Recycling of Polymer Materials

PolyRegion, February 2015
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Outline

• Motivation - why recycling?
  – Market, lifetime, etc.

• Collect – concentration
• Storage
• Conveying

• Mechanical Recycling
• Chemical or feedstock recycling
• Energy recovery
• Other recycling routes - “downcycling”
Motivation - why recycling?
History of Materials

Historical development of relative importance

Quelle: Ashby, 1999

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Economic development of polymeric materials

Global production until 2004

**Produktion** 2004:
- World: 224 Million Tonnes / +5.7%
- Western Europe: 53.2 Million Tonnes / +3.7%
- Germany: 17.5 Million Tonnes / +4.2%

*) incl. Limes, Lacque, Dispersion, Fasern, etc.
Quelle: AA Statistik und Marktforschung Plastics Europe Deutschland

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Economic development of polymeric materials

Global polymer production compared with steel

(volume)

Milliarden Liter

Wordwide production 2004

Polymer 224 Mio t = 224 Mrd Liter
Steel 1.060 Mio t = 133 Mrd Liter

1989: polymer overtake steel

*) inkl. Leime, Lacke, Dispersionen, Fasern, etc.
Quelle: PlasticsEurope Deutschland, Wirtschaftsvereinigung Stahl
Economic development of polymeric materials

Consumption of Plastic Materials* - Forecast 2010
by consumer regions in percent and growth p.a.

Source: PlasticsEurope Deutschland, WG Statistics and Market Research

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Economic development of polymeric materials

Per Capita Consumption of Plastic Materials*


Source: PlasticsEurope Deutschland, WG Statistics and Market Research

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Economic development of polymeric materials

Worldwide consumption of standard polymers (in Mio. t; changes 1998/99 in %)

- PS+EPS: 5.0%
- PVC: 3.4%
- PP: 6.5%
- PE-HD: 9.7%
- PE-LD/LLD: 8.9%

Quelle: BASF
Usage of polymeric materials - Germany 2001

- Electrical devices: 7.5%
- Housewares: 4.5%
- Furniture: 7.0%
- Agriculture: 2.0%
- Packaging: 29.5%
- Construction engineering: 24.5%
- Automotive industry: 9.0%
- Miscellaneous: 16.0%
- Landwirtschaft: 2.0%
- Möbel: 7.0%
- Haushaltswaren: 4.5%

Source: VERBAND KUNSTSTOFFERZEUGENDE INDUSTRIE E.V.
Usage of polymeric materials - India

Plastics Consumption By Application (India)

- Packaging: 24%
- Agriculture: 23%
- Electronic: 16%
- Transportation: 4%
- Furniture: 1%
- Building: 8%
- Others: 14%
- Houseware: 10%
- Others: 14%
Usage of polymeric materials

- Packaging (3040 kt)
- Construction engineering (2520 kt)
- Automotive industry (930 kt)
- Electrical Devices (770 kt)
- Miscellaneous (3040 kt)

Quelle: VKE, Produktions-/Verbrauchs- und Verwertungsdaten für Kunststoffe 2001
Economic development of polymeric materials

**Vision (1975)**
- 50%
  - LCP
  - PEEK PEI
  - PPS PES
- 40%
  - PC PBT PET PA
  - PC/ABS POM PPO/PS
  - ABS PMMA
- 10%
  - HDPE LDPE/LLDPE PP PS PVC

**Reality (1994)**
- 80%
  - PP HDPE PS PVC LDPE/LLDPE
- 19%
- 1%

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Usage of polymeric materials

Western Europe - 2000

- Packaging: 37%
- Construction: 20%
- Automotive industry: 7%
- Industry: 5%
- Agriculture: 3%
- Electrical devices: 8%
- Sonstige: 10%
- Adhesive, paint: 10%
- Other thermoplastics: 9%
- PET: 13%
- PE-HD: 17%
- PE-LD: 15%
- PVC: 7%
- PS/EPS: 7%

Quelle: APME, 2002
Usage of polymeric materials

Western Europe - 2000

- Municipal waste: 67%
- Industrie u. Gewerbe: 21%
- Electrical devices: 4%
- Construction: 3%
- Automotive: 4%
- Agriculture: 1%
- PVC bottles: 6%
- PVC foils: 4%
- PS/EPS bottles: 11%
- PET bottles: 13%
- PE/PP bottles: 19%
- PE/PP foils: 47%

Quelle: APME, 2002
## Service life of polymeric products

<table>
<thead>
<tr>
<th>Field of application</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Packaging for food products</td>
<td>Less than 2 years</td>
</tr>
<tr>
<td>• Bottles, boxes, canister</td>
<td></td>
</tr>
<tr>
<td>• Verpackungsfolien</td>
<td></td>
</tr>
<tr>
<td>• Packaging for housewares</td>
<td>2 to 10 years</td>
</tr>
<tr>
<td>• Household items</td>
<td></td>
</tr>
<tr>
<td>• Electrical devices und kitchenware</td>
<td></td>
</tr>
<tr>
<td>• Automotive applications</td>
<td></td>
</tr>
<tr>
<td>• Pipes</td>
<td>More than 10 years</td>
</tr>
<tr>
<td>• Machine engineering and heavy machines</td>
<td></td>
</tr>
<tr>
<td>• Construction engineering</td>
<td></td>
</tr>
</tbody>
</table>

*Quelle: SEMA Group*
Service life of polymeric products

**Plastic consumption**

- < 2: 15%
- 2 - 10: 28%
- 10 - 20: 29%
- > 20: 28%

**Plastic waste**

- < 2: 62%
- 2 - 10: 24%
- 10 - 20: 14%
- > 20: 0%

Quelle: SEMA Group
Legal Regulation


The European waste hierarchy refers to the 5 steps included in the article 4 of the Waste Framework Directive:

Prevention - preventing and reducing waste generation.
Reuse and preparation for reuse - giving the products a second life before they become waste.
Recycle - any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes composting and it does not include incineration.
Recovery - some waste incineration based on a political non-scientific formula that upgrades the less inefficient incinerators.
Disposal - processes to dispose of waste be it landfilling, incineration, pyrolysis, gasification and other finalist solutions.
Legal Regulation


- According to the Directive, the amount of biodegradable municipal waste must be reduced to 50% in 2009 and to 35% in 2016 (compared to 1995 levels).


- 1 January 2015, for all end-of life vehicles, the reuse and recovery shall be increased to a minimum of 95 % by an average weight per vehicle and year.

**Additional Austrian Regulation:**

- Verpackungsverordnung 2014
- Deponieverordnung 2008
- Abfallwirtschaftsgesetz 2002
- Usw.
Polymer recycling
Utilization possibilities of plastic wastes

- **Treatment of plastic waste**
  - Collecting, storage, conveying
  - Cleaning, separating, drying
  - Agglomeration, repelletise

- **Mechanical Recycling**

- **Chemical recycling**

- **Thermal utilisation**

  - **Primary recycling** (recycling of clean, uncontaminated, single-type waste)
  - **Secondary recycling** (products having less requirements than fresh materials)
  - **Tertiary recycling** (solid plastic materials into smaller molecules)
  - **Quartanary recycling** (energy recovery)
Development trends of the most important recovery options
(for western europe)

Quelle: APME, 2002
Mechanical Recycling
Treatment of plastic waste

- Size reduction
- purification
- Separation
- drying (mechanical and thermal)
- granulating
Treatment of plastic waste
Waste arisings

– **Industrial sector**
  large amount of clean, uncontaminated and single-type waste
    – In-house recycling
    – Transfer to recycling company

– **Private sector**
  – Small amount of different, contaminated polymeric materials

**Possibilities of collecting waste**

selective collection at the industrial sector

Pick-up systems (Yellow Bin or Yellow Bag)

Bring systems
Treatment of plastic wastes - Collecting

- **Single resource container („pick-up-/bringsystems“)**
  definite materials were collected; requirements:
  - Big amounts
  - Easy identification

- **Collecting stations („bringsystems“)**
  municipal receiving office – employee is controlling the waste ➔ high sorting accuracy

**Comparision of collecting systems**

<table>
<thead>
<tr>
<th></th>
<th>Resource bin or bag</th>
<th>Single soure container</th>
<th>Collecting stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture efficency</td>
<td>Very high</td>
<td>low</td>
<td>Very low</td>
</tr>
<tr>
<td>Material purity</td>
<td>Very low</td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td>costs / kg</td>
<td>low</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>
Treatment of plastic wastes - Storage

General requirements to storage systems:

- sufficient amounts
- Constant mass flow over sufficient buffering
- Homogenisierung des Materials (prevention of segregation)
- dwell and residence time

Silo storage of polymers and recyclate

Problems:

- Recyclate possess unfavourable bulk properties
- fines lead to static charging and adhesion effects, dust exposure and higher explosion risk

⇒ Possible solutions: mechanical recirculation and wet storage
Treatment of plastic wastes - **Conveying**

**Mechanical conveying**

- Conveying through gravitation (feed hopper, funnel, etc.)
- Belt transportation
- Vibration conveyor
- Screw conveyor

**Fluid conveying**

- Hydraulic conveyance (liquid transportation)
- Pneumatic conveyance (Transportation with air)
Treatment of plastic wastes – Size reduction

• Size reduction is the initial point for all treatment processes
  
  Goals:
  – Homogeneous bulk material (homogeneous particle size distribution)
  – Reduction of shape effects (e.g.: film)

• Proper material properties:
  – toughness
  – elasticity
  – Thermal sensitivity

• Operational demands for size reduction (industrial scale):
  – Impact (high velocities; between 20 and 100 m/s)
  – Cut (scissor-like cutting)
Treatment of plastic wastes – Size reduction

Particle size classification after size reduction:

- Coarse: > 20 mm
- Medium: 1 bis 20 mm
- Finley granulated: < 1 mm

Size reduction machines for plastic waste:

Size reduction concept „Cut“
- Coarse shredding
  - Guillotine-cutter
  - Cutting roll for prior size reduction
- Medium
- Shredder

Size reduction concept „Impact“
- Coarse and medium
  - Hammer mill
- Finley granulated
  - Impeller breaker
Treatment of plastic wastes – Size reduction

Cutting roll for prior size reduction
Treatment of plastic wastes – *Size reduction*

**Cryogenic size reduction:** embrittlement of polymeric materials at low temperatures (< -40 °C); liquid nitrogen

**Cryogenic fine grinding:** increasing mass flow rate

- **Applications:**
  - Production of fine elastomeric particles with high quality
  - Cryogenic recycling of contaminated thermoplastic resins

- **Example:** plasticised PVC-roofing sheets
Treatment of plastic wastes – Size reduction

Cryogenic milling separation

- separation mechanism: different coefficient of linear thermal extension of materials

**Possible applications**

<table>
<thead>
<tr>
<th>composite materials</th>
<th>Anwendungen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber / metals</td>
<td>tires, coupling</td>
</tr>
<tr>
<td>Paint residues / metals</td>
<td>Household aids, paint bucket</td>
</tr>
<tr>
<td>Oils, fats, resins / metals</td>
<td>Industrial packaging</td>
</tr>
<tr>
<td>Polymer / fibres</td>
<td>carpeting</td>
</tr>
<tr>
<td>polymer / glass</td>
<td>Automotive glass panes</td>
</tr>
<tr>
<td>Polymer / metals</td>
<td>Electronic devices</td>
</tr>
</tbody>
</table>
Treatment of plastic wastes – *Purification*

**Washing process**
- Pre-dissolving of the dirt in big and slow screw conveyor or mixer
- Dissolving by intensify recirculation within big washers, mostly several washers are connected in series (counter flow principle)

**Separation of contamination**
- Mineral contamination by sedimentation (bottom of the basin)
- Non-mineral contamination - contamination and washing liquid will be separated together

**Influence on the process quality:**
- Time for (pre-)dissolving
- Type and temperature from the washing liquid
- Type and amount of additives in the washing liquid
- Mechanical load of the plastic particle (friction washer)

**Purification by extraction**
- Dissolving of migrationable film ingredients (NOREC-process)
Treatment of plastic wastes – Separation

Classify
principle of separation: different particle size

⇒ problems: particle shape may influence the separation quality

Mechanical classification (sieve):
fixed sieves (e.g. part of mills)
moving sieves (e.g. sieving screen)

Fluid sizing:
Principle of separation: different kinesic behaviour of particles in the fluid
- Friction factor of particle (size and shape) ⇒ classify
- Density ⇒ sorting
Treatment of plastic wastes – Separation

Sorting
Principle of separation:

different material properties:
  » Density
  » wettability
  » Electrical conductivity
  » Spectroskopic properties
Treatment of plastic wastes – Separation

Sorting by density
- most commonly used separation process
- **Problems:**
  - Foams (closed-cell)
  - Additives (reinforcements)

<table>
<thead>
<tr>
<th>Werkstoff</th>
<th>Dichte in g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kunststoffe</td>
<td>0,9 bis 2,3</td>
</tr>
<tr>
<td>PE</td>
<td>0,91 bis 0,96</td>
</tr>
<tr>
<td>PP (it)</td>
<td>0,90 bis 0,91</td>
</tr>
<tr>
<td>PS</td>
<td>1,05</td>
</tr>
<tr>
<td>PVC</td>
<td>1,38 bis 1,55</td>
</tr>
<tr>
<td>PUR</td>
<td>1,21</td>
</tr>
<tr>
<td>PET</td>
<td>1,38</td>
</tr>
<tr>
<td>kgfv Kunststoffe</td>
<td>1,0 bis 1,9</td>
</tr>
<tr>
<td>PP-GF (20 bis 40%)</td>
<td>1,05 bis 1,30</td>
</tr>
<tr>
<td>Metalle</td>
<td>2,8 bis 7,9</td>
</tr>
<tr>
<td>Aluminiumlegierung</td>
<td>2,8</td>
</tr>
<tr>
<td>Stahl</td>
<td>7,9</td>
</tr>
</tbody>
</table>
Treatment of plastic wastes – Separation

Heavy-media separation or sink-and-float separation

- Material transport by paddles and flow conditions
- Separation by gravitation; separation into a floating fraction and a sinking fraction; mostly used in cascades with different fluid densities (finely ground heavy mineral)
- Separation quality between 85 and 99% (depends on residence time and density differences of the material)
Hydrocyclone

- **Material transport**
  together with the fluid

- **Separation**
  inner turbulence (lightweight fraction), outer turbulence (heavy fraction);
  Problems: Superposition of classification and sorting effects

- **Quality of the separation process**
  > 98 %; the flow rate is 100 times higher than sink-and-float separation
Treatment of plastic wastes – Separation

Separation centrifuge

- Material: plastic slurry
- **Separation**: heavy fraction to wall and lightweight fraction to fluid surface; discharging by screws
- **Quality of the separation process**
  up to 99 %;
  lower residual moisture content.

http://www.sgconsulting.co.za/industrial-equipment/flottweg/flottweg-sorticanter/
Sorting by wettability

Flotation process

- Selective adsorption of air bubbles to hydrophobic surfaces of polymers ➔ froth with high content of material
- Increasing the surface hydrophilicity ➔ decreasing adsorption of defined polymers
- Chemicals to stabilise froth

http://www.911metallurgist.com/blog/whats-a-froth-flotation-process
Treatment of plastic wastes – Separation

Sorting by electrical conductivity

2 different principals of separation:

- Surface conductivity
- electronegativity

Corona drum separator

- Charging of particles by corona effect (high voltage; 15 to 30 kV).
- Particles to grounded drum; according to electrical conductivity particles are discharging and fall down
- Good tool for separating non-conductor/semiconductor or non-conductor/conductor
- examples: printed circuit board
Treatment of plastic wastes – Separation

Corona drum separator

http://incompliancemag.com/article/useful-static-electricity/
Treatment of plastic wastes – **Separation**

**Electrostatic separating device for sorting triboelectrically charged mixtures**

- Positive or negative tribological charging

<table>
<thead>
<tr>
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<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>PVC</td>
<td>PET</td>
<td>PP</td>
<td>PE</td>
<td>PS</td>
<td>PA</td>
</tr>
</tbody>
</table>

- Free fall **separating** by different charged plate electrodes

- **Quality** depends on: Electronegativity; dirt and moisture on particle surface; particle size; conditions in collecting container
## Sorting by spectroscopic properties

<table>
<thead>
<tr>
<th>Method</th>
<th>Wave length $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrared- (IR) spectroscopy</td>
<td>2500 nm to 25000 nm</td>
</tr>
<tr>
<td>- near IR (NIR)</td>
<td></td>
</tr>
<tr>
<td>Raman-spectroscopy</td>
<td>300 nm to 700 nm</td>
</tr>
<tr>
<td>UV-spectroscopy</td>
<td>200 nm to 600 nm</td>
</tr>
<tr>
<td>X-Ray-spectroscopy</td>
<td>No dependence on $\lambda$</td>
</tr>
</tbody>
</table>
Treatment of plastic wastes – Separation

IR-spectroscopy

- characteristic molecular groups; vibrations;
- Spectrum ➔ molecular structure of polymers

![Graphs of PMMA and PS infrared spectra](image)
Treatment of plastic wastes – Drying

Maximal tolerable humidity:
- Polyolefin (PE, PP), Polystyrene (PS) and ABS: ca. 1 m%
- Polyamide (PA) und Polyester (z.B. PET): < 0,1 m%

Mechanical drying
- Step 1: separation particle-washing fluid (sieve)
- Step 2: centrifugal dryer (moisture content approximately: 0,4 to 0,06 m%)

Thermal drying
- Step 3: flue-curing, hot-air
Treatment of plastic wastes

Agglomeration

- Goal: material should have a defined size for conveying
- Particles are melted and pressed;
- Short thermo-mechanical stress for the material

Re-granulating

- Extrusion process
- Advantages: homogeneous material; possibility of melt purification; additives
Problems for post-consumer plastics:

- purity of variety
- pollution
- usually unknown application
- material degradation
Polymer recycling - Problems

Content of the yellow bag

- 36% polymers
- 25.1% tinplate
- 2.3% aluminium
- 6.6% drink cartons
- 1.7% other composites
- 28.3% sorting residues
Polymer recycling - **Problems**

Share of the different materials of a car (Fiat 1990)

Composition of the plastic portion of a car (Fiat 1990)

*ETP’s stands for technical materials such as PA, PC, etc.*
### Mechanical recycling - *Problems*

**Possible contamination**

<table>
<thead>
<tr>
<th>Contamination</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>label</td>
</tr>
<tr>
<td>aluminium</td>
<td>Packaging</td>
</tr>
<tr>
<td>Particulate matter</td>
<td>Storage, usage</td>
</tr>
<tr>
<td>Print colours</td>
<td>Printing</td>
</tr>
<tr>
<td>Other polymers</td>
<td>Bad separating process; permanent joints (welding, gluing)</td>
</tr>
<tr>
<td>Chemicals</td>
<td>Usage; e.g.: container, petrol tank</td>
</tr>
<tr>
<td>Fat, oil</td>
<td>Usage, e.g.: food packaging</td>
</tr>
</tbody>
</table>
Mechanical recycling - *Problems*

**Solid contamination**

- **Usually bad connection to polymer**
  - embrittlement (impact toughness)

- **Rarely good connection to polymer**
  - positive influence of the mechanical properties:
    - Increase of Young Modulus
    - Impact modification

**Fluid contamination**

- **Diffusion process** (plastification)
Mechanical recycling - *Problems*

Degradation mechanism

- Thermal degradation
- Mechanical degradation
  - oxidative degradation
  - Hydrolytic degradation
- Chemical degradation
  - radiochemical degradation
  - photodegradation
  - biological degradation

During processing

After processing

ageing
Environmental influence on polymeric materials

- **Atmospheric influence**
  - UV- radiation, oxygen, ozone, temperature, moisture, sulphure dioxide

- **Chemicals (sorption, diffusion, degradation)**
  - Physical effects: swelling
  - Chemical effects: chemical degradation

- **Biological and biochemical influences**
  - Microorganism

- **Ionising radiation**
  - Oxidation, cross-linking reaction, degradation
Mechanical recycling - *Problems*

**Chemical aging**

- Non-reversible modification of the chemical structure
  - Post-condensation
  - Partial cross-linking
  - Degradation and oxidation

**Physical aging**

- Changes in molecular structure, texture, microstructure
  - Post-crystallisation
  - Phase separation
  - Plasticiser diffusion
  - Agglomeration
Mechanical recycling - Thermosets

Mechanical recycling:
- As fillers in other applications
Application possibilities for used elastomers

- as filler to virgin material
  
  Examples:
  rubber mat, sport tracks, flooring, sole

- Rubber with bonding agents
  
  Examples:
  construction area; acoustic and thermal insulation
Chemical or feedstock recycling
Chemical recycling - Overview

Chemical Recycling Or Feedstock Recycling of HDPE

Chemical recovery systems

Energy recovery systems

Incineration technology

Chemical recovery systems

Heterogeneous process

Homogeneous process

Cracking

Gasification

Chemolysis

Methanolysis

Glycolysis

Alcoholysis

Thermal Cacking

Catalytic cracking

Hydro cracking
Chemical recycling - Overview

Chemical or feedstock recycling

⇒ **Petrochemical method**: Statistical breakdown of polymers to low molecular weight liquid or gas products, production of monomers or feedstocks for the petrochemical industry.
  
  *e.g.* Pyrolysis, *Delayed Coking (Thermal method)*
  
  *e.g.* Hydrogenation

⇒ **Oxidation method** *(e.g. Synthesis gas)*

⇒ **Solvolytic method**: selective decomposition in low molecular weight substances (monomers).
  
  *e.g.* *hydrogenation, alcoholysis, glycolysis*

⇒ **Blast furnace**

  Pyrolysis of polymeric waste ➔ energy and reducing agents
Recycling options - Overview

Plastic waste

- mechanical recycling
- thermal decomposition
  - oxygen exclusion
  - solvolysis
  - hydrogenation
  - pyrolysis
- oxygen
- incineration

material recovery

goal

energy recovery
Chemical recycling - *Pyrolysis*

**Pyrolysis**

- Thermal decomposition of organic material and no oxygen
- Polymeric chains break into shorter saturated and unsaturated fragments
- Can be used for mixed and contaminated thermoplastics, thermosets and elastomers
- Products: gas, oil, liquid, coke, soot
- Reactor types: autoclave, rotary kilns, fluidized beds, shaft, tube reactors
Chemical recycling - *Hydrogenation*

**Hydrogenation**

- Decomposition of the molecules at temperature (300 to 500 °C) and pressure (100 to 400 bar)
- Saturation of the reactive sites by hydrogen
- Stabilization of the fragments in liquid products
- Heteroatoms (N, Cl, S) are converted into H compounds
- Base reactions in the hydrogenation:
Chemical recycling

Comparison between hydrogenation & pyrolysis

**Pyrolysis**
- 700 °C
- Without oxygen
- Without pressure

**Hydrogenation**
- 300 to 500 °C
- 100 to 400 bar H₂

Methane, olefins, aromatics, coke

Distribution of hydrogen according to physical and chemical laws

Short chains

Crack reaction and saturation of the breaking point with H₂
Chemical recycling

Production of synthesis gas:

- **Partial** oxidation with pure oxygen
- Gasification in the presence of oxygen and water vapor at 1300 to 1600 °C and a pressure up to 150 bar
- Synthesis gas consisting of carbon monoxide (CO) and hydrogen (H2), which allows a wide variety of synthetic chemical recovery (oxo-synthesis, methanol, acetic acid, etc.)

Solvolysis

- Selective decomposition with the help of chemical agents (monomers).
- For polymers with heteroatoms in the main chain, e.g. PET, PA, POM, PUR, PC.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Reagent</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td></td>
<td>Hydrolysis</td>
</tr>
<tr>
<td>Monohydric alcohol</td>
<td></td>
<td>Methanolyis</td>
</tr>
<tr>
<td>Polyhydric alcohol</td>
<td></td>
<td>Glycolysis</td>
</tr>
<tr>
<td>Acid</td>
<td></td>
<td>Acidolysis</td>
</tr>
</tbody>
</table>

(e.g. PU by water vapor in polyols and diamines)
(e.g. PET by ethylene glycol and dimethylterephthalate)
(e.g. PET by intermediate stages of the polycondensation)
(e.g. POM by mineral acid in trioxane)
Chemistry of the blast furnace process in use of plastics as an additional reducing agent

Chemical recycling – recycling in the blast furnace

Individual reactions

Blast furnace

- \( \text{Fe}_2\text{O}_3 + 3 \text{CO} = 2 \text{Fe} + 3 \text{CO}_2 \)
- \( \text{Fe}_2\text{O}_3 + 3 \text{H}_2 = 2 \text{Fe} + 3 \text{H}_2\text{O} \)

Eisenoxidreduktion durch Synthesegas

Lower blast furnace

- \( \text{C}_n\text{H}_m + \frac{3}{2} \text{O}_2 = n \text{CO} + \frac{m}{2} \text{H}_2 \)
- Cracken / Synthesegaserzeugung
Energy recovery

• **Incineration** is an effective way to reduce the volume of organic materials.

• **Plastics** (and plastic waste) are a high-yielding energy source.

• Net caloric value of (1 kcal/kg = 4,187 kJ/kg):
  
  - heating oil: 10200 kcal/l
  - PE: 18720 kcal/kg
  - PP: 18343 kcal/kg
  - PS: 16082 kcal/kg
  - PVA: 8565 kcal/kg
  - coal: 4800 kcal/kg
Energy recovery

Co-combustion:

• Incineration of municipal waste:
  – 1 ton organic waste could save up to 250 l heating oil
  – **Problems:** HCl at PVC; dioxin; polynuclear aromatics hydrocarbons; nitrogen oxide; sulphur oxide
    ➡️ optimal processing and off-gas treatment
  – **Disadvantages:** polymer structure is destroyed; most energy (70 to 85 % of the whole energy consumption) is used for producing monomer ➡️ lost at incineration

• Rubber incineration rotary kilns ➡️ cement industry
  – Additional reduction gas
  – Sulphur and nitrogen is needed in the product cement
  – Natural gas could be saved by the net caloric value of the rubber
Energy recovery

[Bar chart showing recycling rate and energy recovery rate for different countries, with Switzerland having the highest values, followed by Denmark and Germany.]
Energy recovery
Other recycling routes - “downcycling”

Composting or biodegradation

• Every polymer could be biodegradable
  ➔ using the „right“ microorganism

• Disadvantage:
  – Culture the microorganism ➔ effect of them? (on environment,..)
  – Polymer is converted to biomass and energy ➔ destroyed
Thank you for your attention