Measuring the circularity and impact reduction potential of post-industrial and post-consumer recycled plastics

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Supporting Information

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1 Life cycle inventory

This section details the life cycle inventory (LCI) to calculate the environmental impacts of a material over the entire path until the virgin resource input (here set to 1 kg) is lost. Regarding the virgin plastic granulate, the aggregated dataset *EU-28: Polypropylene, PP, granulate* from Plastics Europe (Sphera database) is selected from cradle-to-granulate per kg of virgin granulate (referring to the parameter E_{vir} in Equation 8 in the main article).

The LCI of post-industrial recycling (PIR) of post-industrial waste (PIW) are mostly based on primary data provided by Pöppelmann GmbH & Co. KG Kunststoffwerk-Werkzeugbau in Germany. The inventory captures the system boundaries from PIW-to-granulate per kg of recycled granulate (referring to the parameter E_{PIR} in Equation 8 in the main article). The LCI is shown in Table 1.

Table S1: Collection and mechanical recycling of PIW-to-granulate

Mass/energy flow name	Amount	Unit	Description	LCI data set
INPUT				
PIW	1.042	kg	Waste input collected for PIR	
Transport of PIW to mechanical recycling	100	km	The cargo corresponds to the PIW collected over a distance of 100 km	GLO: Truck-trailer, Euro 6, 34 - 40t gross weight / 27t payload capacity
Diesel demand for PIW waste collection and transportation to recycling	1.74E-3	kg	Amount of fuel calculated with Sphera software	DE: Diesel mix at filling station Sphera
Water	0.698	kg	Water demand for washing for recycling. Data provided from Pöppelmann	EU-28: Tap water from surface water Sphera
Electricity	0.389	kWh	Electricity demand for recycling. Amount of electricity provided from Pöppelmann	DE: Electricity grid mix Sphera
Outputs				
Recycled granulate	1	kg	Reference flow	
Incineration good (waste for treatment)	0.042	kg	Amount of residues provided from real data (Pöppelmann). The treatment of residues is attributed to the end of life (EoL).	DE: Polypropylene (PP) in waste incineration plant

The post-consumer recycling (PCR) of post-consumer waste (PCW) from PCW-to-granulate is modelled according to Frankling et al [1] (referring to the parameter E_{PCR} in the main article). However, used background data of the provision of materials and energy demand for the collection, sorting and recycling of PCW is updated to representative datasets for the market under study (Germany or if not explicitly available data for European union – EU-28). As written in the main article, the collection and sorting rates used to model the effective circularity (eC) are aggregated. However, for the modelling of the light packaging (LP) sorting inventory, the sorting rate need to be specified separately for the modelled system. In line with Franklin et al. [1], the sorting rate at sorting facilities of post-consumer waste is suggested to be around 90 %, which has been adapted to this study to set the amount of collected waste for sorting and recycling. We note that the sorting of polypropylene (PP) from LP as well as the mechanical recycling of PP PCW are assumed to be constant for all scenarios in terms of energy and mass flow inputs. Only the amount of collected and transported waste varies depending on the sorting and recycling rates. Therefore, the diesel demand for transportation varies, since this is directly depending on the mass of transported PCW need to recycle 1 kg of granulate. The LCI of the collection and sorting of PCW is presented in table 2.

Table S2: LCI of PCW collection and sorting

Mass/energy flow name	Amount	Unit	Description	LCI data set
INPUT				
PCW	1.708	kg	Amount of PCW varies for the circular scenarios depending on the assumed recycling rate. The value represents the conservative scenario.	
Municipal waste collection	0.068	tkm	Collection, hydraulic compression and transport of PCW based on a vehicle lifetime of 540'000 vehicle-kilometers including tyre abrasion and stop&go driving	CH: transport, municipal waste collection, lorry 21t (ecoinvent data)
Diesel	2.56E-10	kg	Demand for sorting of PP LVP [1]	DE: Diesel mix at filling station Sphera
Natural gas	3.54E-06	kg	Demand for sorting of PP LVP [1]	EU-28: Natural gas mix Sphera
Electricity	2.15E-03	kWh	Demand for sorting of PP LVP [1]	DE: Electricity grid mix Sphera
Thermal energy	0.126	MJ	Demand for sorting of PP LVP [1]	DE: Thermal energy from LPG Sphera
Output				
Sorted PP (baled)	1.538	kg		
Incineration good (waste for treatment)	0.171	kg	Residues from sorting (for thermal treatment). The treatment of residues is attributed to the EoL.	

The output of the sorting facility is the sorted and baled PP that is then transported to mechanical recycling. The transport to the recycler as well as additional sorting steps at the recycler are modeled and attributed to the recycling according to Franking et al. [1], but with representative background data for this study. Note that reported washing agents and deformants in Franklin et al [1] are neglected here due to missing information and LCI data sets. These inputs are not expected to have a significant influence on the climate change impact. The LCI of PCW recycling is shown in Table 3.

Table S3: LCI of PCW recycling

Mass/energy flow name	Amount	Unit	Description	LCI data set
INPUT				
Sorted PP (baled)	1.538	kg	Amount of sorted PP varies for the circular scenarios depending on the recycling rate assumed. The value represents the conservative scenario.	
Transport of sorted PP (baled) to mechanical recycling	km	100	Assumption of distance	GLO: Truck-trailer, Euro 6, 34 - 40t gross weight / 27t payload capacity Sphera
Diesel for transportation	2.57E-03	kg	Amount of fuel calculated with Sphera software	DE: Diesel mix at filling station Sphera
Water (including waste water treatment)	0.068	tkm	Water demand for washing for recycling [1]	DE: Tap water from groundwater Sphera and for waste treatment DE: Waste water treatment (contains low organic load) PE
Diesel	2.56E-10	kg	Demand for PCR of PP [1]	DE: Diesel mix at filling station Sphera
Natural gas	3.54E-06	kg	Demand for PCR of PP [1]	EU-28: Natural gas mix Sphera
Electricity	2.15E-03	kWh	Demand for PCR of PP [1]	DE: Electricity grid mix Sphera
Thermal energy	0.126	MJ	Demand for PCR of PP [1]	DE: Thermal energy from LPG Sphera
Sodium hydroxide	6.90E-04	kg	Demand for PCR of PP [1]	DE: Sodium hydroxide mix (50%) Sphera
Output				
Recycled granulate	1	kg		
Incineration good (waste for treatment)	0.538	kg	Residues from sorting (for thermal treatment). The treatment of residues is attributed to the EoL.	

Regarding the thermal treatment as last treatment activity of a material (referring to the parameter E_{EoL} in the main article), the dataset *DE: Polypropylene (PP) in waste incineration plant* from Sphera is selected. This dataset reflects the environmental burdens of the treated waste without energy recovery. The amount of recoverable heat (0.11 MJ) and electricity (1.58 kWh) is calculated with Sphera software for 1 kg of PP in the waste incineration plant. The German electricity mix (*DE: electricity grid mix*) from Sphera and the *EU-28: district heating mix* from

Sphera are used to calculate the credits from recovered energy. The sum of credits is referring to the parameter $E_{credits}$ in the main article.

2 Allocation of post-industrial waste in LCA

Existing standards for product life cycle assessment (LCA) recommend to model post-industrial waste (PIW) that is used as a feedstock for post-industrial recycling (PIR) as a joint co-product based on economic allocation [2]. To demonstrate the influence of the allocated impacts of the pre-chain, two exemplary allocation routes are investigated to narrow current LCA requirements on modelling PIW as a feedstock for recycling. The data were collected in 2019 for an LCA study on plant pots made of polypropylene (PP) which was conducted by Fraunhofer UMSICHT. The study was commissioned by the Pöppelmann GmbH & Co. KG Kunststoffwerk-Werkzeugbau in Germany. The company use both re-granulate from PIR and PCR to produce PP plant pots.

For instance, the PP PIW can originate from in-mold label production (IML) or diaper fleece production. Both waste streams from the fleece/label production have a monetary value as it is a rather clean waste fraction which can be sold on the market (between 0.4 and 0.5 €/kg). The quantity of accumulating PIW also varies per specific production route. In an IML process, between 30-40 % of PIW are obtained per kg of PP input. In contrast, the diaper process produces less PIW per kg of PP input (5-10 %). For the main virgin product, volatile prices were obtained and classified as a minimum (Min), maximum (Max) and average (see Table 4). The calculated economic allocation factors are based on the monetary value of the PIW compared to the fleece/label and are summarised in Table 1.

As a result, the PIW from the diaper fleece production carries a burden of 2.37 % of the pre-chain. According to volatile prices, sensitives of 1.30 % up to 3.82 % are calculated. The PIW from the IML production carries a burden of 1.80 % of the pre-chain on average. Sensitivities of 0.94 % up to 4.62 % have been calculated.

Table S4: Quantities and prices to calculate economic allocation factors between PIW and the main virgin product

IML	Quantity [kg]			Price [€/kg]			Economic allocation factor for waste [%]		
Scenarios	Min	Average	Max	Min	Average	Max	Min	Average	Max
Label	0.6	0.65	0.7	5.5	11.75	18	0.94%	1.80%	4.62%
Waste	0.3	0.35	0.4	0.4	0.4	0.4			
Diaper fleece	Quantity [kg]			Price [€/kg]			Economic allocation factor for waste [%]		
Scenarios	Min	Average	Max	Min	Average	Max	Min	Average	Max
Diaper	0.9	0.925	0.95	1.4	1.5	1.6	1.30%	2.37%	3.82%
Waste	0.05	0.075	0.1	0.4	0.45	0.5			

3 References

[1] Franklin Associates (2018). Life cycle impacts for postconsumer recycled resins: PET, HDPE, and PP.

[2] Nessi, S., Sinkko, T., Bulgheroni, C., Garcia-Gutierrez, P., Giuntoli, J., Konti, A., Sanye-Mengual, E., Tonini, D., Pant, R., Marelli, L., Ardente, F. (2021). *Life cycle assessment (lca) of alternative feedstocks for plastics production*, Publications Office of the European Union, Luxembourg, doi: 10.2760/271095.