Circular economy concepts for closing the plastic loop – comparing mechanical and chemical recycling

Material qualities and their impact on assessment results

LCM 2021 | M.Sc. Christoph Stallkamp, Dr. Rebekka Volk, Prof. Dr. Frank Schultmann | Institute for Industrial Production (IIP)

Agenda

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MOTIVATION

Challenges in mechanical plastic recycling affect quality of secondary material

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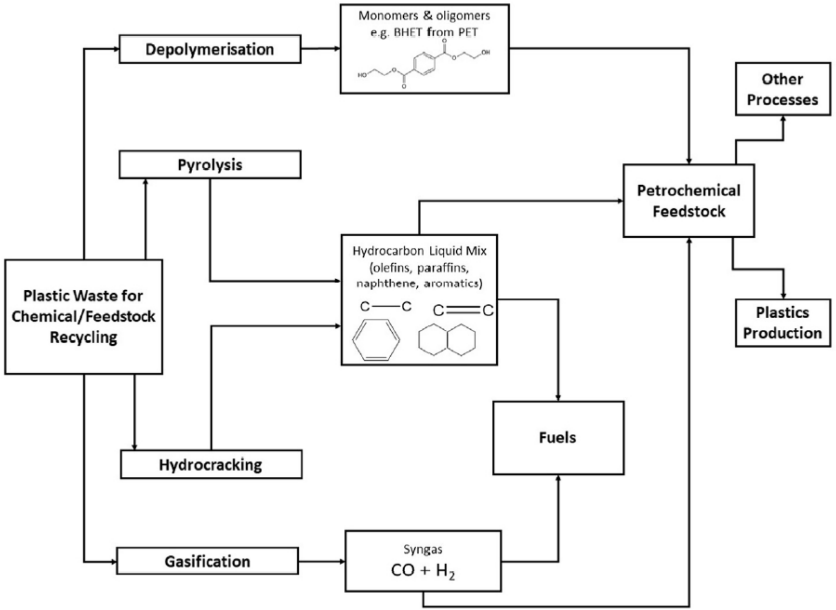
	Non-polymer impurities	Polymer cross contamination	Degradation	Additives
Production				X
Manufacturing incl. design	X	X	X	X
Use	X	X	X	
Segregation	X	X		
Collection				
Sorting	X	X		
Reprocessing incl. upgrading			X	

Source: Pivnenko et al. (2015)

- Multiple challenges affect the mechanical recycling of plastic and the quality of secondary material
- Non-polymer contamination affects the material purity and limit possible applications
- Polymer blends (cross contamination) have poor mechanical properties and unstable morphologies
- Degradation of polymers can lead to different product properties and hinder the reprocessing process
- Additives are not removed within mechanical recycling contaminating secondary plastic and impact possible applications

Chemical recycling has the potential to master the outlined challenges



Source: Davidson et al. (2021)

- Chemical recycling
  - is not influenced by the highlighted challenges; but further treatment steps might be needed
  - converts plastic waste into valuable feedstocks for the chemical industry that can be used to produce virgin-like plastics
  - downcycling is avoided
- Comparison of secondary material of mechanical and chemical recycling is difficult due to different product qualities
- Material quality differences should be addressed in LCAs or other assessments metrics comparing recycling technologies

Quality of secondary plastics must be assessed and included in the comparison of recycling technologies.

Assessing material quality of secondary plastics

No standardized definition of material quality and no standardized assessment approach

Technical properties	*Economic indicators*	*Qualitative discussion*
▪ Substitutability coefficients are based on the technical functionality for secondary material ▪ Assessment of material needed to establish its technical functionality	▪ Market value of primary and secondary material is used as approximated value ▪ Subject to fluctuations of market prices and assumed quality issues of secondary material	▪ Discussing the impact of the quality varying it and highlighting the changes in the assessment ▪ Demonstrates the range of the results and their uncertainty

Required data about assessed material decrease

Standardized definition of material quality and standardized assessment approach should be discussed.

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MATERIAL SUBSTITUTION RATES

Material substitution rates as part of the avoided burden approach within LCAs

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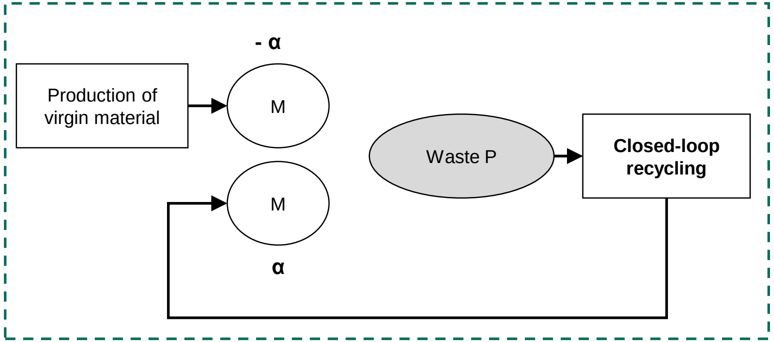

Source: Nakatani (2014)

- Avoided burden approach:
  Secondary material substitutes primary material and impacts of avoided primary production are rewarded
- Rewards for primary material substituted depend on the quality of secondary material at the point of substitution
- Quality is considered via substitution rate putting quality of secondary and primary material in relation to each other

$$LCI_{rec} = (1 - A) * R_2 * (E_{recEoL} - E_V^* * \frac{Q_{Sout}}{Q_P})$$

LCI_{rec}:	life cycle inventory of recycling with credits for avoided primary material
A:	factor for allocation of burdens and credits between supplier and user of recycled materials
R_2:	proportion of the material in the product that will be recycled in a subsequent system
E_{recEoL}:	specific emissions and resources consumed arising from the recycling process at EoL
E^*_V:	specific emissions and resources consumer arising from the acquisition and pre-processing of virgin material
Q_{Sout}:	quality of the ongoing secondary material at the point of substitution
Q_P:	quality of primary material

Source: EC (2018)

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Qualitative discussion of the substitution rate assessing different recycling technologies

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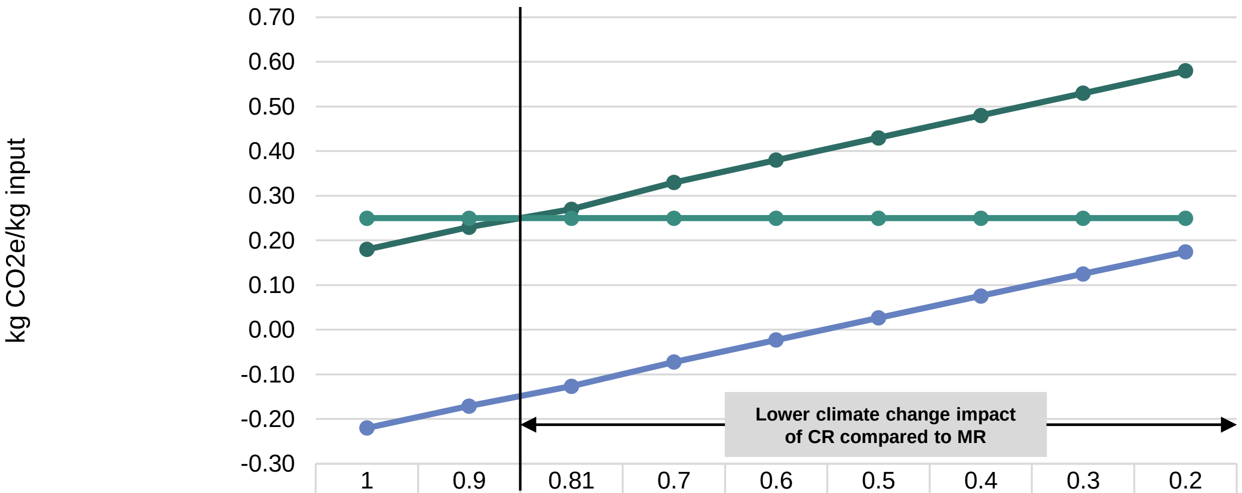
Global Warming Potential (GWP)



	1	0.9	0.81	0.7	0.6	0.5	0.4	0.3	0.2
Mechanical Recycling	0.18	0.23	0.27	0.33	0.38	0.43	0.48	0.53	0.58
Chemical Recycling	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Combined Recycling	-0.22	-0.17	-0.13	-0.07	-0.02	0.03	0.08	0.13	0.17

A variation in the material substitution rate has a direct impact on the environmental impact indicators assessed in an LCA.

Source: Based on Volk et al (2021)

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CIRCULARITY POTENTIAL

The circularity potential expands mass-based recycling rates and addresses material circularity

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- Concept introduced by Eriksen et al. (2019)
- Address the potential of recovery and recycling systems to contribute to a material circularity

η^{rec}	resource recovery efficiency
M^{rec}	amount of material recovered
U^{rec}	resource potential in the waste stream
c^{rec}	circularity potential
MS	market share in which the materials with quality level Q has a potential to be applied
Q^{rec}	quality of recovered material
Q^{disp}	quality of potentially displaced virgin material

(1) Physical losses

$$\eta^{rec} = \frac{M^{rec}}{U^{rec}}$$

(2) Quality losses

$$c^{rec} = \eta^{rec} * \frac{MS(Q^{rec})}{MS(Q^{disp})} \longrightarrow \begin{cases} MS_{high} & \text{for Q = high,} \\ MS_{medium} & \text{for Q = medium,} \\ MS_{low} & \text{for Q = low} \end{cases}$$

The circularity potential includes the economic usability of secondary material in the assessment.

Source: Eriksen et al (2019)

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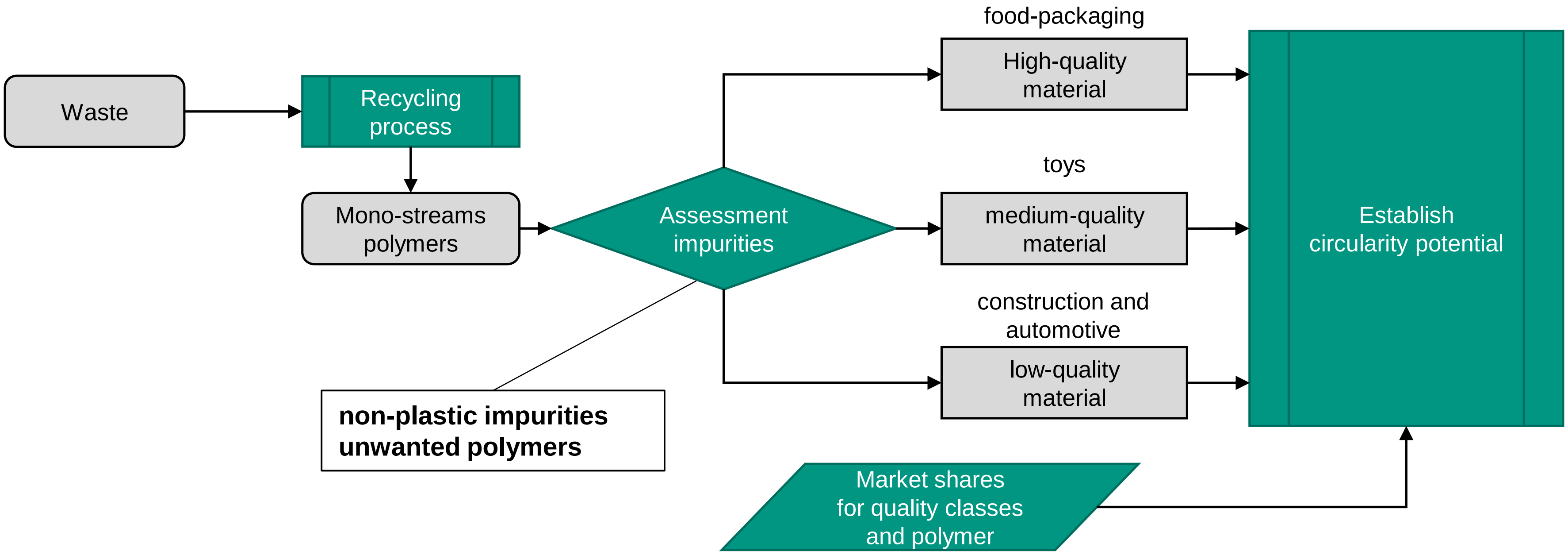
The quality of the feedstock streams for reprocessing facilities is assessed



The quality class of the recovered material determines the potential to close the plastic loop.

Comparing the circularity potential of mechanical and chemical plastic recycling

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- Assessment is based on composition lightweight packaging waste provided by the German collection system.
- Recycling routes established in Volk et al. (2021) are assessed for HDPE (scenarios 1.1 and 2 and 3.1).

	Mechanical Recycling	***Chemical Recycling***	***Combined Approach***
Physical loss	$\eta^{rec} = 0.29$ Higher material losses due to need for homogenous waste streams	$\eta^{rec} = 0.71$ Miscellaneous plastic packaging can be recovered	$\eta^{rec} = 0.70$ Sorting residues can be recovered by chemical recycling
Market share Quality class	$MS(Q_{medium}) = 0.73$ Application within food packaging currently limited by law	$MS(Q_{high}) = 1$ Production of virgin like plastic applicable for all applications	$MS(Q_{high}) = 1$ $MS(Q_{medium}) = 0.73$ Depending on recycling method
Circularity Potential	$\mathbf{c^{rec} = 0.21}$ MR has a theoretical potential to close 21% of the HDPE loop	$\mathbf{c^{rec} = 0.71}$ CR has a theoretical potential to close 71% of the HDPE loop	$\mathbf{c^{rec} = 0.62}$ CO has a theoretical potential to close 62% of the HDPE loop

Chemical recycling has a higher theoretical potential to close the HDPE plastic loop than mechanical recycling and a combined approach.

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COMPARING MATERIAL SUBSTITUTION RATES AND CIRCULARITY POTENTIAL

Comparison of substitution rates and the circularity potential and conclusion

	Material Substitution Rate	Circularity Potential
features	▪ Included in LCA via the avoided burden approach and rewards for substituting primary material ▪ Method to compare recycling technologies regarding economic and environmental performance indicators	▪ Additional performance indicator with no direct impact on environmental indicators ▪ Considers the long term theoretical potential to close the plastic loop and the economic usability of secondary material
challenges	▪ Challenge assessing material quality: combining multiple characteristics in a single indicator; defining quality classes is a simplification that must be considered ▪ No standardized definition of material quality resulting in different assessment approaches ▪ No standardized definition of material quality assessment approaches (material properties, economic indicators, qualitative discussion)	

The circularity potential complements the environmental assessment of secondary material by the potential of its economic use. It faces the same challenges of assessing material quality.

Thank you!

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