaging sector is considered particularly suitable** (average 7.8 out of 10) for chemical recycling (cf. Table 1). The other options are rated more or less equally. It is remarkable that regardless of the origin, a **maximum market share of chemical recycling of about 30 % is expected**.

Table 2: Plastic waste streams according to polymer type and potential suitability for chemical recycling, according to the expert group opinion, inquired in a project for the evaluation of chemical recycling on behalf of the German Environmental Agency [51].

Plastic waste according to polymer type		
Expert opinion on Choice	Suitability for CR [0-10]	Potential share in CR [0-100%]
LDPE	8,3	41
HDPE	7,7	40
PP	7,9	39
PS	7,8	36
PS-E	6,8	31
PVC	3,0	13
ABS | ASA | SAN	4,8	13
PMMA	5,0	14
PA	4,7	19
PET	5,6	20
Other thermoplastics	3,6	15
PUR	5,1	26
Other polymers	2,4	12

In terms of the types of plastics, the experts clearly prefer polyolefins (PE, PP) and polystyrene (Table 2) for CR by liquefaction, pyrolysis or gasification. For these fractions, shares in chemical recycling between 30 and 40 % are expected. PET, PUR, PMMA and several others are also identified as suitable, but the potential share of chemical recycling for these fractions is assessed much more cautiously. However, those types of plastic could be suitable for solvolysis but this was outside of the scope of the project. PVC was identified as particularly unsuitable for chemical recycling.

The judgement of the experts on the suitability of practically available waste streams (defined by waste code number) is depicted in Table 3. Again, packaging fractions are judged as an especially promising feed for chemical recycling processes. **Hazardous waste fractions and composite materials or mixed waste fractions are reflected as problematic for chemical recycling technologies** by the expert group.

Table 3: Plastic waste streams according to waste codes of the European Waste Catalogue and potential suitability for chemical recycling, according to the expert group opinion, inquired in a project for the evaluation of chemical recycling on behalf of the German Environmental Agency [51].

Plastic waste according to waste code		
	Average Expert opinion on Choice	Suitability for CR [0-10]
02 01 04	waste plastics (except packaging)	5,6
03 03 07	mechanically separated rejects from pulping of waste paper and cardboard	4,0
04 02 09	wastes from composite materials (impregnated textile, elastomer, plastomer)	3,7
04 02 21	wastes from unprocessed textile fibres	3,5
04 02 22	wastes from processed textile fibres	2,8
07 02 13	waste plastic	5,5
15 01 02	plastic packaging	6,1
15 01 06	mixed packaging	4,3
16 01 03	end-of-life tyres	5,4
16 01 04*	end-of-life vehicles	2,8
16 01 19	plastic	4,2
16 02 13*	discarded equipment containing hazardous components	1,5
16 02 14	discarded equipment	2,2
16 02 15*	hazardous components removed from discarded equipment	1,8
17 02 03	plastic	4,9
17 02 04*	glass, plastic and wood containing or contaminated with hazardous substances	1,7
17 04 11	cables	2,8
19 10 03*	fluff-light fraction and dust containing hazardous substances	3,0

	Average Expert opinion on Choice	Suitability for CR [0-10]
19 10 04	fluff-light fraction	4,3
19 12 04	plastic and rubber	4,9
19 12 08	textiles	3,4
19 12 10	combustible waste (refuse derived fuel)	4,4
19 12 11*	other wastes (including mixtures of materials) from mechanical treatment of waste containing hazardous substances	1,3
19 12 12	other wastes (including mixtures of materials) from mechanical treatment of wastes	2,2
20 01 10	clothes	3,0
20 01 11	textiles	3,4
20 01 39	plastics	4,9

2.5 Product qualities

It can be stated that all the processes listed in Chapter 2.2 are generally suitable to serve as elements in the chemical recycling of plastic waste as part of an entire process chain. This does not indicate anything about the process specific effort required for the input preparation and product treatment in order to generate qualities of the hydrocarbon fractions that can be used again in production (in some cases in appropriate dilution). Qualities of the chemical recycling products such as pyrolysis oils are defined by the next production step. Organic contaminants are mostly destroyed during thermal processes but other inorganic additives may be transferred into the product, therefore further processing might be necessary before utilization in the chemical industry becomes possible.

Residues like coke from pyrolysis need to be incinerated or treated otherwise for disposal.

If chemical recycling is implemented, it can be assumed – at least in organized and regulated industrial structures – that the goods finally produced from these hydrocarbon fractions do not differ from the products produced from other (usually fossil) raw materials.

Consequently, all CR processes are in principle suitable for partially substituting fossil raw materials in the production of virgin goods – even for applications with food contact. It must be taken into account that the current technical approaches expect blending rates of not more than 10% recycled hydrocarbons from CR in classic production plants (refineries and polymer plants). Only the mass balance approach (cf. Chapter 4.3.3) can achieve polymer recyclates with virtual substitution rates of up to 100%.

The following subsections provide a brief assessment of the achievable product qualities for the individual thermochemical processes and, if available, corresponding data on composition as well as photographic material.

2.5.1 Solvolysis

Solvolytic processes are expected to offer particularly **high product qualities**, since the applied solvents allow a **very selective dissolution of the relevant polymer** or the associated monomers but no reliable data is available yet. After filtration and purification, a material is obtained that is generally indistinguishable from conventionally obtained feedstocks. The process forms residuals which are not suitable for a material utilization and can cause considerable disposal costs.

High contents of inorganic solids, foreign plastics, contaminants **and impurities in the feedstock will significantly hinder the overall functionality** of the process. Negative effects on the product quality are less to be expected as long as the process still functions within the scope of the designated operation limits.

2.5.2 Liquefaction

The liquefaction of plastic waste usually produces several **immiscible aqueous and hydrocarbon fractions**, which themselves contain a vast number of different components as well as inorganic impurities (cf. Figure 15).

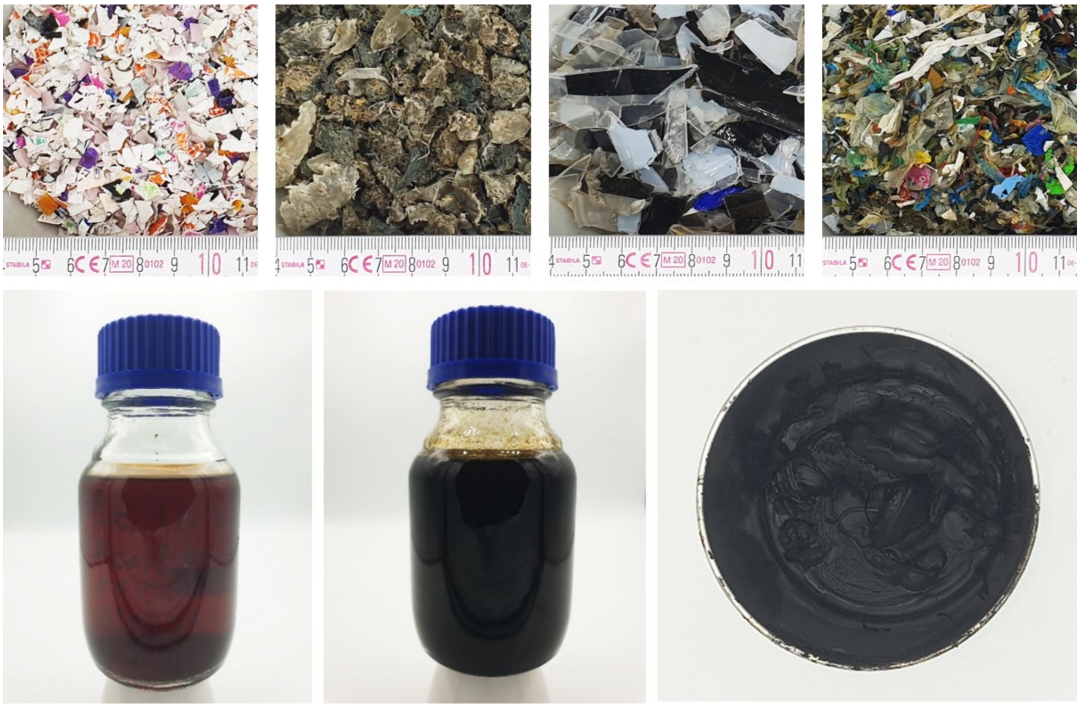

Figure 15: Below: Product spectrum from an industrial oiling plant. Left: Light fraction, middle: Heavy fraction, right: Wax. Top: Typical feed material from this plant [51] (photos: FH Merseburg).

Depending on the feedstock, the achievable oil **yields from liquefaction range from 55 to 80%**. By conversion in the corresponding refinery processes, so-called "high-value chemicals" (ethylene, propylene, butene, butadiene, aromatics), **HVC in the range of 30–45%** (relating to the mass of the input material) can be expected [51]. If the waxes and gases (beginning from C_2) generated during the liquefaction process are also recycled, the HVC yield can be increased to 60% [51]. Therefore, the operation of such plants at the site and in conjunction with refinery technology makes sense in terms of the achievable yields of high-quality products. The process forms residuals which are not suitable for a material utilization and can cause considerable disposal costs.

The visual impression of the products in Figure 15 already shows clearly that the qualities of the oils and waxes are rather low. The exemplary compositions in Table 4 show relevant proportions of heteroatoms and, in part, also ash contents, which prevent a direct high-quality material utilization. The calorific values, on the other hand, are in the range of the fossil feedstocks to be replaced in all the analyses shown.

Table 4: Examples for the composition of products from the liquefaction of different plastic waste fractions (cf. pictures in Figure 15) [51].*

Parameter		Liquefaction I		Liquefaction II	Liquefaction III
Plastic waste type		Polyolefins		Polyethylene-polyamide-composite	Mixed plastic waste
		Light* fraction	Heavy* fraction		
Net calorific value	MJ/kg	43.88	44.35	42.69	41.34
Ash content	wt.-%	0.018	0.044	< 0.0001	< 0.0001
Water content	wt.-%	< 1	< 1	0	1.32
C – carbon	wt.-%	84.9	85.2	81.9	83.7
H – hydrogen	wt.-%	14.3	13.3	13.4	12.3
O – oxygen	wt.-%	0.66	1.33	0	1.24
N – nitrogen	wt.-%	0.07	0.11	0.82	1.28
S – sulfur	mg/kg	65	112	500	1000
Cl – chlorine	mg/kg	75	238	400	400

2.5.3 Pyrolysis

The product qualities achievable in pyrolysis are very similar to those of liquefaction. Again, several fractions with complex compositions are obtained, which cannot be mixed. Figure 16 shows (above) the oils produced in pilot plant trials from different feedstocks, and below them the corresponding waxy products. Significant differences can also be observed between them.

Typical oil **yields in the process- and heat-optimized industrial environment range from 65 to 70 wt.%**. From these oils, **HVC products in the range of 30-45%** (reference feedstock) can be manufactured [51].

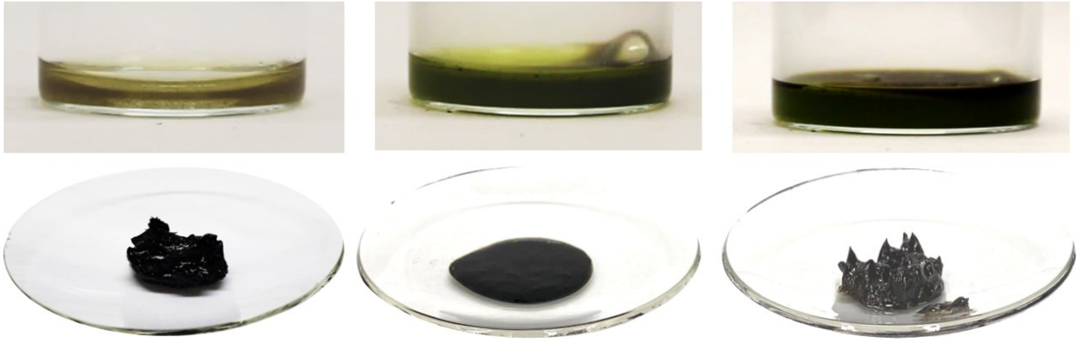

Figure 16: Liquid (upper row) and pasty products (lower row) from pyrolytic treatment of different plastic waste fractions. Left: Mixed packaging plastic waste, middle: Shredder fraction from WEEE, right: SLF from EOL vehicles [51] (photos: F. Roemer).

Table 5 shows the composition of two oils from pyrolysis. Contaminations with heteroatoms and relevant ash constituents, which exclude direct high-quality use, are also apparent in these analyses.

Table 5: Examples for the composition of products from the pyrolysis of different plastic waste fractions [51][62].

Parameter		Pyrolysis I	Pyrolysis II
Plastic waste type		Mixed plastics (esp. polyolefines)	Polypropylen furniture sheets
Net calorific value	MJ/kg	42.52	42.86
Ash content	wt.-%	0.0175	n/a
Water content	wt.-%	< 0.001	0.18
C – carbon	wt.-%	85.9	84.8
H – hydrogen	wt.-%	13.6	13.8
O – oxygen	wt.-%	0.3	< 0.5
N – nitrogen	wt.-%	0.13	0.16
S – sulfur	mg/kg	39	< 5
Cl – chlorine	mg/kg	10	25

For the economic success of a process, not only the desired product but also the quantities and compositions of the resulting residual materials are relevant, since these can cause considerable disposal costs. Figure 17 shows examples of such residual materials from pyrolysis, which correspond to the products shown in Figure 16. A **material utilization of these carbon rich residues is excluded**.

In principle, the remaining coke from pyrolysis can be utilized energetically in a thermal stage. In this case, the standards of waste incineration must be taken into account (operating temperatures and emission limits). In the case of particularly critical feedstocks, e.g. shredder fractions from the automotive or WEEE sectors, the coke may even have to be treated in thermal plants for the treatment of hazardous waste, due to critical constituents.

Figure 17: Solid residues from pyrolytic treatment of plastic waste fractions. Left: Mixed plastic waste from packaging, middle: Shredder fraction from WEEE, right: SLF from EOL vehicles [51] (photos: F. Roemer).

2.5.4 Gasification

In accordance with the denomination, the products from gasification of plastic wastes are mainly gaseous, a visual impression is therefore difficult to provide. Figure 18 (left) shows a gas pipe of a gas generator for the conversion of plastics. The massive deposition of tars is clearly visible, resulting in a reduction of the duct diameter from about 8 to 4 cm (by tarry deposits).

The photograph besides (right picture) gives an impression of a battery of scrubbing bottles, which were used for gas sampling at the same gasification plant. The first (left) wash bottle (which was empty at the beginning of the measurement) contains mainly the aqueous condensate from the process (reaction water) and heavy (fast condensing) organic components, in the other bottles (filled with isopropanol at start of measurement) mainly organic components condense from the gas phase.

Figure 18: Plastic gasification. Left: Raw gas duct section of a gasifier after gasification of plastic waste, right: Scrubbing bottle battery for cleaning a partial gas stream of this gasifier before analysis. (Photo: C. Schmittmann).

These observations highlight the extent to which the **product gases from plastic gasification are contaminated with tars**, which pose a **major challenge to further utilization** and demand **substantial (multi-stage) cleaning efforts**, resulting in the consumption of energy and the generation of residual materials.

Table 6 gives examples for the composition of gases from different gasifiers, operated with plastic waste containing fractions and oxygen-steam-mixtures as reactants. Besides the main components H_2 and CO, the gases contain methane and high concentrations of carbon dioxide. Hydrogen sulfide and higher hydrocarbons indicate again the need for further processing before subsequent utilization in hydrocarbon synthesis. The process also forms solid residuals which are not suitable for a material utilization and can cause considerable disposal costs.

Table 6: Examples for the composition of product gases (vol.-%) from the gasification of different plastic waste fractions of unknown composition.

Parameter		Gasification I	Gasification II	Gasification III
Hydrogen	H_2	35.6	45.9	25.0
Carbon monoxide	CO	37.1	10.3	22.0
Methan	CH_4	n/a	6.9	7.0
Carbon dioxide	CO_2	25.6	34.4	41.0
Higher hydrocarbons	C_xH_y	0.2	0.6	0.4
Hydrogen sulfide	H_2S	0.19	0.0002	n/a
Oxygen	O_2	n/a	0.01	0.6
Nitrogen	N_2	1.5	1.8	4-0

2.6 Economics

Reliable data on the economic viability of processes for the chemical recycling of plastic wastes are hardly available. The information provided by the companies should be viewed with caution. Often, optimistic framework conditions are set and the challenges that inevitably arise in the implementation of an innovative technology, with demanding input materials, are rarely considered realistically in economic terms.

Despite the currently good political and public acceptance of ecological and resource-efficient ventures, several **companies in the field of chemical plastic recycling have recently filed for insolvency**. Promising concepts that received good critiques on a laboratory scale and in pilot plant operation obviously failed in their industrial-scale implementation due to the economic challenges in practical application [24][50]. Nevertheless, **many approaches on chemical recycling are announced all over Europe** (see Figure 19).

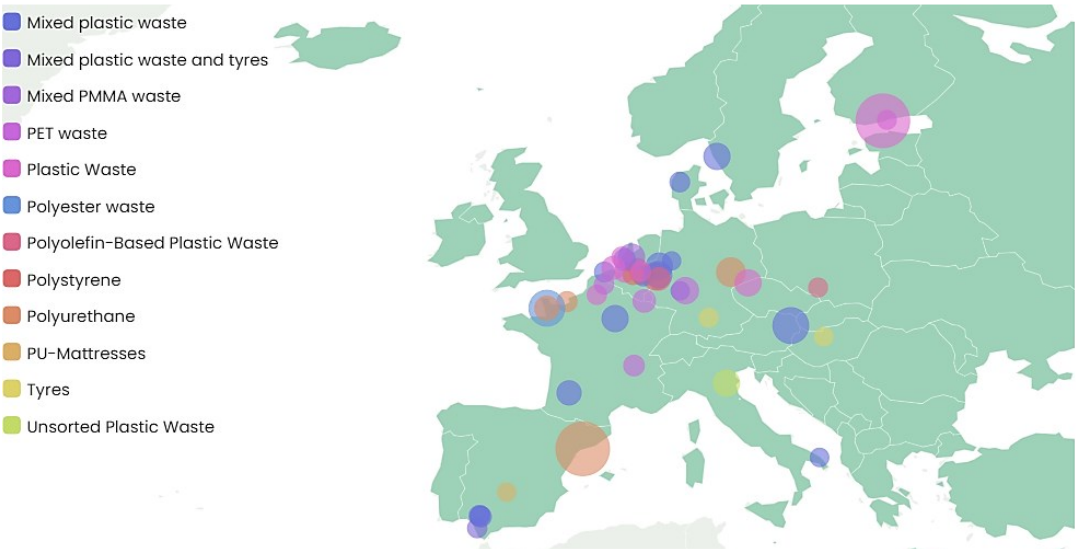

Figure 19: Planned investments in chemical recycling, according to homepage of PlasticsEurope in October 2023. The bubble size corresponds to announced plant capacity. [46]

2.7 Technical conclusions and recommendations

The objective of chemical recycling is to return the carbon, respectively the hydrocarbons, of previously non-materially recyclable plastic waste back into the cycle. The approaches discussed are aimed at waste fractions of different quality and composition.

For largely pure and moderately polluted plastic fractions that cannot be mechanically recycled due to e.g. coatings, **solvolytic processes are suitable**. Those processes merely break down the plastic into its monomers, which after cleaning can be used again directly for polymerization.

Mixed thermoplastic fractions can be treated in liquefaction or pyrolysis processes to produce an oil with a high demand for upgrading that is most suitable for utilization in big refineries or chemical facilities, mostly after pre-processing to enhance the quality.

In the case of **highly heterogeneous and contaminated plastics**, which may even contain toxic components, **gasification is the only classic thermochemical approach available** for generating products that can still be used as materials - in this case synthesis gas.

The incineration is among the least environmentally compatible options for treating plastic waste (cf. 3.4 LCA for chemical recycling of plastics). If the energy is recovered and the resulting CO_2 is captured and converted back into hydrocarbons with (regenerative) hydrogen (CCU), the climate impacts can be alleviated.

Not acceptable is landfilling of those materials, even if some groups and NGOs recommend this questionable approach, due to the supposed climate effect (designated as CCS).

Table 7 summarizes the characteristics and typical parameters of the different processes.

*Table 7: Options for recycling and other treatment methods for plastic waste (*depending on feed purity and polymer-solvent combination).*

Process	**Characteristics**	**Type and yield of products**
Mechanical recycling		
Melting & regranulation	- Energetically preferred option - Only applicable for clean and sorted mono-material - Number of recycling cycles limited	Polymers
Solvolysis	20 - 300 °C | 1 - 40 bar	> 90 % *
Depolymerization to monomers in specific solvents	- Very selective product recovery possible - Problems with real waste mixtures reported	Monomers Oligomers
Solution and precipitation of polymer chains		Polymer chains Oligomers
Liquefaction	300 - 400 °C | ambient pressure - 40 bar	70 – 90 % oil yield *
Depolymerization and cracking of plastic melt in unspecific hot organic liquid	- High effort for product upgrading - Blending into feed (currently discussed max. 10 %) in refineries and chemical plants	Organic liquid with a multitude of components
Pyrolysis	400 - 550 °C | ambient pressure	60 – 80 % oil yield *
Thermal decomposition and cracking in absence of oxygen	- High effort for product upgrading - Blending into feed (currently discussed max. 10 %) in refineries and chemical plants	Organic liquid with a multitude of components
Gasification	800 - 1600 °C | 1 – 50 (80) bar	ca 70 % cold-gas efficiency
Conversion with O_2 | H_2O | CO_2	- Extensive feedstock conditioning required - Sophisticated plant operation - Large effort for gas purification	Syngas ($CO + H_2$) with longer-chain hydrocarbons and contamination of tars, particles, hetero-atom-components (H_2S, COS, NH_3, HCl, HM) etc.
Incineration [& CCU]	850 - 1000 °C | 1 bar	depends on process chain
Oxidation (preferably as oxy-fuel-process), CO_2 capture and conversion with H_2	- Combustion well established - Technologies for CO_2 capture and hydrocarbon synthesis available - Complete process chain not yet realized (esp. oxyfuel operation)	Flue gas ($CO_2 + H_2O$) with contaminants of particles, hetero-atom-components (SO_2, HCl, NO_x, HM) etc.
Landfill		
Deposition in a secured and controlled area	- Loss of resources - Environmental pollution - Perpetual burden for coming generations	Long term deposition

3 Environmental impact

3.1 Potential risks from CR plant operation

To assess the potential risks associated with the operation of plants for the chemical recycling of plastic waste, a distinction has to be made between the regulatory constraints in which the plants are operated.

In regions with governmental supervision of plants and emissions, and highly developed waste management systems, CR plants will not pose a greater environmental risk than other waste treatment plants or thermal processes. Starting with the authorization procedure, the authorities set strict requirements for the emission limits and the treatment of waste that have to be complied with, and these requirements are continuously monitored during the entire life cycle of the plant. **Therefore, the operation of chemical recycling plants in regions with strong implementation of strict environmental regulations (e.g. Europe, North America, Japan or Australia) poses no higher threat to the environment than the operation of comparable industrial plants**.

A fundamentally different situation exists in countries which have no appropriate infrastructure or monitoring administration. In the absence of functioning, official control, the situation in such countries hardly encourages investments in environmental and health protection. Since CR processes involve the handling of substances that are potentially hazardous as additives and solvents or as (by-)products and residual materials, inadequate safety measures inevitably result in risks to humans and the environment. **In countries with insufficient or uncontrolled waste management, the installation of chemical recycling processes,** especially on a small scale, **should therefore be seen critically**.

3.2 Potential benefits and risks from detoxification and residue generation with CR

Since plastics are more or less decomposed during chemical recycling processes, there is generally the possibility of either precipitating or destroying contained impurities and pollutants. In thermal processes at higher temperatures, especially by gasification and even more so by incineration, organic pollutants can be destroyed. The contaminants transferred to the products (e.g. heavy metals, salts, inorganic gases or stable organic compounds) can be removed in the course of further processing and thereby withdrawn from the cycle. Oils produced in liquefaction and pyrolysis can be treated by hydrogenation, while the gases from gasification and combustion are purified by appropriate gas cleaning systems.

Consequently, **chemical and thermo-chemical processes** – in contrast to mechanical recycling – **could potentially remove pollutants during recycling**. With corresponding dissemination, the processes could therefore contribute to a detoxification of society's inventory.

However, it should be noted that the generated residues must also be treated in an environmentally responsible manner (incineration), with the corresponding effort and expense. **It cannot be judged yet whether the processes really offer an ecological advantage overall, since there is a lack of corresponding practical data**. Despite the number and diversity of existing life cycle studies on the chemical recycling of plastics, this important aspect in particular has not yet been examined, as **the fate of the residual materials produced has hardly been considered in the existing LCA studies** – although the fundamental detoxification function of chemical recycling is always emphasized.

3.3 Knowledge gaps regarding the environmental impact of CR

As chemical recycling of plastics has not yet been established on a notable scale, no data is available regarding the environmental impact of this new recovery method.

As already mentioned (cf. Chapter 3.1), the operation of CR plants poses no bigger risk to the environment than the operation of comparable industrial plants if the commonprinciples of environmental and emissions legislation are respected. However, it is currently not possible to predict whether the ecological benefits of detoxification of plastic streams postulated in Chapter 3.2 can be achieved. There is a lack of practical experience showing if in particular the destruction or separation of complex pollutant classes, such as flame retardants (based on bromine) or coatings with PFAS, is possible with CR.

3.4 LCA for chemical recycling of plastics

Life cycle assessment (LCA) is a methodology used to evaluate the environmental impact of a product, process, or system throughout its entire life cycle, i.e. from raw material extraction to production, use, and disposal. It can be used to assess the environmental footprint of waste management practices and to suggest choices to minimize it. In the last decade many LCA investigating the environmental impact of chemical recycling technologies have been conducted.

3.4.1 Rules for conducting LCA

The outlines, principles and framework for conducting Life Cycle Assessment are laid down in a set of international standards that are widely recognized and used globally as a foundation for conducting LCA allowing for a minimum of comparability of environmental performance between different products or systems: ISO 14040 [28] and ISO 14044 [29]. The ISO 14040 standard provides the fundamental principles, framework, and guidelines for conducting LCA studies. It establishes the basic concepts, terminology, and methodology for carrying out LCA. The ISO standard also outlines the four main phases of an LCA: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation of results. ISO 14044 builds upon ISO 14040 by providing more detailed guidance on the practical application of LCA. It covers data collection and quality, impact assessment methodologies, reporting, and critical review of LCA studies. It helps ensure that LCA studies are conducted consistently and transparently.

3.4.2 Impact categories of LCA

In order to evaluate the environmental effects of a system, LCA consider various impact categories. The lower the impact from any category, the better for the environment. Commonly considered impact categories in LCA that are relevant in the context of chemical recycling include, e.g.:

- Global Warming Potential (GWP): The contribution of a product or process to the emission of greenhouse gases, typically measured in terms of carbon dioxide equivalent (CO_2e) is assessed in this category. It’s a measure for a product’s or system’s impact on climate change.
- Acidification Potential (AP): This category measures the potential to release acidic compounds into the environment, which can lead to acid rain and harm ecosystems.
- Eutrophication Potential (EP): Eutrophication occurs when excess nutrients (e.g. nitrogen and phosphorus) enter water bodies, causing algal blooms and disrupting aquatic ecosystems. This impact category assesses this potential.
- Fossil resource depletion (FRD): this category evaluates the depletion of non-renewable resources, such as crude oil, natural gas, and coal. It considers the amount of resources extracted compared to their availability, helping to assess the finite nature of fossil fuel reserves.

Other impact categories might be considered but do not seem as relevant in the context of chemical recycling.

Due to the political relevance of climate change, the LCA category GWP is often named as the most important one. Whether this should be the sole environmental category on which to base decisions about future waste management is a political question to be answered based on scientific knowledge.

3.4.3 System boundaries in LCA

Determining the system boundaries of an LCA study is critical as those choices can lead to trade-offs and increase subjectivity if not chosen carefully. LCA can include the extraction of raw materials, manufacturing, transportation, use, and disposal or recycling.

In case of plastic waste, LCA can include the complete waste management chain, the waste treatment itself, the emissions from the processes involved and production of new material from recycling outputs or it can focus on the waste treatment technology itself.

3.4.4 Functional unit in LCA

The functional unit is defined as a reference unit for which the environmental impacts are assessed. It represents what is being produced, consumed, or used, and it is used as a basis for comparing the environmental performance of different products or systems. The functional unit is typically expressed in quantitative terms and can take various forms, depending on the goal and scope of the LCA study.

In waste LCA commonly one unit of waste (e.g. 1 t of mixed plastic waste) or in case of recycling sometimes one unit of produced product from waste is used (e.g. 1 t of recycled plastic).

3.4.5 Reference year in LCA

The reference year in a LCA is the specific year or time period to which the environmental data and inventory data in the assessment are related. It serves as a point of reference for quantifying and characterizing the environmental impacts associated with the life cycle of a product, process, or system.

In case of chemical recycling, the reference year is mostly relevant when considering assumed technological advances as it influences the reference systems used for calculating possible compensations (i.e. for energy production or raw material substitution). The choice has an impact on the outcome, accuracy and relevance of the assessment.

3.4.6 LCA on emerging technologies

When conducting an LCA on emerging technologies, Thonemann et al. [61] suggest that additional basic considerations should be respected: the Technology Readiness Level (TRL) of the technologies should be stated, expert interviews, literature data or estimated data should be used in order to overcome data availability issues and uncertainty and sensitivity analysis should be conducted to improve the interpretation of results. Additionally, Thonemann et al. emphasize the importance of an evaluation of the reliability of upscaling emerging technologies and recommend doing such an evaluation by analysing the up-scaling assumptions and models along with the development of a technology. The study recommends defining a standard approach for emerging technologies LCA in order to assure comparability and liability, as due to the generally broader approach compared to standard LCA there is more room for (mis)interpretation.

3.4.7 LCA on chemical recycling

Different approaches to LCA on chemical recycling can be found in literature. For comparing chemical recycling with other systems two different approaches can be chosen:

i) **Waste perspective**: Comparison of chemical recycling with other waste management options either on their own or in a system combining different waste management options, or
ii) **Product perspective**: Comparison of plastic material production from raw material originating from chemical recycling or from virgin material. Some studies

even use or combine both approaches in an attempt to paint the full picture. Depending on the choices made, LCA become arbitrarily complex.

The first LCA on chemical recycling go back to the late 1990s. Today's chemical recycling technologies are still comparable to then, but the waste management system in general has changed significantly in the last 25 years. Advances have been made in separate collection of plastic waste, mechanical recycling and energy recovery from incineration.

It is important to note that not all LCA use the term chemical recycling as defined in this study, e.g. some studies include physical recycling (solution and precipitation), others define even the production of fuel as chemical recycling. Older studies often use 'feedstock recycling' congruently to chemical recycling (as defined in this study or including other processes).

Overall, a wide variety in chemical recycling technologies and waste input streams are covered in chemical recycling LCA. The technology most often addressed in LCA for chemical recycling is pyrolysis, followed by gasification (e.g. [2][10]). Solvolysis is also considered in some LCA but due to its more specific waste input streams, it is less used in studies addressing mixed plastic waste. Many of the reviewed LCA define one unit of mixed plastic waste or mixed plastic packaging waste as their reference unit but some also cover specific waste streams such as PLA [9] or PVC [37].

Some (older) studies consider fuel production as chemical recycling [20]. As this is excluded from the definition used in this report, such results are not discussed here. Other studies include landfilling as a valid option for plastic waste. Results where landfilling performed best (e.g. [13]) are also not discussed due to non-alignment with the European waste hierarchy. Eriksson and Finnveden [20] also found that landfill scenarios may pose greater environmental impact if the temporal boundaries would be extended due to the extreme longevity of the impact of landfills compared to any other waste treatment option.

3.4.8 Examples for LCA of chemical plastics recycling

An extensive literature review on LCA for chemical recycling has been conducted. Four relevant reviews were found [2][10][33][39]. Fact sheets on more than 20 LCA covering various aspects of chemical recycling can be found in Annex 1 – Fact sheets: LCA-studies. Individual LCA studies were chosen to be discussed in detail in this report ensuring the coverage of all chemical recycling technologies and due to their relevance and actuality.

All reviews on LCA of chemical recycling have some overlap of the included original studies (e.g. [9][32][45]). However, their approach on choosing the reviewed studies was different. While Antelava et al. [2] only focused on GWP in studies, Lazarevic et al. [39] chose as main criteria that the LCA followed the ISO 14040 framework, was transparent with system boundaries and assumptions, and was able to support decisions in plastic waste management systems. Davidson et al. [10] and Jian et al. [33] did not list any specific criteria for their selection.

Lazarevic et al. [39] give a very detailed review on results from LCA. The reviewed LCA allow for a summary of results in different impact categories. **It was found that mechanical**

recycling is generally preferable to chemical recycling and incineration for most impact categories (e.g. GWP, ARD and EP). This conclusion is backed up by the review by Davidson et al. [10] who even state that any recycling is better than any incineration. The latter study, however, did not state which impact categories were investigated.

For plastic waste fractions that are not currently mechanically recycled, Lazarevic et al. [39] found that chemical recycling is preferable to incineration but incineration in a cement kiln performs equally. However, this review also indicates that the results for some impact categories are very dependent on the waste input and even municipal solid waste incineration may perform better than chemical recycling.

The reviews agree that assumptions on virgin material substitution rate and amount of organic contamination strongly influence the results and thus **recycling (mechanical or chemical) may even show lower environmental benefits than other treatment options such as incineration with energy recovery if low substitution rates and high contamination is assumed**. In general, system boundaries and overall assumptions (substitution rates, energy system etc.) have an important impact on the outcome of an LCA [39]. Antelava et al. [2] also stated that results of the LCA studies examined in their review showed considerable variation even for similar waste types and technologies.

Furthermore, a general lack of information on key issues was identified, such as the scope description of the LCA or more specific information on emissions or residue management [2]. Nevertheless, the review concludes that pyrolysis is an advanced waste treatment technology for plastic waste treatment and the minimization of environmental burdens, leading to the assumption that pyrolysis will potentially play a key role in the future of plastic waste treatment.

In a very recent study by Klotz et al. [27] an LCA of waste management in Switzerland was conducted in order to assess the contribution of chemical and solvent-based (solution and precipitation) recycling on GWP in the future (reference year 2040). Only such waste streams that are currently (and most probably in the future) not mechanically recycled were investigated and attributed to gasification, pyrolysis, solvolysis and solvent based recycling, depending on the technical feasibility of the individual processes. As a main result the study found that the **climate change impact of chemical or solvent-based recycling processes for plastic waste ranges from values similar to incineration (MSWI or incineration in cement kilns) to benefits achievable from mechanical recycling**. Solvolysis (and solvent based recycling) should be prioritized among chemical recycling technologies where possible, due to the higher value products and lower climate impact of the processes. The authors stress that the benefits achievable with chemical recycling are not only dependent on waste input, assumed product quality etc. but also on the process performance at large scale, which is currently mostly unknown.

An LCA focusing on pyrolysis of mixed plastic waste was commissioned by BASF in 2020 [54] and published as a peer-reviewed paper in 2021 [32]. Three different approaches were chosen in this study: the waste perspective where the treatment of mixed plastic waste was compared to treatment in MSWI and incineration in a cement kiln, the product perspective where production of plastic from pyrolysis oil and virgin raw material was compared and a second product perspective where various qualities of plastic products were taken into account. For the waste perspective the **GWP for pyrolysis was found to be lower than for MSWI**. The GWP of incineration of mixed plastic waste in cement kilns is dependent on the assumption what material is substituted in the process: assuming that other alternative fuels (e.g. tires) are substituted leads to a high GWP and thus pyrolysis would be favorable but assuming that lignite is substituted leads to a strongly decreased GWP and incineration in cement kilns becomes favorable. The latter assumption is also made in other studies, e.g. [40]. In **all other impact categories (AP, EP, POF) investigated by Russ et al. MSWI and incineration in cement kilns perform better than pyrolysis** due to credits from electricity production. The study also showed that results were sensitive to changing assumptions around pyrolysis efficiency and GWP was even more favorable for pyrolysis when high overall process efficiencies (of up to 87%) were assumed.

The JRC (Garcia-Gutierrez et al. [23]) also recently conducted a very broad LCA on chemical recycling, including a total of 27 different scenarios. As chemical recycling technologies they included solvolysis, pyrolysis and/or gasification, depending on the scenario and chosen input material. A total of 14 impact categories were investigated but focused on GWP, PMF, AP and FRD, which the authors identified as most relevant for chemical recycling. In line with results from other LCA Garcia-Gutierrez et al. found that **any kind of recycling is preferable to energy recovery (MSWI) in all scenarios, especially in the case of mixed polyolefin waste that is currently not mechanically recycled, when it comes to impact on the GWP**. However, for **other categories such as AP, PMF, HT or EP, energy recovery can perform better** than energy intensive recycling pathways due to credits from energy production. The study stresses, however, that the benefit from these compensations will reduce with a shift to renewable energy in future, leading to less favorable results for energy recovery. Overall, the results of the study do not provide a clear recommendation whether chemical recycling is a favorable option and how to include it into future management of plastic waste. Nevertheless, they name three main criteria that should be observed: i) the maximization of material recovery while minimizing processing impacts, in line with the waste hierarchy, ii) the specificity of the plastic waste stream and the treatment thereby required (technical feasibility), iii) the economic feasibility. The authors also stress the need for **more reliable data on waste input to be able to determine potential competition of mechanical and chemical recycling as well as the technical feasibility of chemical recycling for the different plastic waste streams**.

Several LCA focusing on gasification have been published by a research group from TU Bergakademie Freiberg in Germany in the last years (e.g. [34], [67], [68]). All studies focus mainly **on GWP and conclude that gasification is preferable to incineration independent of the input waste stream** (municipal solid waste, light weight packaging waste or others). The technical feasibility of gasification to treat investigated waste streams was not part of the LCA and in general ideal conditions for substitution rates (energy, material etc.) were assumed. In Voss et al. 2021 [67] and Voss et al. 2022 [68], outputs from gasification were identical even though different waste streams were used as input (municipal solid waste and light weight packaging waste, respectively).

LCA on more specific waste input streams were published e.g. by Kreißig et al. [37] and Cosate de Andrade et al. [9] with the former focusing on PVC from mixed cable waste and the latter on waste streams containing PLA.

PVC from mixed cable waste was found to be suitable for solvent-based recycling (i.e. solvolysis) in case of relatively pure waste streams while pyrolysis and incineration were better suited for mixed waste input [37]. However, GWP was highest for incineration, followed by pyrolysis and lowest for solvent-based recycling, independent of the waste input. As PVC is difficult to recycle mechanically, this option was not considered.

Biodegradable plastics like PLA are often used in consumer products like packaging, thin plastic bags or disposable cutlery. In an LCA Cosate de Andrade et al. [9] compared solvolysis, mechanical recycling and composting to treat PLA waste. Mechanical recycling was identified as the option with the overall lowest environmental impacts. Composting was the least desirable option for treating this waste stream, mainly due to the fact that the two other options produce a polymer product but the PLA has no positive impact on the compost produced.

3.4.9 Executive summary of LCA

The category **GWP is addressed in all reviewed LCA** and often named as the most important one. The political decision about the relevance of different LCA categories should be taken based on scientific knowledge.

For those waste streams for which **mechanical recycling** is an option, it **generally performed better than any other option** (for most impact categories of most of the reviewed LCA).

One of the **main influences on LCA results are substitution rates for energy and material** assumed in the respective LCA. Varying substitution rates can e.g. completely change the output of an LCA. Choosing low material substitution rates can decide whether mechanical recycling is considered favorable or not to chemical recycling in terms of LCA impact categories.

In the following, results for individual impact categories are given:

- **Global warming potential (GWP)**: **Mechanical recycling performs best** for those waste streams where it is applicable. **Chemical recycling always performs better than MSWI**. **Incineration in cement kilns often performs better than chemical recycling** when lignite substitution is assumed. In those LCA where plastic waste substituted other alternative fuels for cement production, GWP for chemical recycling is lower than for any incineration.
- **Eutrophication potential (EP)**: This category is mainly determined by nitrogen (and phosphorous) emissions from industrial processes and influenced by compensations from energy production or use. Therefore, in many studies, **any kind of incineration**

shows lower EP than chemical recycling when energy production is substituted (energy production from fossil fuels has a high impact on this category).

- **Acidification potential (AP)**: The acidification potential is mainly caused by sulphur dioxide and nitrogen oxide emissions. As for EP it is closely related to energy use and production. Thus, **incineration shows lower AP than chemical recycling when energy production is substituted** (energy production from fossil fuels has a high impact on this category).
- **Fossil resource depletion (FRD)**: **Chemical recycling often performs better than mechanical recycling or incineration** due to the assumption of higher substitution rates and higher quality products than from mechanical recycling.

Only some of the reviewed LCA studies contain enough description of the LCA modelling and of the technologies themselves (e.g. technical feasibility, air-pollution-control, residue management) in order to generate a meaningful link between the functional unit, the waste composition and the waste technology assessed. Thus, the results cannot be assessed in depth nor validated.

A problem when dealing with emerging technologies in LCA is the often unknown technical reality of upscaling and, thus, **unrealistic assumptions for chemical recycling technologies** are used but realistic conditions are applied to state-of-the art technologies. Even though this is addressed in many LCA, the studies often draw conclusions on the environmental impact of different technologies without the underlying data supporting the conclusions fully. As Meys et al. [30] pointed out, it may be challenging for chemical recycling technologies to compete with these state-of-the-art technologies like energy recovery in cement kilns and mechanical recycling under more realistic conditions.

It was not possible to compare different LCA because no two LCA have chosen the same system boundaries, waste input, general assumptions etc.

In order to create comparable LCA under realistic assumptions a standard approach for LCA on emerging technologies is needed. As of now, the described limitations of LCA on emerging technologies unfortunately limit their value for decision makers.

4 Governance

4.1 Current status

4.1.1 Legal framework on CR

At the moment there is **no specific legislation within the EU addressing chemical recycling** or even plastic waste as such. However, the legal framework for chemical recycling within the EU is set by the Waste Framework Directive [18], which defines the 5-tier waste hierarchy (prevention – preparing for re-use – recycling – recovery – disposal), and the Directive on Packaging and Packaging Waste (short Packaging Directive [15]). Furthermore, the work on implementing the regulation corresponding to the "Single-use Plastics Directive" or short "SUPD" [16] will probably address the allocation rules for a mass balance approach (cf. chapter 4.3.3).

The Waste Framework directive also addresses the general topic of "end-of-waste" criteria. Currently there are different sets of rules for certain waste types (e.g. iron, steel and aluminum or copper scrap, glass cullet) but not so for plastic waste. However, the JRC is currently working on a proposal that is expected for Q1 of 2024.

Overall recycling targets for different waste streams are set by the Waste Framework Directive. More specific recycling targets for certain packaging types (i.e. plastic packaging) are defined in the Packaging Directive.

Countries and regions even within the EU have very different authorization procedures, environmental and safety regulations and policies regarding chemical recycling. Some may consider these technologies as waste treatment, some as thermal waste treatment processes, while others may recognize them as forms of manufacturing of fuels or chemicals. In general, the categorization for authorization is decided by the competent authority if there is no overall legislation.

4.1.2 Industry pledges on CR

The European chemical industry has the goal to reach climate neutrality by 2050 (some national chemical associations even until 2045, e.g. VCI in Germany) [6][11]. On a global level, no such concrete goals for reducing the climate change impact of the chemical industry can be found, but the ICCA responsible care status report from 2018 highlights the importance of sustainable development of the industry [26].

One of the pillars to reach climate neutrality in the chemical industry is chemical recycling (e.g. [60] [65]), including CCU from thermal processes such as MSWI, cement kilns or power plants. When it comes to the contribution from chemical recycling, the industry states that "as secondary raw materials, plastic waste can cover a large part of the carbon requirements of the chemical industry" [64]. Studies like the one recently published by Agora Industrie emphasize this as well [1].

In order to be able to reach their goal, the industry makes various demands on policy: including chemical recycling in the waste hierarchy, accepting the mass balance approach, defining end-of-waste criteria, funding of chemical recycling projects etc. These topics are covered in detail in Chapter 4.3.

4.1.3 Public perception

Chemical recycling has received a lot of public attention in the last five years. This is mainly due to stakeholders of various industry sectors (chemical industry, waste management and plastic producers) announcing countless projects to be initiated all over the world. These press releases paint the picture of chemical recycling as a technology which is ready to be applied to plastics recycling any time at industrial scale and with numerous advantages compared to state-of-the-art technologies in waste management.

Many environmental NGOs, however, **are concerned about the environmental impact of chemical recycling processes** [44][58]. They argue that while these processes may divert plastic waste from landfills and incineration, they may also involve **the release of harmful chemicals and greenhouse gases**. NGOs often call for thorough life-cycle assessments to determine the net environmental benefit of chemical recycling compared to other waste management options. Concerns over the technological readiness and scalability of chemical recycling processes are also often raised. It is emphasized that there is a need for rigorous testing and evaluation to ensure that these technologies can deliver on their promises without causing unintended harm. NGOs emphasize that the energy and resources required for chemical recycling processes may outweigh the benefits in certain cases. Additionally, the question whether chemical recycling is the most efficient use of resources when compared to traditional recycling or reduction of plastic production is raised. The need for transparency and accountability in chemical recycling operations is also often underlined (see chapter 4.3.3 [59]. Environmental NGOs advocate for strict regulatory oversight and monitoring to ensure that these processes are carried out safely and without harm to human health and the environment.

In an open letter some NGOs demand “that only chemical recycling technologies which produce polymer materials are legislated as ‘recycling’ while processes that produce feedstock for petrochemicals are defined as ‘chemical recovery’”[72].

4.2 Impact of CR on society and plastic waste treatment industry

At present, it is not yet possible to judge whether and to what extent chemical recycling may have an impact on our society and the way plastic waste is treated. This will largely depend on whether the approach can gain a relevant share of the plastic recycling market.

4.2.1 Impact on countries with well-developed and controlled waste management

In nations with high safety standards, as previously mentioned, **running a chemical recycling plant poses no higher threat to the environment than the operation of comparable industrial plants.** Positive effects, for example through detoxification, are postulated, but must first be proven.

A fundamental problem may arise from creating a lock-in effect by the construction of plant infrastructure for the new technologies on a larger scale. Once the currently planned chemical recycling projects, which are being massively promoted through subsidies (e.g. in the EU), venture capital and corporate investment, have been implemented, they will also have to be supplied with feedstock. It is already evident that bottlenecks in the supply of feedstocks are to be expected in certain regions when all the announced projects are implemented. Under certain circumstances, this could lead to mechanical recycling processes being disadvantaged or even cut off from feedstock supply and squeezed out of the market, since the new CR approaches, as mentioned above, receive massive financial support. **To protect the environmentally advantageous mechanical recycling against market distortions, suitable mechanisms must therefore be introduced by the legislator in time**.

4.2.2 Impact on countries with less or uncontrolled waste management

In many countries around the world, the infrastructures and the governmental controls are insufficient to ensure environmentally sound operation of waste management facilities, thus creating a risk to environment and health (cf. Chapter 3.1). Under such circumstances, **technically demanding processes with potentially hazardous material flows should not be implemented**. The risks associated with plant operation cannot be controlled and in case of accidents or violation of regulations, effective countermeasures can hardly be implemented. Another reason why the **operation of plants for chemical recycling of plastics is not recommended in countries with less or uncontrolled waste management**, is that the operation of such plants could encourage the shipment of plastic waste to these countries, with the **risk of large material quantities entering improper disposal routes**. This has recently been the subject of initiatives by affected countries, resulting in more stringent regulations.

4.3 Classification within the legal framework

4.3.1 Chemical recycling in the waste hierarchy

As pointed out before, no legally binding definition of chemical recycling exists yet. Nevertheless, its position in the waste hierarchy is already being discussed. Figure 20 shows the connection between definitions on legal and technological levels, which are not congruent. The European waste hierarchy is depicted on the left side and the different technologies and the corresponding technological classification is shown on the right. The product resulting from the chemical recycling (i.e. pyrolysis, liquefaction, gasification) determines the categorization in the waste hierarchy. Taking pyrolysis as an example, **it is crucial for the legal classification whether a raw material for the chemical industry is produced** – pyrolysis would then be considered a recycling process – **or whether a fuel is produced** – the same pyrolysis technology would then be considered to be an energy recovery process.

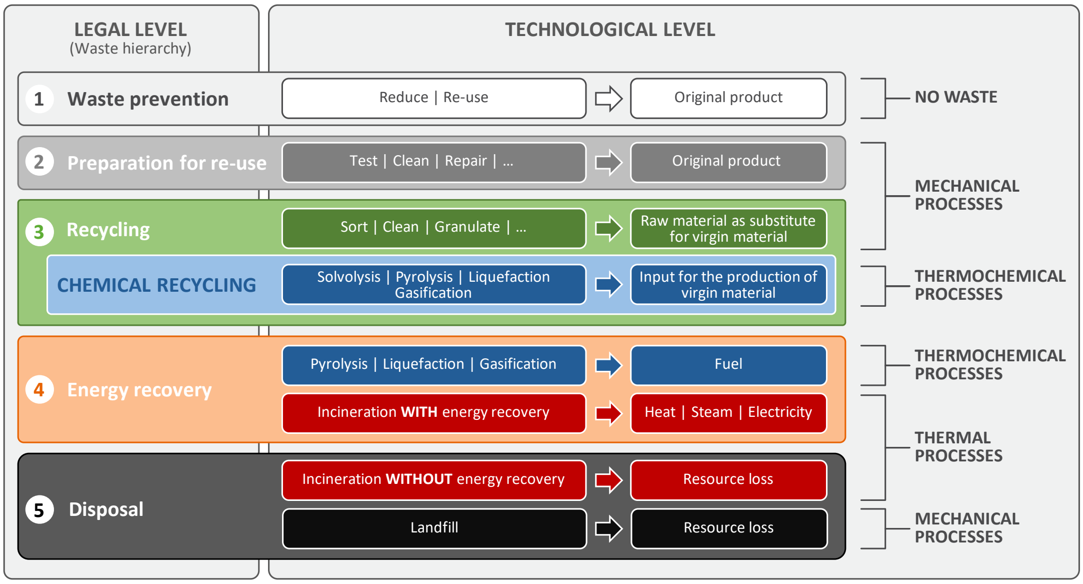

Figure 20: Legal and technological levels of plastic waste treatment options (figure: P. Quicker) [51].

The industry in general expects chemical recycling to be classified as a treatment option on the third level of the waste hierarchy (recycling), as shown in Figure 20 (e.g. [12][60]). The NGO Zero Waste Europe on the other hand suggested to expand the waste hierarchy into a seven-step hierarchy [70]. While the first expansion step at the top of the hierarchy deals with reducing waste in general, the second expansion includes a separate hierarchy level for chemical recycling. This level, called “material and chemical recovery” and described as “technologies to recover materials from mixed waste and discards from sorting processes into new building blocks for high quality applications” is set between recycling and energy recovery (which for the purpose of Zero Waste Europe was renamed to “residuals management”).

4.3.2 End-of-waste criteria

End-of-waste criteria define the point in the recycling cycle when a material is not considered a waste anymore. The criteria ensure it fulfills the technical requirements of the industry as well as the legal requirements for products and does not lead to environmental or health damage. For a successful implementation of chemical recycling in a waste treatment system in Europe, the **definition of the end-of-waste criteria is essential** as the whole chemical production chain can be influenced depending on the point set for end-of-waste.

For mechanical and physical recycling processes the definition of end-of-waste is relatively simple: the output from the recycling process are sorted and cleaned polymer flakes or regranulated pellets. These possess a market value and are sold as raw material for plastic production. Reaching end-of-waste status may be defined at one of those two easily detectable points in the production chain.

For chemical recycling technologies the situation is more difficult. It would in general be possible to choose the point in the recycling chain when a polymer recyclate is produced. This would be in analogy to mechanical recycling. However, this approach presents several problems:

First of all, processes vary widely, so that it is unlikely that one common point in the production process can be chosen for all chemical recycling technologies. Furthermore, chemical production plants mostly do not have an authorization to use wastes as input material. In order to use monomers from solvolysis, pyrolysis oil or syngas as input, it would therefore be necessary to define the end-of-waste for those chemical recycling “intermediate products” before they enter a production plant for further processing.

4.3.3 Mass balance approach

On EU level the mass balance approach for recycling content from all chemical recycling technologies is currently being discussed in the course of the work on the implementing regulation corresponding to the “SUPD” [16]. The decisions taken in this context are likely to set a crucial precedent for future circular economy strategies by providing for mandatory minimum recycled content requirements for plastics in packaging and all other markets. Furthermore, this regulation’s new allocation rules for determining recycled content for recycling methods where a physical traceability is not possible will probably set the standard for all future regulations.

If a physical separation and tracing is not feasible due to the complexity of the production processes and the product use in numerous markets, **the mass balance approach can be used** [30].

Mass balance provides a model of the chain of custody where inputs and outputs are monitored and ideally certified by third parties (e.g. independent certification organizations such as ISCC [27]) at each step of the production process. It is critical to ensure the **credibility and transparency** of the recycled content claims in order **to prevent greenwashing** and enable consumers to take informed decisions. The EU suggested a so called “Green Claims Directive” [17] with the aim to create a level playing field and solid framework for claims on sustainability of products. Different methods – proportional or credits – can be used for allocation.

The so-called **rolling average** (Figure 21, top) is a proportional allocation system, where the ratio of recycled to virgin input materials is proportionally assigned as recycled content to each unit of output [3][30], i.e. a product is sold as being X % recycled based on the ratio of recyclate (pyroil) and virgin (fossil naphta) input material (in case of the example in Figure 21, the recycled content of all products would be 10%). This percentage is attributed to the complete batch and averaged over a certain time period. This ensures that the actual recycled content of final products is known and a physical link between input and output is established [69].

In a mass balance system (cf. Figure 21), the **credit methods** establish and allocate “credits” of recycled content to certain outputs [30]. **With a credit method, credits for recycled content can be freely allocated, within certain limits, among products in a non-proportional way**. Different methods for non-proportional allocation are currently discussed for chemical recycling, e.g. within the SUPD framework [3]:

- **Free allocation**: all credits can be allocated freely between products and even production sites. The latter is also called group level or multi-site mass balance. Therefore, assuming 10% feedstock from pyrolysis oil, theoretically 10% products with 100% recycled content could be sold (cf. Figure 21).
- **Proportional allocation**: all credits are allocated proportionally to all products produced. Within a product group allocation is free to any produced product. Cf. Figure 21: If 10% pyrolysis oil is used as feedstock and 10 % of polymer A is produced, 1 out of 10 products produced from polymer A could be sold as having 100% recycled content. This applies in analogy for every polymer produced. The overall recycled content in polymer products would be 3% under the assumption that 30% polymers (P_1 + P_2) are produced in the chemical plant. Additionally, also the other products from the chemical plant could be labelled as containing material from plastic waste.
- **Polymers only**: only those outputs that are directly linked to the production of polymers can be allocated freely within the polymer product group; all others are not accounted towards the recycled content of polymer products. Theoretically, polymer products can be sold as having 100% recycled content. Cf. Figure 21: if 10% pyrolysis oil is used as feedstock and in total 30% polymers are produced 3 out of 10 products produced from any polymer could be sold as having 100% recycled content. Additionally, the other products from the chemical plant could be labelled as containing material from plastic waste.
- **Fuel use excluded**: all outputs can be counted toward the recycled content of polymer products, except those that are used as fuels for energy purposes. Theoretically, products can be sold as having 100% recycled content Cf. Figure 21: if 10% pyrolysis oil is used as feedstock and in total 30% polymers, 40% other products and 30% fuels are produced, 7 out of 10 polymer products could be sold as having 100% recycled content. The overall recycled content in polymer products would be 7%. Additionally, any kind of product from the chemical plant could be labelled as containing material from plastic waste.

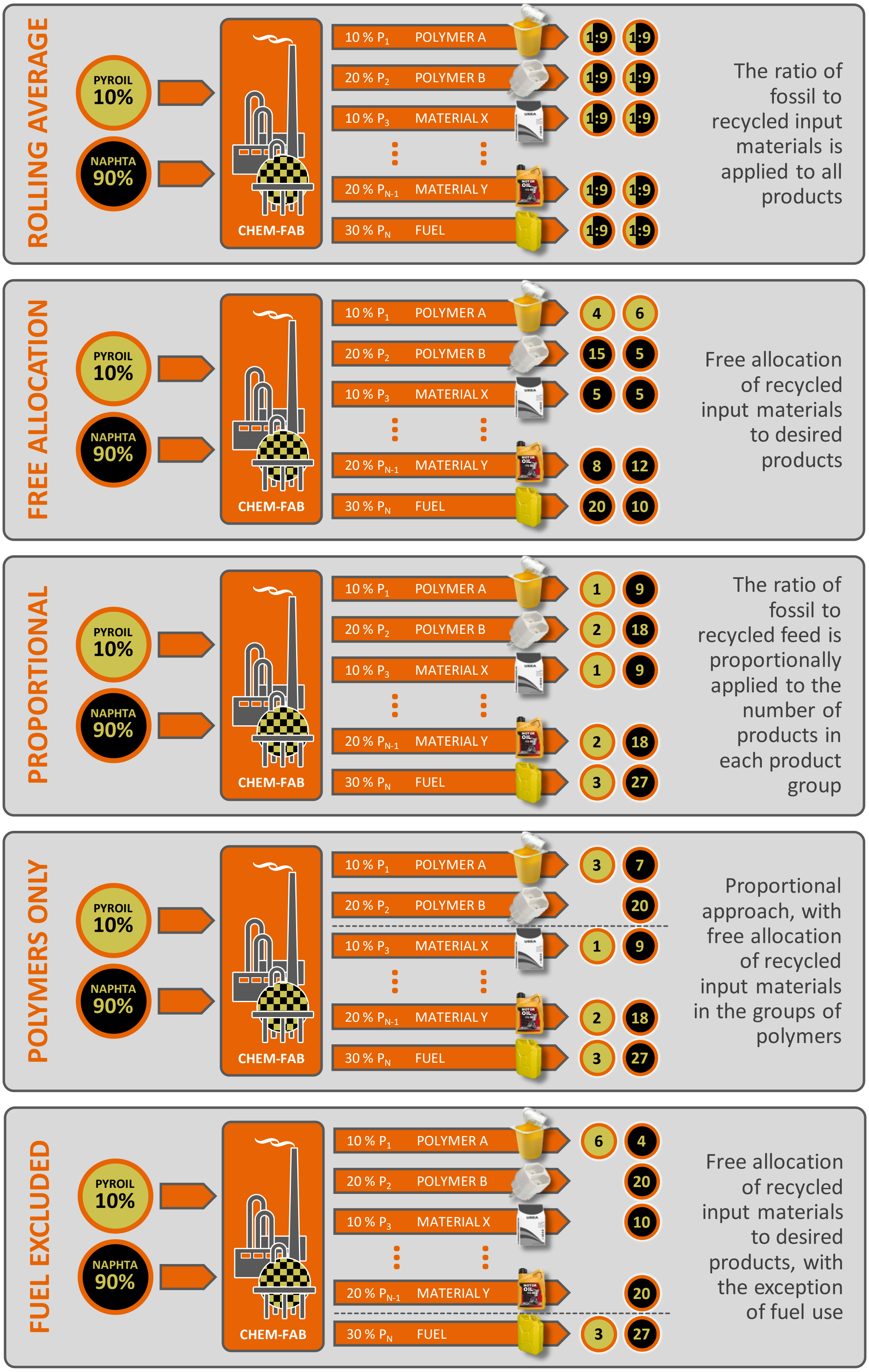

Figure 21: Options for implementation of the mass balance approach (P_x describes different product lines. Pyroil = oil from pyrolysis; Chem-Fab = Chemical fabrication. (Figure: P. Quicker).

Within the frame of the chosen credit method the producer is thus able to e.g. sell products with up to 100% attributed recycled content and other products with 0% attributed recycled content, while the recycled content is actually the same for all products (the average recycled input). When using the rolling average all products contain the same percentage of recycled content.

The **free allocation** with credit transfer allows the producer to attribute the recycled content to the products of his choice, e.g. with the highest market value, even though these products contain the same amount of recycled content as other products from the same producer. Therefore, producing such products containing chemically recycled material becomes advantageous compared to the use of mechanically recycled material as a free allocation is not possible in systems with a physical traceability. The industry clearly favors this calculation method or as a compromise a fuel use excluded allocation [19] and states that investments into chemical recycling projects will probably not be carried out if a stricter approach is chosen [48].

The use of **proportional allocation** systems for determining recycled content from chemical recycling results in an allocation of the recycled content that is closer to the physical reality of the production process [69]. Therefore, it may lead to more equal opportunities for both mechanical and chemical recycling as recycled content in mechanically recycled products is often restricted by technical feasibilities. NGOs and some Governments (e.g. Germany [14]) prefer this type of allocation method if a mass balance approach is necessary (e.g. [25][60][71]) but go as far as to suggest that the best option would be to physically segregate recycled and non-recycled feedstock in the production process [59].

There is agreement, however, that independent, traceable, third-party certification systems are needed to be able to declare the recycled content in plastic products in order to inform consumers and avoid greenwashing [47][65].

4.4 Recommendations on governance and legal framework

4.4.1 Administrative recommendations

4.4.1.1 Authorization

Chemical recycling technologies are considered to be thermal processes (exception solvolysis or solvent-based recycling). Also, the EU BREF Waste Incineration includes gasification and pyrolysis in the emerging techniques section (they were not considered state-of-the-art at the time of compiling data for the BREF as no industrial plant was running). Therefore, **the authorization for chemical recycling should follow the authorization process of waste incineration**. In case of availability of industrial plants at the time of the next EU BREF update, chemical recycling plants should be integrated into the BAT conclusions.

4.4.1.2 CO_2 taxes | CO_2 emissions certificates

Chemical recycling should be treated equally to waste incineration, meaning that those emissions which result from energy recovery are taxed, e.g. the emissions of that part of the pyrolysis gas which is used (internally) for energy supply. This ensures equality of different thermal processes resulting in energy production.

4.4.1.3 Support for chemical recycling

If the political will is to support chemical recycling as an emerging technology in waste management, different options are available. One option is the establishment of so called “living labs”. Those enable innovative processes to be tested in a real-life environment with scientific support and feedback. Apart from governmental partial funding of the living labs, experimental authorizations that allow for more flexibility in operating the plant are often granted. Those authorizations are only valid for a limited period of time and must then be transitioned into “real” authorizations if the plants are transferred into real industrial operation. In order to harmonize the handling of such living labs, a general set of rules on the design, authorization process and scientific program to follow would be useful. This also would ensure comparable conditions in different countries.

Any other options to technically, legally or financially support chemical recycling will be a decision on a policy level and dependent on the question whether chemical recycling is a route to be pushed forward or not within a specific country.

4.4.2 Policy recommendations

4.4.2.1 Legal definition for chemical recycling

An internationally recognized or even legally binding definition for chemical recycling is essential. The term is not used consistently in scientific studies or the general discussion. This leads to confusion about processes included in chemical recycling and ambiguity about the waste hierarchy level those processes are to be assigned to. A clear definition would ensure compatibility of different legal regulations and planning security for businesses.

The definition developed in a stakeholder process for the German Environment Agency could be used as a blueprint (cf. Chapter 2.1):

“Chemical recycling of plastics refers to process chains in which polymers are completely or partially broken down into their components and subsequently used as a feedstock, to produce new polymers or other substances, and – apart from by-products or residual materials – are not used for energy recovery.”

4.4.2.2 Waste hierarchy

No expansion of the waste hierarchy system as presented in Figure 20 is needed if an internationally recognized definition is used for chemical recycling. In Europe the Waste Framework Directive (Article 4 paragraph 2) already includes a requirement for the best environmental treatment option:

"When applying the waste hierarchy referred to in paragraph 1, Member States shall take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by life cycle thinking on the overall impacts of the generation and management of such waste. […]"

This principle could have worldwide recognition for waste management in general. Combining it with an internationally recognized or legally binding definition for chemical recycling should be sufficient to guide decisions on waste management strategies.

4.4.2.3 End-of-waste criteria

A general definition of end-of-waste criteria is necessary to ensure equal opportunities for all chemical recycling plants as well as planning security for companies. This would also help the administrations which issue authorizations. To this end, a checklist of detailed characteristics, which a chemical needs to fulfill to reach product status, would be a practical tool. However, it is necessary to **differentiate between chemical recycling technologies when defining the point for reaching end-of-waste** status:

- Solvolysis: purified monomer, suitable to replace virgin monomer as a raw material for polymerization
- Pyrolysis: pyrolysis oil with a quality that allows for use in a steam cracker (depending on specific plant parameters but also general specifications according to REACH)
- Gasification: syngas in quality needed for downstream processing (depending on specific plant parameters but also general specifications according to REACH)

4.4.2.4 Mass balance approach

The need to use a mass balance approach for chemical recycling is undeniable as a physical tracing of recycled material is next to impossible in common production processes of the chemical industry. A strict set of rules regarding allocations is necessary also in order to establish comparability between waste treatment options.

The **rolling average allows to portray reality as correct as possible** without the need for a physical traceability as it incorporates realistic shares of recycled raw material used for manufacturing products (e.g. pyrolysis oil used in steam cracker processes). This could however mean that chemical recycling technologies would not be able to reach targets for recyclate use in products. For example, if the maximum possible share of pyrolysis input into a steam cracker is 10% (due to availability of waste or technical restrictions), a 20% target for recycled content in food packaging could not be reached by chemical recycling only.

Choosing the less strict system of free allocation and credit transfer would lead to economic advantages for chemical recycling, as "chemical recyclers can attribute the recycled content to products with the highest market values and increase financial benefits." [4]. Approaches like the polymers only or proportional allocation credit systems should be preferred, in order to maintain a minimal equality between mechanical and chemical recycling. **Allowing**

transfer of credits between production sites should be avoided as traceability is lost and possibilities for greenwashing amplify.

Setting targets for recycling rates or recyclate input rates in such a way that recycling technologies in general are able to fulfill the demands or not is a political decision. Requiring high rates which are not (yet) reachable could incentivize technological innovation and increase recycling. Using recyclates in food contact applications is so far only allowed for chemically recycled recyclates (apart from separately collected PET beverage bottles which are mechanically recycled). Therefore, it is recommended that the political decision on targets considers the capabilities of these technologies. Allocation rules which do not allow unrealistic calculations in order to maximize recyclate content should be chosen.

5 Summary and conclusions

In the course of this study, the technologies for chemical recycling of plastics were discussed and evaluated with regard to:

- **technology**
- **environmental impact**
- **governance**

In the following, the main findings of the study are summarized, possible risks and opportunities of chemical recycling of plastics are presented and, finally, recommendations for the management of chemical recycling are given in a compact form.

5.1 Current status

5.1.1 Technology

Process approaches for chemical recycling of plastics include **solvolysis, liquefaction, pyrolysis and gasification**.

Although single processes have been in operation for years, **chemical recycling of plastics as a whole cannot yet be described as a state-of-the-art technology**. Particularly in the case of contaminated input material, problems occur in practice. Consequently, many attempts to implement a process fail at the development stage or during commissioning. Due to the complexity of the processes in connection with the demanding feedstocks, it is **not to be expected that chemical recycling can reach similar availability and operational times as waste incineration**.

It can generally be stated that the processes of chemical recycling have significant **economic disadvantages compared to incineration with energy utilization**, due to the considerably higher effort. It is also assumed that chemical recycling has economic disadvantages over mechanical recycling.

5.1.2 Environmental impact

For those waste streams for which **mechanical recycling** is an option, it **generally performs better than any other option**.

LCA studies consistently postulate an ecological benefit of chemical recycling on global warming potential GWP. Due to the usually chosen comparative scenario of incineration, in which all the carbon contained in the plastic waste material is released as CO_2 into the atmosphere, the (calculative) complete material use of the products from chemical recycling inevitably leads to advantages of CR in this criterion.

It should be noted, however, that **many studies do not consider the treatment or disposal of by-products and residual materials of chemical recycling**. Since the amounts of generated residues can be quite relevant (depending on the quality of the waste feed), this simplifying assumption may distort the assessment significantly.

Regarding the other investigated criteria in LCA, chemical recycling often shows disadvantages compared to energy recovery, e.g. in eutrophication (EP) or acidification potential (AP), depending on the selected scenarios and framework conditions.

5.1.3 Governance

5.1.3.1 Stakeholder positions

Industry is currently generating the greatest impact on the chemical recycling topic. The idea that the chemical recycling of plastic waste could in future contribute significantly to the carbon supply of the chemical industry has gained acceptance among companies active in that field. Since the availability of suitable input material is fairly limited, **many large companies are in a rush to invest in this area**.

Legislators have so far paid little attention to the issue. **NGOs are concerned** that the new approaches are causing environmental damage.

5.1.3.2 Administration and policy

So far, no specific administrative or political regulations concerning chemical recycling are established (c.f. chapter 4.1.1).

5.2 Risks and opportunities

5.2.1 Framework conditions to establishment of CR industry

The operation of technically sensitive plants for the chemical recycling of plastics has to be regarded as a permanent technical risk and is associated with economic disadvantages compared to the established (state of the art) processes of energy recovery.

A long-term takeover of the recycling market by CR processes therefore seems unlikely under the general conditions of a free market economy. Due to the high expenditure for the preparation of the input materials and the cleaning of the generated products, together with continuously occurring operating problems, **high economic burdens** are constantly created, which cannot be eliminated even in the long term. In addition, **suitable input materials for the chemical recycling processes are limited**.

Nevertheless, due to the socio-political situation and the available financial resources, a large number of processes is currently under development and corresponding pilot plants are realized. The opportunities and risks that arise are dependent on the specific environment and the general conditions of the respective countries.

5.2.2 Risks from chemical recycling

In countries with well-developed and controlled waste management, there is a risk of "cannibalizing" mechanical recycling by extensively funding and investing in chemical recycling. This means that the market may **shift away from mechanical recycling**, which is undoubtedly the ecologically more sensible alternative, to chemical recycling.

Direct **negative impacts of chemical recycling process operation on the environment are unlikely**, provided that the usual plant and emission standards are respected. Particular attention must be paid to the handling and recycling or disposal of the residual materials produced, in order to prevent (especially in the case of small plants) the discharge into uncontrolled disposal pathways.

The establishment of structures for CR of plastics in **countries with insufficient infrastructures and governmental controls** to ensure environmentally sound operation, is viewed with particular concern. It would result in **uncontrollable environmental risks** from the plant operation and would also encourage **the export of plastic waste for recycling, with the risk of ending up in the environment**.

5.2.3 Opportunities from chemical recycling

Besides the **reduction of climate-affecting emissions**, another main reason for the development of chemical recycling processes is the **option for a detoxification of the recycled material flow**.

This statement is correct from a chemical-physical point of view, but in practice it is strongly dependent on the general conditions. Particularly in the case of heavily contaminated fractions, the further processing of the products generated is very difficult. **It has yet to be proven that the postulated detoxification potential of chemical recycling processes can actually be realized** and that contamination is not merely shifted to other products or residues. This appears to be a challenge, particularly in the case of small-scale processes that can be implemented on a decentralized basis (e.g. solvolysis or pyrolysis).

5.3 Recommendations

5.3.1 Technology operation

The operation of chemical recycling equipment is **technically very demanding**. Therefore, the established rules of engineering should be applied with foresight and accuracy, and only **suitable and appropriately processed feedstocks should be used**. Under these circumstances, and under favorable general conditions such as the availability of suitable feedstock, chemical recycling processes may contribute to the recycling of plastic waste.

It has been shown that the operation of such plants ideally takes place in **conjunction with refinery or chemical sites**, in order to ensure high-quality recovery of all products (especially gases) and to be able to dispose of residual materials in the existing facilities as well. This increases the achievable yields and minimizes costs and effort for residue disposal. **Operation at sites of MSWI plants** could have advantages for smaller CR installations for the same reason.

5.3.2 Environmental impact evaluation

As with all emerging technologies, LCA of chemical recycling should be read with care, because often unrealistic assumptions are made for the performance of chemical recycling. Comparison of different LCA is mostly not possible due to different system boundaries, waste input and general assumptions. A standard approach for LCA would be needed.

5.3.3 Governance

Several key questions regarding the classification of chemical recycling need to be clarified by policymakers.

Decisions on these issues should be made very rapidly in order to create reliable framework conditions for industry.

During the current phase of establishment of technologies for chemical recycling of plastics, their feasibility is not proven and the environmental assessment is ambiguous. **No excessive (state) subsidies should be provided**, as there is a risk to lock in on processes and infrastructure that are subsequently not environmentally advantageous and/or economically viable.

Governmental **guidance should be limited to environmental protection**, the **legal classification of the recycling route** and **setting a framework to facilitate practical implementation** (e.g. determination of a mass balance approach) and should **not create an artificial market situation through further restrictions or support mechanisms**, which could possibly lead to disadvantages for mechanical recycling processes.

A special classification of chemical recycling is not necessary, the waste hierarchy offers sufficient orientation in this regard. Basically, the ecologically more advantageous way should be chosen.

Regarding the mass balance approach for the quantification and allocation of the recycled material flows, the **use of the "rolling average" or "polymers only" approach is recommended** in order to reflect the physical conditions as closely as possible. As a general rule, **accounting across company sites or even national borders should be rejected** in order to prevent dubious practices.

A general **definition of end-of-waste criteria** for products from chemical recycling is necessary in order to **ensure equal opportunities for all chemical recycling plants** as well as planning security for companies. This also would help administrations in the authorization issuing process.

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Annex 1 – Fact sheets: LCA-studies

The following fact sheets summarize the contents and other important information of relevant LCA studies on the chemical recycling of plastics. Strengths and weaknesses are also addressed. The studies were identified through extensive literature and internet research. There is no claim to completeness.

Recovery options for plastic parts from end-of-life vehicles: an eco-efficiency assessment [31]			
Jenseit W, Stahl H, Wollny V		Year of publication	2003
Authors affiliations	Öko-Institut e.V., BASF	Commissioning/ Funding	APME Brussels (now PlasticsEurope)
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	2005-2010
Geographical reference	Western Europe	Impact categories	AP, GWP, POF
Software used	-	Functional unit	1 kg of discrete plastic parts in vehicles
Chemical recycling technologies	Gasification (Schwarze Pumpe), blast furnace		
Reference technologies	MR, MSWI, incineration RDF in CK, LF		
Waste types and qualities	7 different plastic (PP, PE, PC, PUR, ABS, PA) components of EOL vehicles (bumper, seat cushions, intake manifold, wash-liquid tank and lid, air duct, headlamp lens, mirror housing)		
Scenarios	None		
Main outputs, residual materials, losses	Energy (electricity 12%, heat 28%) and raw materials, depending on technology		
Emissions	Not specified		
Other key assumptions	▪ Comparison between chemical production processes and waste treatment options as whole systems (e.g. conventional chemical production, partial MSW treatment in MBT vs. RDF gasification for methanol or ammonia synthesis). ▪ Gasification and pyrolysis technically feasible for treating MSW/RDF, example Ebara Showa Denko and own research reactor (TU Freiberg).		
Main results			
General	▪ MR can only compete with other technologies for easily accessible mono-materials, e.g. bumpers, MR is strongly dependent on raw material substitution rate. ▪ RDF in CK results are dominated by coal substitution. ▪ LF is the worst scenario independent of the waste component. ▪ The GWP is highest for MSWI.		
Strengths			
Clearly defined waste streams| additional information through eco-efficiency analysis			
Weaknesses			
Only exemplary data shown, e.g. not all impact categories for each waste stream shown in detail | assumptions for technologies not concrete | substituted electricity mix unclear			

Global warming potential and economic performance of gasification-based chemical recycling and incineration pathways for residual municipal solid waste treatment in Germany [67]			
Voss R, Lee RP, Seidl L, Keller F, Fröhling M		Year of publication	2021
Authors affiliations	TU Bergakademie Freiberg, Fraunhofer IMWS, TU Munich	Commissioning/ Funding	BMBF
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	Not specified
Geographical reference	Germany	Impact categories	GWP
Software used	EASETECH V3.1.7	Functional unit	1 t wet MSW
Chemical recycling technologies	Gasification of RDF with syngas conversion: includes pretreatment, gasification, gas treatment, synthesis (syngas-to-methanol synthesis, a methanol-to-olefins synthesis, and an olefins recovery stage)		
Reference technologies	▪ Direct incineration of MSWI: energy efficiencies of 17% for electricity and 32% for heat. ▪ RDF incineration in RDF power plant: energy efficiencies of 23% for electricity and 35% for heat.		
Waste types and qualities	MSWI, RDF (from MBT plant, assumptions for MBT in article)		
Scenarios	▪ Basic: current emission factors for heat and electricity supply. ▪ PREP: predominantly renewable energy supply. ▪ CNEP: nearly climate neutral energy supply via wind power.		
Main outputs, residual materials, losses	▪ MSWI & RDF: energy, heat, fly ash (backfilling material in salt mine), bottom ash (metal recovery and landfilling). ▪ Gasification: 240 kg olefins (120 kg ethylene, 130 kg propylene), fuel gas, LPG, butadiene, butene, heat as process steam, sulfur, slag (numbers given in study).		
Emissions	▪ MSWI: 260 kg fossil CO_2/t MSW, other air emissions. ▪ RDF: 810 kg fossil CO_2/t RDF, other air emissions assumed to be similar to MSWI. ▪ Gasification: 405 kg fossil CO_2/t RDF.		
Other key assumptions	▪ Electricity, heat, and chemical recycling products are assumed to substitute conventional products at a substitution rate of 100%. ▪ Gasification technically feasible for treating MSW, example ENERKEM and own research reactor (TU Freiberg). ▪ Ideal synthesis unit (thermodynamically optimal conversion).		
Main results			
General	Gasification shows a lower GWP than MSWI or RDF incineration		
Scenario analysis	Results for incineration are strongly affected by the reference energy system chosen, less so for gasification.		
Strengths			
Detailed process descriptions and data given in main text			
Weaknesses			
Ideal assumptions for chemical recycling process and chemical synthesis, but realistic assumptions for incineration			

Chemical Recycling of Plastic Waste: Comparative Evaluation of Environmental and Economic Performances of Gasification- and Incineration-based treatment for Lightweight Packaging Waste [68]			
Voss R, Lee RP, Fröhling M		Year of publication	2022
Authors affiliations	TU Bergakademie Freiberg, Fraunhofer IMWS, TU Munich	Commissioning/ Funding	BMBF
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	2021-2028
Geographical reference	Germany	Impact categories	AP, FFP, GWP
Software used	EASETECH V3.1.7	Functional unit	1 t LWP waste
Chemical recycling technologies	Gasification via fixed-bed gasification of LWP sorting residues with syngas conversion: includes pretreatment, gasification, gas treatment, synthesis (syngas-to-methanol synthesis, a methanol-to-olefins synthesis and an olefins recovery stage)		
Reference technologies	▪ LWP waste directly incinerated in RDF power plants without pre-sorting (i.e. no material recovery). ▪ Incineration of LWP sorting residues (rest to MR).		
Waste types and qualities	Lightweight packaging (LWP) waste		
Scenarios	▪ BASIC: current emission factors for heat and electricity supply. ▪ PRED: predominantly renewable energy supply. ▪ CN: nearly climate neutral energy supply via wind power-		
Main outputs, residual materials, losses	▪ MSWI & RDF: energy, heat, fly ash – backfilling material in salt mine, bottom ash – metal recovery and landfilling. ▪ Gasification: 240 kg olefins (120 kg ethylene, 130 kg propylene), LPG, butadiene, butene, heat as process steam, sulfur, slag (numbers given in study).		
Emissions	▪ Process specific emissions of LWP waste incineration: 750 g NO_x (4.3 g N_2O), and 2.5 g CH_4, 150 g SO_2, 260 g fossil CO_2/t LWP waste input. ▪ Gasification: Airborne emissions are accounted for with 710 kg fossil CO_2, 0.042 kg CO, 0.13 kg SO_2, 0.1 kg NOx per t sorting residue input.		
Other key assumptions	▪ Electricity, heat, and chemical recycling products are assumed to substitute conventional products at a substitution rate of 100%. ▪ Gasification technically feasible for treating MSW, example Ebara Showa Denko and own research reactor (TU Freiberg). ▪ Ideal synthesis unit.		
Main results			
General	▪ Gasification shows a lower GWP and FFP than incineration (with and without pre-sorting/MR). ▪ Results for AP are not given in detail.		
Scenario analysis	Results for incineration are strongly affected by reference energy system chosen, less so for gasification.		
Strengths			
Detailed process descriptions and data given in main text and supplementing information			
Weaknesses			
Ideal assumptions for chemical recycling process and chemical synthesis | realistic assumptions for incineration | emissions/outputs identical to Voss 2021 although different input| reference technology direct incineration of LWP without pre-sorting not realistic for Germany (geographical reference) | unclear results for AP (no details for incineration with pre-sorting) | RDF power plant definition unclear			

PVC recovery - options concept for environmental and economic system analysis [37]			
Kreißig J, Baitz M, Schmid J, Kleine-Möllhoff P, Mersiowsky I		Year of publication	2003
Authors affiliations	PE Europe GmbH, Reutlingen University, TU Tech Hamburg	Commissioning/ Funding	VINYL 2010 (Association)
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	2001/2002
Geographical reference	Europe	Impact categories	AP, GWP, primary energy demand
Software used	-	Functional unit	1 t of mixed cable waste
Chemical recycling technologies	Pyrolysis, hydrolysis combined with pyrolysis		
Reference technologies	MSWI, solvent based recycling, LF		
Waste types and qualities	PVC (mixed cable waste)		
Scenarios	none		
Main outputs, residual materials, losses	▪ MSWI: Energy, HCl, metals, gypsum, slag. ▪ Pyrolysis: oil, solid residue (coke), heavy metal product, NaCl solution. ▪ Hydrolysis combined with pyrolysis: Sodium chloride, oil, solid residue (coke), $CaCl_2$, Cu, Al, Pb. ▪ Solvent-based: PVC compound.		
Emissions	MSWI: emission limits of the respective plants used as values for emissions		
Other key assumptions	-		
Main results			
General	▪ Primary energy demand is the lowest for solvent recycling, followed by both CR technologies and MSWI. ▪ The GWP is highest for MSWI, followed by CR and LF. The lowest GWP is calculated for solvent-based recycling. ▪ AP was found to be the highest for LF. AP for MSWI was only lightly higher than CR and solvent based. ▪ CR and MSWI were found to be better suited for mixed wastes than defined wastes, solvent-based recycling was found to be better suited for defined input.		
Strengths			
Concrete waste treatment facilities used as data basis for processes | detailed data			
Weaknesses			
Very specific waste stream			

A Life Cycle Assessment of Mechanical and Feedstock Recycling Options for Management of Plastic Packaging Wastes [45]			
Perugini F, Mastellone ML, Arena U		Year of publication	2005
Authors affiliations	University of Naples	Commissioning/ Funding	Unknown
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	Unknown
Geographical reference	Italy	Impact categories	EN, air & water emissions, fuels and feedstock consumption, GWP SWG, WC
Software used	-	Functional unit	2.35 plastic packaging waste
Chemical recycling technologies	Pyrolysis, hydrocracking		
Reference technologies	LF, MR, MSWI		
Waste types and qualities	PET & PE liquid containers		
Scenarios	▪ Landfilling ▪ Incineration ▪ Mechanical recycling ▪ Combination of mechanical recycling & pyrolysis ▪ Combination of mechanical recycling & hydrocracking		
Main outputs, residual materials, losses	▪ MR: PE, PET, scraps (not specified), no air emissions. ▪ Pyrolysis: oil, gas, wax, air emissions, residues to incineration. ▪ Hydrocracking: gas, air emissions, solid waste, residues to incineration. ▪ MSWI: not specified.		
Emissions	▪ MR: no air emissions. ▪ Pyrolysis: CO_2, NO_x, SO_2. ▪ Hydrocracking: NH3, hydrocarbons. ▪ MSWI: not specified.		
Other key assumptions	▪ MSWI overall electric efficiency of 25%, avoided electricity generation: 15.9 $MJ_{electr.}$ ▪ MR: credits: 5.8 MJ_{electr} from avoided waste incineration. ▪ Pyrolysis efficiency: 80% converted to petrochemical products, additional 10-15% used as fuel in process, credits: 0.15 kg gas, 0.45 kg heavy wax, 0.26 kg light fraction, 1.92 $MJ_{electr.}$ From avoided waste incineration. ▪ Hydrocracking: Veba Combi-Cracking process: efficiency 82% crude oil substitute, credits: 0.74 kg syncrude, 0.08 kg gas, 1.92 $MJ_{electr.}$ from avoided waste inciner.		
Main results			
General	▪ MR was found to be the preferable treatment option in comparison to landfilling & incineration in terms of energy and resource consumption. ▪ MR was found to be environmentally preferable in comparison to all other treatment options, with the exception of the category energy consumption. ▪ Chemical recycling (particularly under conditions of the hydrocracking process) has been identified as preferable in terms of energy consumption.		
Strengths			
No “conventional” LCA categories but other meaningful parameters chosen			
Weaknesses			
Waste management system (2005 or prior) not comparable to modern system | no “conventional” LCA categories | “Chemical recycling” refers to solvolysis only, “feedstock recycling” is used for pyrolysis, hydrocracking, gasification| input would preferably be mechanically recycled today if collected separately| incineration process, flue gas treatment, residue treatment not specified			

Evaluation of pyrolysis with LCA 3 case studies [54]			
RUSS M, GONZALEZ M, HORLACHER M		Year of publication	2020
Authors affiliations	Sphera Solutions GmbH	Commissioning/ Funding	BASF
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	2030
Geographical reference	Germany	Impact categories	AP, EP, GWP, POF, resource use, human toxicity (BASF method)
Software used	GaBi 9 Software system	Functional unit	1 t mixed plastic waste
Chemical recycling technologies	Pyrolysis with purification		
Reference technologies	MSWI, RDF incineration, RDF in CK		
Waste types and qualities	Mixed plastic waste (MK352 fraction from sorting of mixed plastic waste)		
Scenarios	(1) waste perspective (2) product perspective: virgin-grade quality (3) product perspective: various qualities of plastic products		
Main outputs, residual materials, losses	▪ MSWI, RDF incineration: energy ▪ Pyrolysis: oil, char (can be used as fuel in CK) ▪ RDF in CK: clinker		
Emissions	▪ MSWI, RDF incineration: mean emission values from BREF WI		
Other key assumptions	▪ Energy mix 2030 for credits and production. ▪ MSWI: net energy efficiency 44,6% (11.3% electricity, 33.3% steam). ▪ RDF: net energy efficiency 52% (15% electricity, 37% steam). ▪ RDF in CK: real emission data (not given in detail) used.		
Main results			
Waste perspective scenario	▪ GWP: CR is preferable to MSWI. ▪ AP, EP, POF: MSWI, RDF in incineration and CK perform better than CR or MR (due to credits for electricity production). ▪ No significant impact on any category was found due to purification of pyrolysis oil.		
Product perspective	▪ LDPE production from naphtha is favorable to pyrolysis concerning AP, EP, POF but pyrolysis is favorable for GWP. ▪ Emissions from the pyrolysis process are ~40% lower than those from virgin LDPE production. ▪ CR and MR are similar in all impact categories. ▪ EP: MSWI lowest impact, followed by MR, followed by CR.		
General	▪ The collecting of more precise data on these processes was identified to be crucial for more robust and transparent results. ▪ The level of decarbonisation of the energy mix has a large impact on the credits. ▪ Changing assumptions on pyrolysis efficiency impacted the results strongly: Increasing efficiency from 71% to 77% and 87% results in reductions in climate change burdens of 27% and 69% respectively.		
Strengths			
Detailed data given in main text			
Weaknesses			
Very specific assumptions for very specific settings| unclear how boundaries are set in detail, e.g. bottom ash treatment (metal recovery is mentioned, but rest is not)			

<table>
<tr><td colspan="4">Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery [32]</td></tr>
<tr><td colspan="2">JESWANI H, KRUGER C, RUSS M, HORLACHER M, ANTONY F, HANN S, AZAPAGIC A</td><td>Year of publication</td><td>2021</td></tr>
<tr><td>Authors affiliations</td><td>University of Manchester, BASF, Sphera Solutions GmbH, Oeko Institut e.V, Eunomia Research & Consulting Ltd</td><td>Commissioning/ Funding</td><td>BASF</td></tr>
<tr><td colspan="4">Premises of the LCA</td></tr>
<tr><td>Scenarios</td><td colspan="3">Peer reviewed publication of Russ et al. 2020 [54]</td></tr>
<tr><td colspan="4">Main results</td></tr>
<tr><td>General</td><td colspan="3">Peer reviewed publication of Russ et al. 2020 [54]</td></tr>
</table>

Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach [56]			
Schwarz AE, Ligthart TN, Godoi Bizarro D, De Wild P, Vreugdenhil B, van Harmelen T		Year of publication	2021
Authors affiliations	Netherlands Organization for Applied Scientific Research	Commissioning/ Funding	Ministry of Economic Affairs and Climate Policy of the Netherlands
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	Unclear
Geographical reference	Netherlands	Impact categories	GWP
Software used	-	Functional unit	Unclear
Chemical recycling technologies	CR (gasification, pyrolysis, glycolysis, hydrolysis for biopolymers)		
Reference technologies	MR (plastic to plastic, same quality), MR (plastic-to-X, lower quality), MSWI with energy recovery, MSWI without energy recovery		
Waste types and qualities	▪ Top 25 produced polymers in Europe ▪ PP and LDPE foil material, injection molded ABS from electronic equipment, containing 2% flame retardants as case studies		
Scenarios	-		
Main outputs, residual materials, losses	▪ MSWI: pure polymers – no residual, complete combustion to CO_2, ash is landfilled. ▪ MR: residues are incinerated. ▪ CR: depending on polymer and method.		
Emissions	▪ Given in detail in supporting information for all types of treatments		
Other key assumptions	▪ MSWI energy recovery (efficiency 21% electricity, 6% heat). ▪ Recycling efficiency given but dependent on polymer (refer to study). ▪ High sorting effort needed for pyrolysis and MR, less for gasification. ▪ All scenarios include MSWI of sorting residues (varying amounts). ▪ For all recycling technologies general assumptions were used, i.e. data not based on specific /real technologies ▪ In total 10 different technologies were considered.		
Main results			
General	▪ MR was mostly identified as the best treatment option (depending on polymer). ▪ Pyrolysis and gasification have lower CO_2 emissions than MSWI. ▪ Gasification has lowest CO_2 footprint for the polyolefins (LDPE, HDPE, PP, LLDPE) compared to all other options (incl. MR). ▪ Pyrolysis performed best for polymers HIPS, EPS and PS. ▪ Solvolysis was identified as best solution for special polymers (e.g. ABS). ▪ For products containing additives (e.g. WEEE plastics) pyrolysis and gasification perform best.		
Strengths			
Details given in supporting information, very detailed information			
Weaknesses			
Very theoretical method | results refer to pure polymers (technology performance assumed to be ideal for each pure polymer) | sometimes mixed wastes were assumed as input but no purification steps of products considered, not related to results | no data from real technologies used			

Life cycle assessment of paper and plastic packaging waste in landfill, incineration, and gasification-pyrolysis [13]			
Demetrious A, Crossin E		Year of publication	2019
Authors affiliations	RMIT University Australia, Swinburne University of Technology Australia	Commissioning/ Funding	Unknown
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	Not specfied
Geographical reference	Australia (state Victoria)	Impact categories	AP, EP, GWP, POF
Software used	-	Functional unit	Not specified
Chemical recycling technologies	Gasification (Thermoselect process)		
Reference technologies	MSWI, LF		
Waste types and qualities	Mixed plastic waste		
Scenarios	-		
Main outputs, residual materials, losses	▪ MSWI: energy, bottom ash and flue gas treatment residues to landfill ▪ LF: leachate ▪ Gasification: syngas, solid residues to landfill		
Emissions	▪ MSWI: not detailed, inventory data not directly correlated to input. ▪ LF: unclear if any. ▪ Gasification: general assumption not directly correlated to input.		
Other key assumptions	▪ Mixed plastic waste based on the chemical composition and energy content based off a Swiss inventory. ▪ Gasification process: Thermoselect, 0.82 kg syngas from 1 kg waste, 9.1 MJ per kg, 93.4% syngas to motor with gross efficiency for electricity production 32%. ▪ MSWI: Ecoinvent 3.0 database, Swiss MSW incineration 2007, gross efficiency for electricity production in MSW incineration was 15.84%, no heat recovery due to lack of consumer.		
Main results			
General	▪ AP, GWP are highest for gasification, MSWI is better mainly due to electricity credits ▪ Landfill has the highest EP ▪ Landfill was identified as the overall best option for plastic waste		
Strengths			
-			
Weaknesses			
Mixed plastic waste composition unknown, based on assumptions | Australian data – not fitting for Europe, e.g. no heat demand from MSWI, avoided electricity heavily dependent on coal | landfilling as alternative for untreated waste not accepted in Europe			

LCA of plastic waste recovery into recycled materials, energy and fuels in Singapore [35]			
KHOO HH		Year of publication	2019
Authors affiliations	Institute of Chemical and Engineering Sciences Singapore	Commissioning/ Funding	ExxonMobil Chemical Company
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	Unknown
Geographical reference	Singapore	Impact categories	AP, EP, GWP, PMF, SWG
Software used	-	Functional unit	Not specified
Chemical recycling technologies	Pyrolysis (P), gasification (G)		
Reference technologies	MR, MSWI		
Waste types and qualities	Mixed plastic waste (PE, PVC, PP, PS, PET, mixed fraction)		
Scenarios	1) Recycling rate of 7.24% sent to MR, the rest is sent to WTE. 2) Recycling rate of 10.64% sent to MR, the rest is sent to WTE. 3) Recycling rate of 7.24% sent to MR plus potential P, the rest is sent to WTE. 4) Recycling rate of 7.24% sent to MR plus potential G, the rest is sent to WTE. 5) Recycling rate of 7.24% sent to MR plus potential P+G, the rest is sent to WTE. 6) Recycling rate of 10.64% sent to MR plus potential P+G, the rest is sent to WTE. 7) Recycling rate of 10.64% sent to MR plus potential 2 x P, the rest is sent to WTE. 8) Recycling rate of 10.64% sent to MR plus potential 2 x G, the rest is sent to WTE.		
Main outputs, residual materials, losses	▪ Pyrolysis: 65% pyrolysis oil, solids sent to MSWI. ▪ Gasification: 27.8% ethanol, solids sent to MSWI. ▪ MR: 87.7% PE & 75.8% PET recycling rate, solids sent to MSWI. ▪ MSWI: 2300 MJ energy production from 1 t, solids sent to landfill.		
Emissions	▪ Air emissions specified in detail for each process		
Other key assumptions	▪ Incineration: 950 kg/t CO_2, 0.01 g/m³ CO, 0.142 g/m³ SO_2, 0.153 g/m³, $2.5x10^3$ g/m³ dust, others ▪ P: 150 kg/t CO_2, 0.07 kg/t CO, 0.6 kg/t NO_x, others ▪ G: 181 kg/t CO_2, 0.45 kg/t CO, 0.907 kg/t CH_4, 0.091 kg/t SO_2, 0.18 g/kg dust, others		
Main results			
General	▪ GWP: main impact caused by MSWI. ▪ AP: main impact caused by gasification. ▪ SWG: main impact caused by gasification. ▪ Scenario combining WTE (83%), MR (10%) & pyrolysis (7%) was considered best in terms of overall performance.		
Strengths			
Realistic scenarios for overall waste treatment for Singapore by combining methods			
Weaknesses			
Mixed scenarios including MR, CR & MSWI in different ratios – comparability low | CR produces fuels not feedstock for plastics recycling | assumptions concerning quality of fuels from CR unknown | technological assumptions for CR unknown, data combined from various sources			

Towards a circular economy for plastic packaging wastes – the environmental potential of chemical recycling [40]			
Meys R, Felicitas Frick F, Westhues S, Sternberg A, Klankermayer J, Bardow A		Year of publication	2020
Authors affiliations	RWTH Aachen University, HTP GmbH & Co. KG, Forschungszentrum Juelich GmbH, ETH Zuerich	Commissioning/ Funding	BMBF
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	Unknown
Geographical reference	Europe	Impact categories	GWP, FRD, AP, EP
Software used	Unknown	Functional unit	1 kg plastic packaging waste
Chemical recycling technologies	26 CR processes (not specified) producing refinery feedstock or monomers, chemical upcycling (i.e. solvolysis and catalyst processes), (fuel production)		
Reference technologies	MSWI, RDF in CK, MR		
Waste types and qualities	Packaging waste: PET, LDPE, HDPE, PP, PS		
Scenarios	75 waste treatment scenarios		
Main outputs, residual materials, losses	Depending on process, theoretical approach		
Emissions	Depending on process, theoretical approach		
Other key assumptions	▪ Theoretical approach of what could ideally be produced by chemical recycling. ▪ District heating was modelled including heat supply based on 44 % natural gas and 56 % other sources, e.g. biomass, oil and lignite. ▪ Cement kilns: lignite, natural gas and biomass is substituted based on equal net calorific values and equal thermal energy efficiency. ▪ MSWI: energy efficiency of 41% and a power to heat ratio of 0.35. ▪ MR: substitution factor 0.7 for HDPE, LDPE, PP, 0.9 for PS, 1 for PET. ▪ Ideal chemical recycling: product used as refinery feedstock (up to 100% substitution rate, depending on waste and CR process).		
Main results			
General	▪ All CR technologies had lower impact on GWP than MSWI (low credits for electricity & heat production for incineration due to electricity mix). ▪ Incineration in CK leads to even lower impact on GWP than CR to refinery feedstock due to high credits from lignite substitution. ▪ MR has lower impact on GWP than CR for refinery products due to substitution of polymers. ▪ Results for CR to monomers were found to be diverse, depending on many factors such as assumed conversion rates, substitution factors etc. ▪ Credit for virgin polymer production is largely influenced by the type of virgin polymer as well as the substitution factor. ▪ Monomer production of PET and PS seem more promising than monomer production from polyolefins.		
Strengths			
Very broad considerations and many scenarios			
Weaknesses			
Theoretical model considering ideal performance of CR but realistic benchmark technologies (MR, MSWI) (this was done in order to identify such CR technologies that are worse than benchmark even under ideal conditions) | no technical information on processes of chemical recycling, just theoretical approach			

Life Cycle Assessment of Poly(Lactic Acid) (PLA): Comparison Between Chemical Recycling, Mechanical Recycling and Composting [9]			
COSATE DE ANDRADE MF, SOUZA PMS, CAVALETT O, MORALES AR		Year of publication	2016
Authors affiliations	University of Campinas, Laboratório Nacional de Ciência e Tecnologia do Bioetanol	Commissioning/ Funding	São Paulo Research Foundation, Ministry of Education
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	2013
Geographical reference	Brazil	Impact categories	FRD, GWP, HT
Software used	SimaPro software	Functional unit	1 kg PLA
Chemical recycling technologies	Solvolysis		
Reference technologies	MR, composting		
Waste types and qualities	PLA		
Scenarios	-		
Main outputs, residual materials, losses	▪ MR: recycled PLA, residual waste from sorting to landfill. ▪ Solvolysis: lactic acid, residual waste to landfill. ▪ Composting: compost.		
Emissions	▪ Waste heat (all processes), water ▪ Composting: CO_2		
Other key assumptions	▪ Data for composting from lab scale experiments. ▪ Data for solvolysis from simulation. ▪ MR combination of data from lab scale and commercially available data. ▪ Complete degradation by composting assumed (degradation time was 52 days). ▪ MR and solvolysis: polymer as product, composting: no plastic product.		
Main results			
General	▪ MR presented the lowest environmental impacts, followed by CR and composting. ▪ MR and solvolysis have highest electricity consumption.		
Strengths			
PLA very specific polymer therefore limitations, treatment and input very defined			
Weaknesses			
PLA is a very specific polymer and therefore not comparable to other plastic waste streams			

Environmental performance of chemical and solvent-based 2 recycling of plastics on a system level — the devil is in the detail [36]			
Klotz M, Oberschelp C, Salah C, Subal L, Hellweg S		Year of publication	2023
Authors affiliations	ETH Zuerich	Commissioning/ Funding	Swiss Federal Office for the Environment
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Unclear	Reference year	2040 (but unclear)
Geographical reference	Switzerland (representing EU)	Impact categories	GWP
Software used	-	Functional unit	unclear
Chemical recycling technologies	Gasification, pyrolysis, solvolysis, (solvent-based recycling)		
Reference technologies	MSWI, incineration in CK		
Waste types and qualities	Mixed plastic waste from sorted residual waste and from sorting/recycling residues of separately collected plastic waste		
Scenarios	4 scenarios: referred to supporting information which was not yet available		
Main outputs, residual materials, losses	▪ Gasification: syngas, solid product, liquid product (depending on input) ▪ Pyrolysis: oil, solid char, others (depending on input) ▪ Solvolysis: monomers and byproducts		
Emissions	▪ not specified		
Other key assumptions	▪ Maximum possible amounts for each type of recycling assumed: Max. MR rate 31% for main plastics, from sorted residual waste: 40% pyrolysis or gasification, 60% solvolysis, from separately collected waste: 50% pyrolysis or gasification, 50% solvolysis. ▪ Pre-print: supporting information with details not yet available.		
Main results			
General	▪ GWP for CR varies strongly from similar to incineration to high benefits comparable to MR. ▪ Performance of gasification and pyrolysis GWP mainly dependent on input, efficiency of heat transfer and heat recovery, product quality (determining possibilities for substituting other products). ▪ Solvolysis should be prioritized where possible due to lower GWP. ▪ Upscaling was identified as critical factor for success and therefore uncertainty remains.		
Strengths			
Consideration whether CR technologies are technically feasible for waste stream			
Weaknesses			
Unclear if ISO compliant | information missing due to pre-print			

Techno-economic assessment and comparison of different plastic recycling pathways: A German case study [66]			
Volk R, Stallkamp C, Steins JJ, Yogish SP, Müller RC, Stapf D, Schultmann F		Year of publication	2021
Authors affiliations	KIT	Commissioning/ Funding	THINKTANK Industrielle Ressourcenstrategien by UM BW & industry partners
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	Unknown
Geographical reference	Germany	Impact categories	GWP, CED, carbon efficiency
Software used	Unknown	Functional unit	1 kg LWP waste
Chemical recycling technologies	Pyrolysis		
Reference technologies	MR, MSWI, incineration in CK, incineration in coal power plant (depending on scenario)		
Waste types and qualities	Mixed LWP waste (separate collection) for MR, RDF from LWP sorting for CR		
Scenarios	▪ MR (42% sorting yield), 100% MSWI for sorting residues. ▪ MR (42% sorting yield), 25% MSWI, 75% RDF combustion plant for sorting residues. ▪ MR (42% sorting yield), 18% MSWI, 58% RDF combustion plant, 13% CK, 11% coal power plant for sorting residues. ▪ MR (22% sorting yield), 100% MSWI for sorting residues. ▪ MR (22% sorting yield), 25% MSWI, 75% RDF combustion plant for sorting residues. ▪ MR (22% sorting yield), 18% MSWI, 58% RDF combustion plant, 13% CK, 11% coal power plant for sorting residues. ▪ Combined CR and MR (42% sorting yield). ▪ Combined CR and MR (22% sorting yield).		
Main outputs, residual materials, losses	▪ MR: sorted plastic fractions, re-granulated. ▪ CR: 30 wt% oil/liquid phase (to steam cracker), 38 wt% gas (to cold downstream part of the steam cracking process), 32 wt% solids (to combustion for energy use: internal and excess for district heating).		
Emissions	Not specified		
Other key assumptions	▪ Combination of mass flow analysis and LCA. ▪ Additional pretreatment (sorting) of RDF. ▪ MR: emissions & compensations from incineration of sorting residues were included. ▪ CR: rotary kiln, 650°C, 8.1 t/h pyrolysis process operating 8’000 h/year.		
Main results			
General	▪ MR & CR are advantageous compared to virgin plastics production. ▪ CR performs better in CED, MR better in GWP, combination is best. ▪ Results are depending on sorting yield, thermal recycling paths of sorting residues and substitution rate.		
Strengths			
Realistic scenarios chosen | additional economic assessment was carried out			
Weaknesses			
Assumption that combustion of solid fraction leads to so much excess energy that it can supply district heating seems unrealistic, thus creating high credits to scenarios including chemical recycling | unclear whether compensation for district heating was also applied for MSWI			

Environmental and economic assessment of plastic waste recycling. A comparison of mechanical, physical, chemical recycling and energy recovery of plastic waste [23]			
Garcia-Gutierrez P, Amadei AM, Klenert D, Nessi S, Tonini D, Tosches D, Ardente F, Saveyn H		Year of publication	2023
Authors affiliations	JRC	Commissioning/ Funding	JRC
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Yes	Reference year	unclear
Geographical reference	EU	Impact categories	AP, EP, ET, FRD, GWP, HT, IR, PMF, POF, SOD
Software used	Unknown	Functional unit	1 t of wet plastic waste (depending on scenario)
Chemical recycling technologies	Solvolysis, pyrolysis, gasification (depending on input and scenario)		
Reference technologies	MR, solvent-based recycling, MSWI		
Waste types and qualities	PET packaging (bottles and trays), PS packaging, mixed polyolefins, PE films, PE/PA multilayer films, RDF, tires, shredded plastics from WEEE (small and large) Scenarios define chosen waste stream		
Scenarios	In total 27 scenarios: ▪ Comparison of MR with CR, incineration (sub scenarios). ▪ Comparison CR and incineration of wastes currently not in MR (sub scenarios). ▪ Comparison MR and incineration (sub scenarios).		
Main outputs, residual materials, losses	▪ Depending on scenarios and waste input		
Emissions	▪ Depending on scenarios and waste input		
Other key assumptions	▪ Data from stakeholder questionnaires combined with literature data		
Main results			
General	▪ Choice of the preferred management option for plastic waste depending on 3 main criteria: i) the maximization of material recovery while minimizing processing impacts, in line with the waste hierarchy, ii) the specificity of the plastic waste stream and the treatment thereby required (technical feasibility), iii) the economic feasibility. ▪ GWP: Any recycling is preferable to energy recovery in all scenarios, esp. for mixed polyolefin waste (currently not mechanically recycled). ▪ Environmental savings from energy recovery are not sufficient to compensate for the environmental impacts from MSWI and the related CO_2 emissions. ▪ For some categories (e.g. AP, PMF, IR, HT, EP), energy recovery can perform better than energy intensive recycling pathways due to compensation from energy mix. ▪ Conclusion: Data for input needed to determine potential competition of MR and CR and technical feasibility of CR, data needed for waste input and technical feasibility in order to decide best pathway.		
Strengths			
Very detailed | many different waste streams and scenarios			
Weaknesses			
Only MSWI as incineration option although RDF and tires often used in CK			

Exploration chemical recycling – Extended summary [4]			
Bergsma G, Lindgreen ER, Broeren M		Year of publication	2020 (original dutch report published 2018)
Authors affiliations	CE Delft	Commissioning/ Funding	prepared for the Dutch Ministry of Economic Affairs and Climate Policy
Premises of the LCA			
Compliant with DIN EN ISO 14040/14044	Unclear	Reference year	2020 & 2030
Geographical reference	Netherlands	Impact categories	Carbon footprint
Software used	Unknown	Functional unit	Unknown
Chemical recycling technologies	Pyrolysis, gasification, hydropyrolysis,		
Reference technologies	MR, incineration		
Waste types and qualities	Sorting residues, PET trays, mixed plastics (DKR350, currently mechanically recycled), EPS (bromine contaminated)		
Scenarios	-		
Main outputs, residual materials, losses	Not specified		
Emissions	Not specified		
Other key assumptions	▪ Technologies can directly be utilised to process the selected plastic waste streams at large scale. ▪ Various outputs of chemical recycling (e.g. syngas) can be sold on the market (thereby avoiding conventional production processes).		
Main results			
General	▪ Sorting residues: hydropyrolysis lowest carbon footprint, incineration highest. ▪ PET trays: MR lowest carbon footprint, incineration highest carbon footprint, gasification& pyrolysis similar and in between MR and MSWI. ▪ DKR350: MR and hydropyrolysis lowest carbon footprint, pyrolysis slightly higher carbon footprint than gasification (incineration no treatment option for this waste stream). ▪ EPS results not shown.		
Strengths			
Includes policy recommendations			
Weaknesses			
Only extended summary, therefore information missing (original in dutch) | processes not defined, not described in detail (e.g. unclear what kind of process hydropyrolysis is, no specification of incineration) | assumptions for outputs optimistic (i.e. all products can be used as substitution of raw material)			

Annex 2 – Fact sheets: Exemplary CR-processes

Annex 2.1: Solvolysis – revolPET

revolPET		**TRL**	**4**
Provider | Operator	RITTEC Umwelttechnik GmbH Feldstraße 29 21335 Lüneburg Operator: TU Braunschweig Institut für Chemische und Thermische Verfahrenstechnik	Number of reference plants	1
		In operation since	2017
		Patents granted	Ja
		Site(s)	Braunschweig [D]
Website	https://www.rittec.eu/		

Type of process	Solvolysis [Alkaline hydrolysis]
Aim | Product	Production of the monomers terephthalic acid [TA] and ethylene glycol [EG]
Characteristics	-

Process			
Input	Pretreatment of plastic waste	Thermochemical process	
PET-rich plastic waste fractions	Sorting Crushing < 3 mm	Reactor	Extruder Stirred tank reactor
		Reagent	MEG, NaOH, H_2SO_4
		Temperature	20-180 °C
		Pressure	Atmospheric
		Capacity	14 kg/h [Pilot]
		Additives	-

Output	
Solid	Terephthalic acid [r-TPA] Residues [unreacted components] Salts [$NaSO_4$]
Liquid	MEG Unconsumed reactants [NaOH]
Gaseous	-

Product utilization
Production of PET

Annex 2.2: Liquefaction – ReOil®

ReOil®- OMV		**TRL**	**8-9**
Provider | Operator	OMV Downstream GmbH Manswörther Straße 28, 2320 Schwechat, Österreich	Number of reference plants	1
		In operation since	2009
		Patents granted	Yes
Website	https://www.omv.com/de/nachhaltigkeit/klimaschutz/reoil	Site(s)	Schwechat [AT]

Type of process	Liquefaction
Aim | Product	Production of oils processed in the refinery
Characteristics	Material and heat integration in refinery

Process			
Input	Pretreatment of plastic waste	Thermochemical process	
Plastic waste LDPE HDPE PP PS	Application of selected plastics which are difficult to recycle mechanically [mixed plastics] Removal of impurities [metals, paper, etc.]	Reactor	Continously operated tubular reactor
		Reagent	Starting oil
		Temperature	390-450 °C
		Pressure	Overpressure
		Capacity	800 Mg/a 16’000 Mg/a [2023]
		Additives	Solvent

Output	
Solid	Residues
Liquid	Hydrocarbon oils
Gaseous	Exhaust gas [combustion of the permanent gases]

Product utilization
Refinery | Chemical Industry

Annex 2.3: Liquefaction – Carboliq

CARBOLIQ GmbH		**TRL**	**8**
Provider | Operator	CARBOLIQ GmbH Karlstraße 8 b D-42897 Remscheid Deutschland	Number of reference plants	1
		In operation since	2012
		Patents granted	
Website	https://www.carboliq.com/de/	Site(s)	Ennigerloh [D]

Type of process	Liquefaction
Aim | Product	Production of hydrocarbon oils for chemical industry
Characteristics	Heat generation by friction [circulation of the reactor content by turbines] REACH certification of the oils

Process

Input	Pretreatment of plastic waste	Thermochemical process	
Plastic waste LDPE HDPE PP PS RDF	Grain size < 30 mm Water content < 5 % Ash < 10 % Calorific value < 20 MJ/kg	Reactor	Continuous stirred tank reactor
		Reagent	Starting oil
		Temperature	< 400°C
		Pressure	50-100 mbar underpressure
		Capacity	6 000 Mg/a
		Additives	Lime Catalyst Fe_2O_3

Output

Solid	Residues
Liquid	Hydrocarbon oils
Gaseous	Off gas

Product utilization

Chemical industry [supply of steam cracker]

Annex 2.4: Pyrolysis – Arcus

Arcus		**TRL**	**7-8**
Provider | Operator	Arcus Greencycling Leonberger Str. 30 71638 Ludwigsburg	Number of reference plants	1 [pilot]
		In operation since	2016
		Patents granted	Yes
Website	https://arcus-greencycling.com/	Site(s)	Hoechst [D]

Type of process	Pyrolysis
Aim | Product	Production of hydrocarbon destillates
Characteristics	Fractionated gas withdrawal, hot gas filtration

Process			
Input	Pretreatment of plastic waste	Thermochemical process	
Mischpolyolefine (MPO-Flex)	Delivery of pretreated material by commercial provider	Reactor	Screw reactor
		Reagent	None
		Temperature	Up to 750 °C
		Pressure	Slight underpressure
		Capacity	10 kg/h pilot 4000 Mg/a Hoechst
		Additives	Lime

Output		
Solid	Coke/ash	
Liquid	Oils	By condensation and upgrading
Gaseous	Off gases from post combustion	Utilization in motor

Product utilization
Feedstock for chemical industry

Annex 2.5: Pyrolysis – Quantafuel

Quantafuel (Waste4Fuel)		**TRL**	**7-8**
Provider | Operator	Quantafuel ASA Lilleakerveien 2C 0283 Oslo, Norwegen	Number of reference plants	1
		In operation since	2014
		Patents granted	Yes
Website	https://www.quantafuel.com/	Site(s)	Skive [DK] Kristiansund [NO]

Type of process	Pyrolysis
Aim | Product	Production of oils
Characteristics	Catalytic hydrocracking and -treating of pyrolysis gases upstream condensation

Process			
Input	Pretreatment of plastic waste	Thermochemical process	
Plastic waste [Polyolefins]	Mechanical pretreatment: Crushing [NIR-]Sorting	Reactor	Rotating kiln
		Reagent	-
		Temperature	380-460 °C
		Pressure	Slight underpressure
		Capacity	20 000-30 000 Mg/a
		Additives	H_2 for hydrocracking

Output	
Solid	Coke
Liquid	Oils [fractions with different boiling points]
Gaseous	Off gas [Incineration of permanent gases]

Product utilization
Chemical industry Refineries

Annex 2.6: Pyrolysis – Recycling Technologies

RT 700 / RT 7000		**TRL**	**7**
Provider | Operator	Recycling Technologies Ltd. Unit 6 Woodside Road South Marston Industrial Park Swindon, United Kingdom	Number of reference plants	1
		In operation since	2013-2022 (insolvent)
		Patents granted	Yes
Website	https://recyclingtechnologies.co.uk/	Site(s)	Swindon [UK] Perth [UK] Geleen [NL]

Type of process	Pyrolysis
Aim | Product	Production of hydrocarbon destillates
Characteristics	Insolvency in October 2022

Process			
Input	Pretreatment of plastic waste	Thermochemical process	
Sorted plastic waste Polyolefines, esp. PE PP	Complex processing necessary: Crushing Metal separation Drying Classification	Reactor	Fluidized bed
		Reagent	None
		Temperature	450-550 °C
		Pressure	Slight overpressure
		Capacity	7 000 Mg/a
		Additives	None

Output		
Solid	Coke/Ash	Incineration
Liquid	Hydrocarbon destillates [Plaxx]: Waxes and oils	By condensation/destillation
Gaseous	Off gases from post combustion thermical regeneration	Off gas cleaning by fabric filter

Product utilization
Purchase of liquid products and waxes [Plaxx]

Annex 2.7: Gasification – Ebara | Showa Denko

Ebara UBE process		**TRL**	**9**
Provider | Operator	Ebara Environmental Plant Co., Ltd. UBE Industries, Ltd. Operator: Showa Denko K.K., Japan	Number of reference plants	1 [formerly 3]
		In operation since	2003
		Patents granted	Yes
Website	https://www.eep.ebara.com/en/ https://www.ube.com/	Site(s)	Kawasaki [JP]

Type of process	Two-stage pressurised gasification
Aim | Product	Production of hydrogen for ammonia synthesis
Characteristics	Co-production of liquid carbon dioxide (dry ice)

Process			
Input	Pretreatment of plastic waste	Thermochemical process	
Plastic waste	Crushing Metal separation Briquetting	Reactor	Two-stage pressurized gasification 1. Rotating fluidized bed 2. High temperature gasifier
		Reagent	O_2 | H_2O
		Temperature	1. 600-800 °C 2. 1 300-1 500 °C
		Pressure	5-16 bar
		Capacity	195 Mg/d
		Additives	-

Output	
Solid	Unburnt material Sand, slag CO_2 [dry ice] Residues [sulphur, salts]
Liquid	Ammonia
Gaseous	-

Product utilization
Ammonia synthesis Production of dry ice

Annex 3 – List of CR-processes

The following table contains a list of processes that can be used for the chemical recycling of plastics. The processes were identified through extensive internet research. Due to the volatile market, there can be no claim to completeness.

Table 8: List of processes for chemical recycling of plastic waste.

Process	Type of CR	Company
Advantage Fuel Technologies	Liquefaction	Advantage Fuel Technologies
Alter NRG	Plasma	Westinghouse Plasma Corp. (WPC)
Altis	Pyrolysis	Altis Co., Ltd.
Alucha	Pyrolysis	Alucha
Anhui Oursun Resource Technology	Pyrolysis	Anhui Oursun Resource Technology
APC Agile Process Chemicals	Pyrolysis	APChemi Pv Ltd.
APK newcycling	Solvolysis	APK AG
Arcus	Pyrolysis	Arcus Greencycling
Babcock MSW-Pyrolysis	Pyrolysis	BKMI Industrieanlagen GmbH (Babcock – Krauss Maffei), Burgau
BASF-Thermolyse-Verfahren	Liquefaction	BASF
BASURA Multiwaste-Gasification	Gasification	ProCone GmbH
Beston	Pyrolysis	Beston (Henan) Machinery Co., Ltd.
BGL British Gas Lurgi Process (SVZ)	Gasification	Envirotherm GmbH
Big Atom	Pyrolysis	Big Atom
Bio Oil	Pyrolysis	Bio Oil Holding NV, All Green AG
BioBTX Integrated Cascading Catalytic Pyrolysis	Pyrolysis	BioBTX
BioFabrik White Refinery	Pyrolysis	Biofabrik Technologies GmbH
Biofy	Pyrolysis	Biofy
Black Bear Carbon	Pyrolysis	Black Bear Carbon
Blest	Pyrolysis	Blest Co.

Process	Type of CR	Company
BlueCycle	Pyrolysis	BlueCycle
Blueplasmapower	Plasma	Blueplasmapower
BNPetro	Pyrolysis	BNPetro
Bolder Industries	Pyrolysis	Bolder Industries
BP Infinia	Solvolysis	BP, Demeto, Gr3n, INEOS Infinia
carboliq (Dieselwest)	Liquefaction	Recenso GmbH
CASO Technology	Pyrolysis	Cassandra Oil
Cat-HTR	HTL	Licella Holdings, Tourian Renewables Limited, Renew ELP, MURA, iQRenew
Cielo	Liquefaction	Cielo Waste Solutions Corp.
Circular Plas	Pyrolysis	Circular Plas, Siam Cement Group (SCG)
Clariter	Pyrolysis	Clariter
Climax Global Energy	Pyrolysis	Climax Global Energy
Concord Blue	Gasification	Concord Blue Energy
Conorra	Solvolysis	Conorra Technologies
CPD Process	Liquefaction	CPD Swiss Ltd.
Creacycle (CreaSolv)	Solvolysis[1]	Fraunhofer IVV
CuRe Technology	Solvolysis	CuRe Technology B.V. (former: Cumapol B.V.)
DePoly	Solvolysis	DePoly
DestruGas	Pyrolysis	Pollution Control Ltd
DRON	Pyrolysis	Elixir Group
Eastman Carbon Renewal Technology	Gasification	Eastman Chemical
Ebara PTIFG Process	Gasification	Ebara Environmental Plant Co.,Ltd

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[1] This company prefers to name its own technology a "solution-precipitation-process", in which the polymer structure of the plastic is supposed to remain in the solution. The goal of this postulation is to assign the process to mechanical recycling. In certain countries, this provides advantages in the accounting of recycling quotas.

Process	Type of CR	Company
Eco Creation	Pyrolysis	Eco Creation Co. Ltd.
Eco Energy	Pyrolysis	Niutech Environment Technology Corporation, Jinan Eco-Energy
EcoFuel	Pyrolysis	Vadxx Energy LLC, Alterra Energy
Ecomation Oy	Pyrolysis	Ecomation Recycling Technologies
Elysium Nordic	Pyrolysis	Elysium Nordic
Encina	Pyrolysis	Encina
Enefit | Eesti Energia	Pyrolysis	Eesti Energia AS
Enerkem Inc.	Gasification	Enerkem Alberta Biofuels LP
Enval	Pyrolysis	Enval Ltd.
Envion	Pyrolysis	Envion Oil Generator (also Climax Global Energy)
Enviro	Pyrolysis	Enviro Systems AB
EREKA process	Pyrolysis	MEE Intermediate Pyrolysis
Ervo Eco | Log Eco	Pyrolysis	LOGeco
Europlasma	Plasma	Europlasma (INERTAM, TORCH & PRO-CESS, C.H.O-POWER und Europe Environment)
FastOx	Gasification	Sierra Energy
FBTS	Pyrolysis	Felső-Bácska Tározós Szélpark
Fuenix Ecogy	Pyrolysis	Fuenix, Ecogy, Plasma Power BV
Fulcrum BioEnergy	Gasification	Fulcrum/Waste Management
FWD:Energy	Pyrolysis	FWD:Energy
Garbo	Solvolysis	Garbo Srl
Global Gateways	Pyrolysis	GG I - Saxony-Anhalt
Global Green International	Pyrolysis	Global Green International
Golden Renewable Energy Braven	Pyrolysis	Golden Renewable Energy, Pi Eco, Braven
Green EnviroTech	Pyrolysis	Green EnviroTech Holdings
Green Plasma Technology	Plasma	Graforce GmbH
Handerek	Pyrolysis	Handerek Technologies

Process	Type of CR	Company
HelioStorm	Plasma	Cogent Energy Systems
HiCOP	Pyrolysis	Environmental Energy Co., Ltd., YK Clean, Kankyo
Hoop	Pyrolysis	Versalis, Eni
High Speed Catalytic Depolymerization	Liquefaction	Quamm AG
HTW	Gasification	Gidara Energy
HydroLoop | loop-HTL	HTL	TerraWaste
iCycle (CreaSolv)	Solvolysis	Fraunhofer IVV, PolyStyreneLoop (PSLoop)
IGES	Pyrolysis	IGE Solutions Amsterdam BV, ehemals: Bin2Barrel
INEOS New Planet BioEnergy	Gasification	Indian River County BioEnergy Center
Ioniqa	Solvolysis	Ioniqa
IPV Process	Gasification	ReEnvision GmbH, SiCon GmbH
Itero	Pyrolysis	Itero Technologies Ltd
KDV Process	Liquefaction	Clyvia Inc., Alphakat Holdings International LTD, Waste 2 Oil GmbH, Polymer-Engineering
Klean Industries	Pyrolysis	Klean Industries
Konstanz Uni	Solvolysis	Uni Konstanz
Logoil	Liquefaction	Logmed Cooperation GmbH
Loop Industries	Liquefaction	Loop Industries
Low sulfur fuels	Pyrolysis	Low sulfur fuels Ltd
LTC Technology	Gasification	Recupera Doo
Millenium	Plasma	Millenium Technologies
MK Aromatics	Liquefaction	Polymer Energy LLC
MLM-R Technology	Pyrolysis	Pruvia
MoReTec, CirculenRevive	Pyrolysis	LyondellBasell
MPC (mixed plastics to crude) Gen6	Pyrolysis	Agilyx, ehemals: Plas2Fuel, Agriplas
MyRechemical	Gasification	Nextchem, Maire Tecnimont (vgl. Thermoselect)
Neoliquid	Pyrolysis	Neoliquid

Process	Type of CR	Company
New Energy	Pyrolysis	New Energy
New Hope Energy	Liquefaction	New Hope Energy, Trinity Oaks Tyler
Nexterra Systems Corp.	Gasification	UBC Bioenergy Research & Demonstration Facility
Nexus Fuels	Pyrolysis	Nexus Fuels
Noell Conversion Process	Gasification	Noell KRC GmbH
Obbotec HYDRO CAT 3	Pyrolysis	Obbotec
Oneida Seven Generations Corporation	Gasification	Oneida Seven Generations Corporation
Orlen Unipetrol	Pyrolysis	Orlen Unipetrol, University of Chemistry and Technology Prague, Orlen Unipetrol Centre for Research and Education
P2C Plastics2chemicals	Pyrolysis	Indaver
PARAK	Pyrolysis	Baufeld AG
PARC	Pyrolysis	Plastic Advanced Recycling Corporation
Paterson Energy	Pyrolysis	Paterson Energy
Patpert Gasolysis	Pyrolysis	Patpert Teknow Systems Pvt. Ltd.
PEM Process	Plasma	Plagazi AB, InEnTec Inc., Bock Handelsvertretung
PK Clean	Pyrolysis	Renewlogy, ehemals: PK Clean
Plas-Tcat	Pyrolysis	Anellotech, ifp Energies nouvelles, Axens, Johnsn Matthey, Intercat
Plastcon	Liquefaction	Makeen Energy
Plastic Back	Solvolysis	Plastic Back
Plastic Energy	Liquefaction	Plastic Energy
Plastic2Oil	Pyrolysis	JBI, Inc. (also Rational Energies, P2O)
Plastics Green Energy	Pyrolysis	Plastics Green Energy, ProProcess, Global Asset Management (GAM New Energy)
Plaxx RT7000	Pyrolysis	Recycling Technologies Ltd
Plazarium	Plasma	Plazarium GmbH, Plazarium LLC
Polycycl	Pyrolysis	Polycycl, Ventana CleanTech
Polyfuel	Pyrolysis	Polyfuel Group Limited

Process	Type of CR	Company
Polypetron	Pyrolysis	Sepco Industries
Polystyvert	Solvolysis	Polystyvert
Poseidon Plastics	Solvolysis	Poseidon Plastics
Powerhouse DMH	Gasification	Powerhouse Energy Group
Processi Innovativi	Gasification	Processi Innovativi s.r.l.
Promeco	Pyrolysis	Promeco
Pryme	Pyrolysis	Pryme Cleantech
PTR Process	Pyrolysis	Hedviga Group, a.s.
PureCycle UPRP	Solvolysis	PureCycle
Pyreg	Pyrolysis	Pyreg GmbH
Pyro One	Pyrolysis	Pyro One BV, Plant One
Pyro Recycling | PyroRec	Pyrolysis	Pyro Recycling Ltd
Pyrocrat	Pyrolysis	Pyrocrat Systems LLP
Pyrolyx	Pyrolysis	Pyrolyx AG
Pyrowave	Pyrolysis	Pyrowave Inc.
Pyrum Innovations	Pyrolysis	Pyrum Innovations AG
QCI-PCF | QCI-TCF | QCI-MSW	Pyrolysis	QCI LLC
Quantafuel	Pyrolysis	Quantafuel
ReOil	Liquefaction	OMV Group
REP-500	Pyrolysis	Recycle Energy Co. Ltd., CFP Group
RES Polyflow | Brightmark	Pyrolysis	RES Polyflow, Brightmark
Resynergi	Pyrolysis	Resynergi
revolPET	Solvolysis	Rittec Umwelttechnik
RODECS	Gasification	Chinook Sciences
Royco Process, EZ-Oil Generator	Pyrolysis	Beijing Roy Environment Technology Co., Ltd (Royco)
Schraufstetter Process	Pyrolysis	Biocon Energy
Siemens-Schwel-Brenn	Pyrolysis	Siemens, Mitsui, Takuma

Process	Type of CR	Company
Smuda Process	Pyrolysis	AgRob EKO, S.A.
Soleco	Pyrolysis	Soleco Energy, Sweet Gazoil
Sustane Chester Technologies	Pyrolysis	Sustane Technologies Inc.
SVZ Entrained flow gasification	Gasification	Standardkessel Baumgarte
SVZ Fixed bed gasification	Gasification	Standardkessel Baumgarte
Swestep Catalytic Conversion	Liquefaction	Swestep
Synova	Gasification	Synovatech, ECN, Milena
Synpet Thermal Conversion Process	HTL	Synpet Technologies
Syntech	Gasification	SYNTECH, enviromental technologies d.o.o., Geopolis
Syntrol	Liquefaction	Nill-Tech, PlastOil, Renasci, BlueAlp
T:CRACKER	Pyrolysis	Next Generation Elements GmbH (NGE), BDI, Syncycle
TCG	Gasification	TCG Energy, TCG Global
TCR process	Pyrolysis	Fraunhofer UMSICHT, Susteen
Thermo Catalytic Depolymerization	Liquefaction	Rudra Environmental Solutions (India) Ltd.
Thermofuel	Pyrolysis	Ozmotech Pty Ltd
Thermoselect	Gasification	Vivera Corporation
Trifol	Pyrolysis	Trifol
UHTH Ultra Hochtemperatur Hydrolyse	HTL	CleanCarbonConversion, Exoy Green Systems AG
Valoren	Pyrolysis	Valoren
VEBA-Combi-Cracking	Liquefaction	Kohleöl-Anlage Bottrop, VEBA OEL Technologie und Automatisierung GmbH
Velocys	Gasification	Velocys
VinyLoop	Solvolysis	Solvay, VinyLoop
VolCAT	Solvolysis	IBM
Waste4Me	Pyrolysis	Waste4Me
Waste-Material-Converter	Pyrolysis	Reststoffwandler UG, Clean Up Energy GmbH

Process	Type of CR	Company
Ways2H	Gasification	Ways2H, Clean Energy Enterprises, Japan Blue Energy
WPU	Pyrolysis	WPU Waste Plastic Upcycling