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Report

The environmental benefits of PET recycling

Taking multiple recycling into account

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Contents

1 Introduction

Switzerland is the world champion in recycling. You hear this sentence again and again, and it is also true for certain materials, although not for everyone. Be that as it may, that we should recycle as much as possible seems to make sense to all of us. Recycling is also nothing new. Since the Bronze Age at the latest, man has recognised that certain materials can be recycled and reused as raw materials. So it is to be welcomed that the recycling efforts are constantly being expanded. In PET recycling, we are now achieving a recycling rate of 80 % in Switzerland, i.e. 80 % of the PET bottles put into circulation are available again as PET granulate for material use after recycling. PET recycling in particular means that around 30 % to 35 % goes directly back into bottle production (closed loop recycling). The remaining 45% to 50% are used as regranulate in other products that no longer require the same inherent material properties (open loop recycling).
The two terms open loop (OL) and closed loop (CL) recycling are used as follows in the life cycle assessment.

Closed loop (CL)
In this cycle, products of the same quality can be produced again from recycled material. The recycled material practically replaces 100% of new material. In the context of life cycle assessment, this approach does not mean that the same product is manufactured, but whether the recycled material has the same inherent material properties as the original material and thus products of the same quality can be manufactured, see also ISO 14'040 ff .

Open loop (OL)
In this cycle, the recycled material is recycled in a different way. The reason for this is usually that the material has changed properties. If the quality of the recycled material does not meet the same requirements as the virgin material, it cannot replace 100% of the virgin material due to the limited use. It is therefore necessary to carry out a so-called allocation to illustrate the reduced value. According to ISO 14040 ff, physical properties or economic values can be used as the basis for the allocation. The economic allocation is driven by the fact that, in most cases, the economy is the driver why something is done. On the other hand, the volatility of prices, e.g. due to overcapacity in the market, can lead to distortions. We therefore use the technical replacement potential if possible. This is the amount of primary material that can be replaced by R material in order to achieve the same desired technical properties, such as mechanical strength, for the respective application. In practice, PET recyclates can replace up to 100 % of primary material, depending on the product. This is the case, for example, with PET carrier bags. As an empirical value, we use a conservative replacement potential of 0.8 to 0.9 for the allocation factor. This is closer to the actual replacement of primary material than the economic factor.

Questions and procedure
For the recycled material to be reused in a bottle in the PRS system, it must be of food grade quality. This is associated with higher costs than the production of a granulate not suitable for food use for an OL application. Accordingly, the question arises whether this additional effort is worthwhile from an ecological point of view. The additional benefit results on the one hand from the higher replacement potential and on the other hand because the use in bottles leads to the fact that these in turn are collected by the PRS and fed to material recycling. This means that the material is at least partially recycled several times.
The aim of this study is to investigate how high the ecological added value of CL recycling is compared to OL recycling. In this context, CL recycling will be understood in the following as reuse as food-grade PET for beverage bottles. OL-Recycling is understood to mean reuse in an application outside the food sector. This corresponds to a somewhat narrower definition than that in the ISO standard.
The following assumptions have also been made:

- CL recyclate is used in bottles which are used in Switzerland and then collected by the PRS system.
- OL recyclate is used in applications that are disposed of after use in a MSW incineration plant including energy recovery.

Both the CL and the OL recyclate could also be used in applications outside of Switzerland and accordingly recycled or disposed of in a different way. Such applications are not dealt with in this analysis.
The ecological benefit for the current PRS system and possible variations thereof are calculated. These are compared with the situation in which the collected material would go to OL recycling only. The ecological benefit is measured with the method of ecological scarcity in environmental impact points (UBP). In addition, the climate potential is determined in CO2 equivalents (CO2eq).

2 The environmental benefits of PET recycling

The basic advantage of recycling is that a waste material is converted into a raw material and can therefore replace primary material. By recycling PET, the fossil raw materials required for the production of primary PET and the associated environmental impact are saved. This is the resource benefit of recycling a material. In addition, PET does not have to be disposed of as a material, or only after one or more further uses. As long as the cost of recycling is no greater than the production of the primary material and its disposal, recycling pays off from an ecological and/or economic point of view.
For combustible materials, especially for plastics and paper, however, an additional benefit can also be provided by energy recovery. Sometimes, this is absurdly referred to as "thermal recycling", although it is of course not a recycling, but a one-off recovery. With the operation of ever more efficient waste incineration plants, which nowadays generate on average around 28% district heating and 17% electricity in relation to the calorific value of the waste, this thermal benefit becomes ever more important. The benefit results from the fact that MWIPs directly replace fossil fuels with district heating, and MWIP electricity replaces electricity produced elsewhere, e.g. Swiss or European electricity mix. Which heat and electricity mix will really be replaced is another topic and will not be discussed here. For the calculations, the same replacement was assumed as in the KuRVe study, i.e. MWIP electricity replaces the European electricity mix and heat replaces 45% gas and 55% oil.

The assessment of the benefits of CL- and OL-Recycling is examined in the following from different angles:

- Waste management:
  This raises the question: Which is the most optimal use of a collected amount of PET waste?
- Resource management - plastic as a resource:
  The central question is: How can a given quantity of PET best be used?
- Demand management:
  Society needs PET and energy. This leads to the question: How can these two needs be best met?

In the following, the ecological benefits for the different approaches are calculated and discussed.

2.1 Waste management perspective

There are various life cycle assessment studies which consider the recycling benefit from the waste perspective. This means that the question is how a certain amount of PET can best be recycled or disposed of after use (post-consumer). In the context of this study, this perspective is called "waste management". It compares the ecological benefits of the different recycling routes, thermal or material, with each other. It is taken into account that material recycling makes a contribution to PET demand and thus saves the corresponding fossil resources. In addition, PET is not disposed of or is only disposed of after further use. However, other energy sources and thus other resources are needed to cover the energy demand. If PET were to be thermally recycled after a single use, a contribution could be made to covering the energy demand, which is still often based on fossil fuels today. But fossil fuels would be needed to meet the demand for PET. This approach is typically and justifiably used in life cycle assessments of recycling systems that address the question of which is the optimal recovery of a given amount of used PET. Figure 1 shows the different influencing factors of the investigated systems.

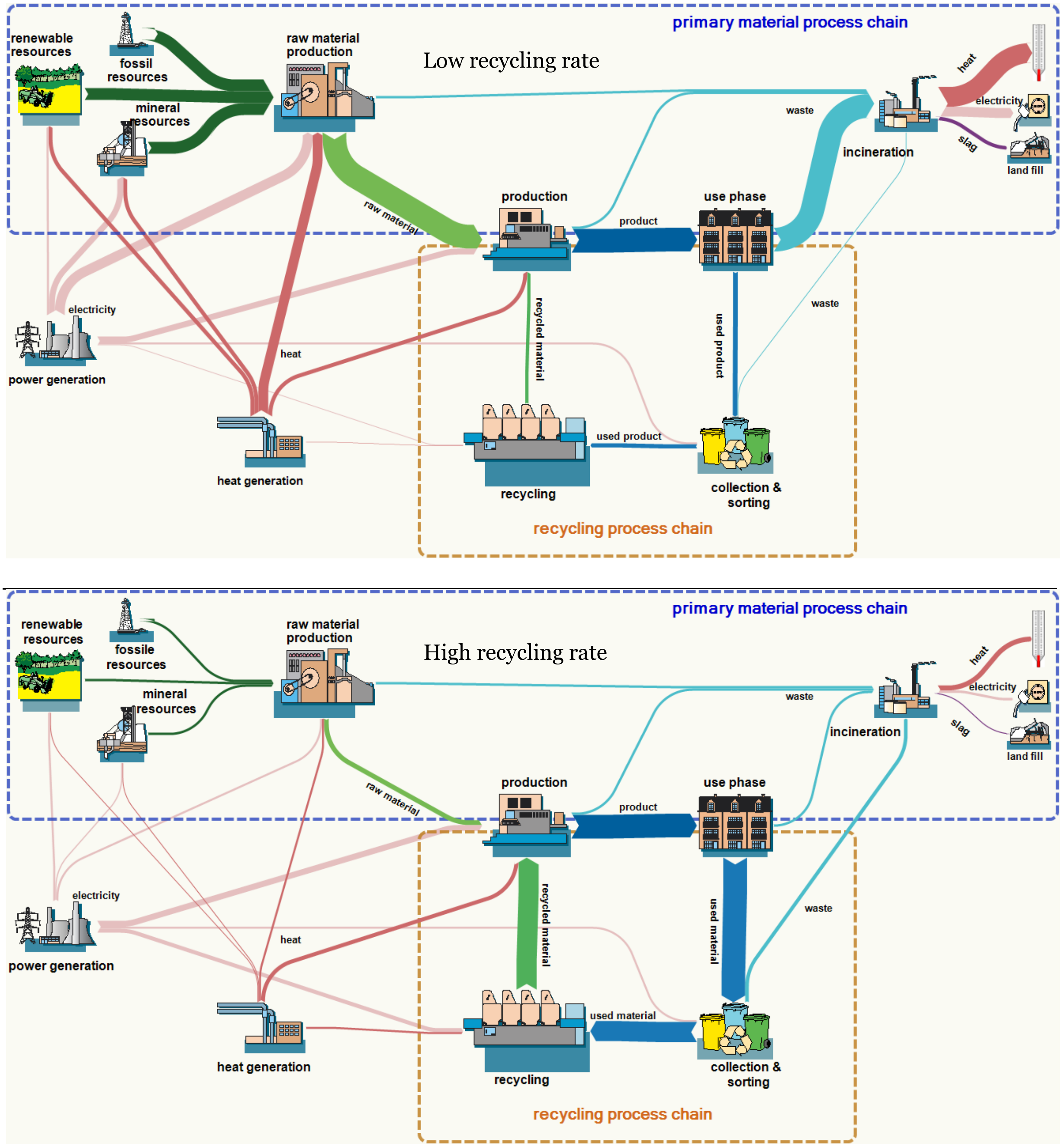

Figure 1: considered system with high and low recycling rate respectively

The environmental benefit from the waste management point of view is typically calculated per defined quantity of collected PET bottles (e.g. 1 t PET bottles) and is calculated as follows from the difference between the environmental impact of the recycling system and the environmental impact of the reference system "Disposal in MWIP":

$$NR = UR - UE \quad (1)$$

With
NR: Environmental benefits of the recycling system
UR: Environmental impact of the recycling system
UE: Environmental impact of disposal

The environmental impact of the recycling system results from the environmental burden of primary material production and the recycling system minus the credit for the replacement of new, primary material:

$$UR = AP + Pc * (Ac - ec * AP) + Po * (Ao - eo * AP) + (1 - Pc - Po) * UE \quad (2)$$

With:
Ac: Effort of the CL recycling system with the corresponding environmental impact
Ao: Effort of the OL recycling system with the corresponding environmental impact
AP: Effort of primary production with the corresponding environmental impact
ec: Replacement factor: Expresses how much primary material can be replaced by the CL recycling material.
eo: Replacement factor: Expresses how much primary material can be replaced by the OL recycling material.
Pc: Percentage which goes into CL recycling
Po: Percentage which goes into OL recycling
UE: Environmental impact of disposal

The environmental impact of disposal UE is calculated as the burden of incineration minus the benefits of energy supply.

$$UE = UV - (Aw + Ae) \quad (3)$$

With:
UV: Environmental impact of incineration in a waste incineration plant
Aw: Environmental impact of the effort to provide heat from fossil fuels
Ae: Environmental impact of the cost of providing electricity from the grid

Table 1 shows the environmental benefits of PET recycling per kg of PET. In order to determine the benefit ratio between CL and OL recycling, the same system as CL was calculated with OL only, i.e. Pc = 0 and Po = recycling rate. From this the benefit CL to OL was calculated. In addition to realistic parameter values, a calculation with theoretical maximum values was also carried out. In this case the recycling rate CL was set to 99% and the replacement factor to 100%. Clearly, these values are not feasible either for reasons of material properties or logistics. This calculation should simply show where the theoretical limit of the environmental benefit would lie at this angle.

Table 1 Environmental benefits of OL and CL recycling of PET from a waste management perspective. Data per kg PET. For better legibility, the values changed from the previous line were printed in bold.

Recycling rate	Closed Loop		Open Loop		Environmental benefit		Benefit CL to OL	
	Fraction	Replacement factor	Fraction	Replacement factor	kUBP	kg CO_2 eq.	UBP	CO_2 eq
80%	30%	95%	50%	90%	1’800	2.7	1.08	1.04
80%	30%	95%	50%	**80%**	1’700	2.5	1.14	1.08
80%	30%	95%	50%	**70%**	1’550	2.4	1.23	1.13
80%	**50%**	95%	**30%**	**80%**	1’800	2.7	1.24	1.13
80%	**70%**	95%	**10%**	80%	2’300	3.2	1.57	1.35
99%	**99%**	**100%**	**0%**	**100%**	2’700	3.7	1.06	1.13

Compared to a PET recycling system, which only consists of 80 % OL recycling, the environmental benefit, measured in UBP, of the current PRS system is about 1.08 times higher, i.e. the additional benefit generated by CL recycling is 8 %. This sounds like little. As the previous table shows, the additional benefit strongly depends on the replacement potential of the R-PET and on the proportion which reaches the OL. With an OL substitution factor of 70%, the additional benefit of CL recycling is a factor of 1.23. If 70% is in the CL, the additional benefit would be just under a factor of 1.6 higher than a pure OL system.

It should also be noted that only the next cycle of the collected goods is taken into account in this approach. I.e. it is not defined, what happens with the recyclate after the next application. However, it can be assumed that in CL recycling, thanks to the PRS system, the used PET is recycled again, while used PET, which reaches OL recycling, is very likely disposed of after a further cycle (or two). How this changes the benefit is considered in chapters 2.2 and 2.3.

2.2 Resource management perspective

The following objections are sometimes raised in relation to the approach taken in Chapter 2.1:

- It makes more sense to look at new PET as a starting point and not used PET.
- Instead of only considering the benefits of the next recycling step, all further recycling steps and the resulting benefits should also be included.
- With each additional recycling step, the benefit increases and at the end of the life cycle the PET can still be incinerated and used energetically. This certainly makes more sense than burning it after a single use.

These objections can be taken into account when we change our perspective, and now no longer from the point of view of waste management, but from the point of view of resource management, i.e. from the point of view of a selected (thought-provoking) tonne of PET. This means the following: When it comes to using the PET resource as useful as possible (let us assume that we only have one ton available), it makes sense to recycle the PET as often as possible and only to incinerate the parts that can no longer be used at the end. In this way, the optimum material is extracted and thermal recycling is also taken into account. From the point of view of this one tonne of PET, we have generated significantly more benefits than if we thermally recycled the PET after using it once.

It is obvious that the higher the CL content, the greater the environmental benefit generated, because with each cycle new material is saved. At a theoretical CL rate of 100%, the environmental benefit would be infinitely high. The question now arises as to what happens to the material that enters the OL recycling process. In principle, this material can also be recycled again and again. At present, there is a very high probability that the PET material will be thermally recycled after the one-off OL recycling process. This means that the benefit is only generated once. Since this corresponds largely to reality today and we want to elaborate how high the maximum additional benefit of CL recycling is, it is assumed for the following calculation that the material which was recycled into OL is then thermally recovered.

The calculation of the environmental benefit from the point of view of one resource results from the difference between the environmental impact of the recycling system and the environmental impact of the reference system "primary material production and disposal in MWIP" as follows:

$$N_R = U_P + U_R + U_E - X * (U_P + U_E) = U_R - (X - 1) * (U_P + U_E) \qquad (4)$$

With:
NR: Environmental benefits of the recycling system
UR: Environmental impact of the recycling system
UE: Environmental impact of disposal
UP: Environmental impact of primary material production
X: Number of material uses through recycling as a multiple of the first use of primary materials

The environmental impact of the recycling system results from the sum of the efforts of the recycling cycles minus the credit for the replacement of new, primary material plus the environmental impact of the disposal if the material is no longer recycled at the end. The following formula has been used to approximate repeated recycling.

$$X = \sum_{n=0}^{\infty} p^n = \frac{1}{1-p} - 1 \qquad (5)$$

Where:
P: Percentage that enters CL recycling.

This formula tends to overestimate the number of recycling cycles. For polymers, a high number of cycles is not possible for material-specific reasons, since the intrinsic material properties change in the course of use and recycling. The reason lies in the molecular structure of the polymers, which can break down under stress. At today's CL recycling rate of 30%, the error due to the application of this formula is less than 5% after just three cycles. At a recycling rate of 50%, the defect after five cycles is about 3%. With a polycondensate such as PET, this is justifiable because the chain breaks can be "repaired" to a certain extent during recycling by solid state polymerisation. At a recycling rate of 80%, 15 cycles would have to be completed before the defect is less than 5%. This is not a realistic number. When interpreting the results, the limit of this approximation must be taken into account.
The following formula applies to the environmental impact of the recycling system (UR) recycling under the assumption that the OL recyclate is fed into a thermal recycling process after a single use:

$$U_R = X * (A_c - e_c * A_{Pc}) + X * p_o * (A_o - e_o * A_{Po}) \qquad (6)$$

With:

Ac: Effort of the CL recycling system with the corresponding environmental impact
Ao: Effort of the OL recycling system with the corresponding environmental impact
AP: Effort of primary production with the corresponding environmental impact
    APc: for CL, i.e. food grade PET
    APo: for OL, i.e. non food grade PET
ec: Replacement factor: Expresses how much primary material can be replaced by the CL recycling material.
eo: Replacement factor: Expresses how much primary material can be replaced by the OL recycling material.

This results in

$$N_R = X * (A_c - e_c * A_P) + X * p_o * (A_o - e_o * A_P) - (X - 1) * (U_P + U_E) \quad (7)$$

Table 2 shows the environmental benefits of PET recycling per kg of PET from a resource perspective. In order to determine the utility ratio between CL and OL recycling, the same system as CL was calculated with OL only, i.e. the OL content corresponds to the recycling rate and pc = 0. The material is thermally recovered after the one-time OL recycling.

Table 2: Environmental benefits of OL and CL recycling of PET from a resource point of view. Data per kg PET.
For better legibility, the values changed from the previous line were printed in bold.

Recycling rate	**Closed Loop**		**Open Loop**		**Environmental benefit**		**Benefit CL to OL**	
	Fraction	**Replacement factor**	**Fraction**	**Replacement factor**	**kUBP**	**kg $CO_{2\,eq}$**	**UBP**	**$CO_{2\,eq}$**
80%	30%	95%	50%	90%	3’400	4.9	2.1	2.8
80%	30%	95%	50%	**80%**	3’200	4.7	2.3	3.1
80%	30%	95%	50%	**70%**	3’000	4.5	2.5	3.5
80%	**50%**	95%	**30%**	**80%**	4’600	6.7	3.3	4.3
80%	**70%**	95%	**10%**	80%	7’700	10.6	5.5	6.9
99%	**99%**	**100%**	**0%**	**100%**	355’000	471	157	192

Compared to a PET recycling system, which only consists of 80 % OL recycling, the environmental benefit, measured in UBP, of today's PRS system is around 2 times higher, i.e. the additional benefit generated by CL recycling is 100 %. As the previous table shows, the additional benefit strongly depends on the replacement potential of the R-PET and on the proportion that reaches the OL. With an OL replacement factor of 70%, the additional benefit of CL recycling is a factor of 2.5. If 70% reaches CL, the additional benefit is a factor of 5.5 higher than that of a pure OL system.
With this approach, the additional benefit of the CL system is considerably higher from the point of view of waste management.

However, it should be noted that this approach has a decisive blind spot from a holistic point of view: This can be illustrated by the following theoretical example: Assuming that 99% went into CL recycling, 1 tonne of PET would generate around 100 tonnes of PET material thanks to CL recycling. In order to obtain the same material benefit without recycling (reference system), 100 tonnes of primary PET would have to be produced and disposed of. What this approach does not take into account is that the disposal of 100 tonnes of PET in the reference system generates energy. In order to ensure comparability, the overall benefit must be the same, i.e. in the case of the recycling system, appropriate energy resources must be added. This aspect is taken into account in the requirements view in Chapter 2.3.

2.3 Demand management perspective

The demand management perspective is based on the consideration of resource management, but also takes into account the fact that, in order to obtain the same overall benefit, corresponding energy resources must still be provided in the case of the recycling system.

Thus formula (6) must be supplemented with the benefit of energy supply in the MWIP, shown in bold in the following formula:

$$N_R = X * (A_c – e_c * A_P) + X * p_o * (A_o – e_o * A_P) – (X -1) * (U_P + U_E - \mathbf{U_{En}}) \qquad (7)$$

With:
UEn:. Environmental impact of the energy supply: Environmental impact of the energy supply, if it would not be provided by the MWIP.

Formula (7) changes to formula (6) if the environmental impact of the energy supply UEn goes towards 0. This means that the better a country's energy supply is from an environmental point of view, the greater the multiple benefits of CL recycling compared with one-off OL recycling and the closer it is to that of resource use.

Table 3 shows the environmental benefits of PET recycling per kg of PET from a demand perspective.

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Table 3: Environmental benefits of OL and CL recycling of PET from the point of view of demand. Data per kg PET.
For better readability, the values changed from the previous line were printed in bold type..

Recycling rate	Closed Loop		Open Loop		Environmental benefit		Benefit CL to OL	
	Fraction	Replacement factor	Fraction	Replacement factor	kUBP	kg CO_2 eq.	UBP	CO_2
80%	30%	95%	50%	90%	2’600	3.7	1.5	1.5
80%	30%	95%	50%	**80%**	2’400	3.4	1.6	1.6
80%	30%	95%	50%	**70%**	2’200	3.2	1.8	1.7
80%	**50%**	95%	**30%**	**80%**	3’500	5.0	2.4	2.3
80%	**70%**	95%	**10%**	80%	5’800	8.2	4.0	3.7
99%	**99%**	**100%**	**0%**	**100%**	270’000	370	113	106

Compared to a PET recycling system, which only consists of 80 % OL recycling, the environmental benefit, measured in UBP, of today's PRS system is about 1.5 times higher, i.e. the additional benefit generated by CL recycling is 50 %. As the previous table shows, the additional benefit depends strongly on the replacement potential of the R-PET and on the proportion that reaches the OL. With an OL replacement factor of 70%, the additional benefit of CL recycling is a factor of 1.8. If 70% reaches the CL, the additional benefit is a factor of 4 higher than that of a pure OL system.
In this approach, the added value of the CL system lies between the waste management perspective and the resource view.
In the following, the different views, their applicability and limitations are discussed.

3 Discussion

As the results in chapters 2.1 to 2.3 show, there are very different results depending on the angle of view. Accordingly, it must be discussed in the following under which conditions which viewing angle is to be chosen sensibly. The following points are discussed for this purpose:

- Which assumptions are made with the different approaches and which limits result from it.
- How the different approaches relate to each other.
- When which approach should be chosen.

This discussion will be conducted in the following subchapters and the result will be presented in chapter 4.

3.1 Assumptions and limitations of the approaches

Waste management perspective

As the name suggests, this approach is based on a certain amount of used PET and answers the question as to which is the optimal recycling of this post-consumer waste from an environmental point of view. Essential factors that determine the result are:

- The quality of the recycled material, i.e. how much primary material can be technically replaced. The OL or CL can play an important role here.
- The energy use during disposal, i.e. how high the energy use is e.g. in the MWIP and which energy sources are replaced.

Accordingly, the results depend on the regional conditions and the technical possibilities for recycling. Typically, average values such as the energy use of MWIPs and the provision of useful heat and electricity to be replaced are used.

Since no assumptions regarding the further recycling of the recyclate are necessary, the results are relatively accurate and meaningful for a specific regional situation. However, this consideration of the uses of CL recycling tends to underestimate the fact that CL recycling, at least in the case of PET bottles in Switzerland, does not take into account the fact that when PET recyclate is used in bottles, CL recycling means that these are collected and recycled again and that, on the other hand, it is highly probable that the OL recyclate will no longer be recycled after further use.

Resource management perspective

In this view, the production of PET is assumed and the specific quantity of PET is regarded as a resource. With this approach, no assumptions have to be made with regard to energy use in thermal recycling. Therefore, the results are strongly dependent on the recycling rate and the assumptions regarding future recycling. It must also be taken into account that polymers cannot be recycled as often as desired because the molecular structures change during use and processing, see also the discussion on formula (5).

This view is partly justified by the argument that a combustible material can still be incinerated after various recycling cycles and that this makes more sense than incinerating it after its first use. This is correct from the point of view of the material resource, but a part of the overall system in which PET is also involved is completely ignored. The waste management and demand perspectives, on the other hand, take a more holistic view by taking into account that

- While recycling contributes to meeting PET's needs (thus saving oil as a resource) as described above, more other energy sources and therefore other resources are needed to meet our energy needs.

- Direct thermal recycling of PET contributes more to meeting our energy needs, but requires additional oil to meet our PET needs.

Because the resource perspective neglects the energy aspect, it provides the highest benefit.

Demand management perspective

The demand management perspective does not only consider the use of the material resource PET, but also the recycling dilemma of combustible materials. This means that from the point of view of demand for combustible materials such as plastics or paper, the question arises as to whether it makes more sense to recycle the material or to recycle it thermally. In both cases, a benefit is generated or a demand can be met. Essential factors that determine the result are:

- The quality of the recycled material, i.e. how much primary material can be technically replaced. The OL or CL can play an important role here.
- The energy use during disposal, i.e. how high the energy use is, e.g. in the MWIP or a cement plant, and which energy sources are replaced.
- How the recycled material is recycled after use. Or how many recycling cycles are assumed.

Accordingly, the results depend on the regional conditions and the technical possibilities for recycling. Typically, average values are used for this purpose. There are also uncertainties due to the assumptions about recycling cycles and the changes over time resulting from multiple recycling. This uncertainty is the price paid to get a comprehensive view and is typical for complex systems.

3.2 Relation of perspectives to each other

As discussed in the previous chapter, the demand management perspective is the most comprehensive and the resource view the most one-sided, since the latter excludes the fact that our society needs energy and the provision of this energy is also associated with environmental impacts. In an ideal world where the environmental impact of energy supply would be virtually zero, the results of the demand perspective would be transferred to those of the resource perspective. Since this is not the case even with the best alternative energy supply options, the resource view can at best be used to determine the theoretical marginal utility of multiple recycling.

In contrast, the waste management perspective represents the lower limit of the recycling benefit for a certain situation, since the benefit of a possible additional recycling is not considered. This can be essential for PET, as PET allows multiple recycling with high environmental benefits, depending on the application, due to the effort involved in production, the type of polymerisation and the chemical structure. This may be different for other polymers. With regard to the ratio of the benefit of CL recycling to OL recycling, the results of the demand management perspective are transferred to those of the waste management if the same number of recycling cycles for CL as for OL were realized and the OL recyclate would always have the same replacement factor. Typically, these conditions are only partially fulfilled or not fulfilled at all. In Switzerland, the PRS system means that the recycled material is collected and recycled during CL recycling. However, it must be assumed that PET, which enters the OL recycling process, is almost always thermally recycled at the end of the next use phase. Accordingly, the waste management perspective can be regarded as the lower limit of environmental benefit.

3.3 Appropriate approach

The appropriate approach depends essentially on the question!

In many life cycle assessments, the question is of the following nature: "What are the environmental impacts of providing a certain function? E.g. storage and protection of a certain amount of product or recycling of a certain amount of waste". For the latter, the waste management perspective is the appropriate approach. This is also the reason why this approach is typically and justifiably used in life cycle assessments of recycling schemes when it comes to the environmental benefits of recycling schemes. In addition, this perspective has the advantage that no assumptions need to be made about subsequent steps. On the other hand, this can lead to a tendency for CL recycling to be presented too badly, as the results in Chapter 2 show.

For a question such as the one posed in this study, which deals with the effects of two systems, CL and OL, the demand perspective is the appropriate approach. On the one hand, it takes into account the fact that CL recycling enables multiple use of the material and, in its holistic approach, takes into account the recycling dilemma of flammable materials. This is dealt with in the following chapter 3.4.

The view of material resource management does not take this dilemma into account and takes the view that material recycling always makes sense if the cost of recycling is less than that of new production. The energy requirements of our society are not taken into account. Accordingly, this approach cannot be recommended for decision-making from a holistic point of view such as life cycle assessment.

3.4 The recycling dilemma of combustible materials

When focusing on the material and its material resource, it is clear that recycling is worthwhile as long as the costs involved are lower than for the production of the primary material. From the point of view of waste management and demand, however, the question arises as to whether it makes more sense to recycle or thermally recycle combustible materials such as plastics or paper. In both cases a benefit is generated. This shows that the more fossil the energy mix that is replaced by thermal recycling, the greater the benefit of incineration. And this benefit can be so high that the bottom line is that it makes more sense to use a material once with subsequent thermal recycling than to recycle it several times. In other words, the worse a country's or region's energy strategy is, the less it seems worthwhile to recycle combustible materials. On the other hand, material recycling would be all the more worthwhile if a country or region was supplied exclusively with renewable and ecologically compatible energy. In the ideal case, i.e. if the energy had practically no environmental impact, we would have the same results from the point of view of resource management and from the point of view of demand. This means that the resource management perspective reflects the environmental benefit if the energy replaced during disposal was free of environmental pollution. The failure of energy policy at least from an ecological point of view hinders the recycling of combustible materials. We can ask ourselves the legitimate question to what extent this ecological punishment of recycling systems is justified for energy policy failure. This dilemma also highlights the difficulty of interpreting life cycle assessments.

4 Conclusion

PRS's PET CL recycling system enables the recycled PET granulate to be directly reused in bottles. Since these in turn are collected with the PRS system and fed to recycling, this generates a significant additional benefit from an environmental point of view compared with OL recycling, which is often associated with downcycling and then thermally recovered. This fact applies independently of the three approaches examined in this study. However, the level of benefit varies according to the perspective. It is highest for the perspective of PET as a material resource, followed by the demand management perspective. The smallest difference shows the waste management perspective. For the current PRS system, as of 2016, the ratio between CL and OL recycling is 1.5 for the demand management perspective, which is regarded as the adequate approach. From the waste management perspective, the additional benefit is considerably lower with a factor of 1.08 and correspondingly higher with a factor of 2.1 from the perspective of resource management.

The reason for this is that in the waste management perspective only the following cycle is considered. This means that the benefits of multiple recycling are not taken into account in CL, but no assumption needs to be made as to what happens to the OL recyclate after the next use. There are also applications in which multiple recycling cycles are possible in OL recycling. Today, however, these are rather rare. In addition, OL recycling can also have a high substitution factor. In the theoretical borderline case in which OL recycling also repeatedly leads to recycling of the material and the replacement factor does not decrease, the ratio of CL to OL of the demand management perspective would approach that of waste management.

On the basis of the current figures of the PRS system and the assumptions made, the most important of which is that the OL recyclate is not recycled after the subsequent use cycle, but is thermally recovered, the CL recycling is worthwhile compared to the OL recycling, as it brings a 50% higher ecological benefit. Depending on the circumstances, this value can change as follows:

- An increase in the CL recycling rate would further increase the ratio, e.g. 50% CL recycling leads to a factor greater than 2. For even higher CL recycling rates, it should be noted that the formula used overestimates the ratio, see also the discussion in Chapter 2.2.
- The federal government's intended energy strategy, which among other things leads to a reduction in the environmental impact of energy supply, also leads to an increase in the CL to OL factor, see Chapter 3.4.
- An increase of the factor CL to OL also results if the replacement factor of the OL recyclate is smaller, i.e. the quality of the OL recyclate is worse. For the standard variant, a high replacement factor of 90% was used for the OL recyclate.
- If OL recyclate were also recycled several times, this would result in a reduction of the factor CL to OL.

Since none of these influencing factors leads to a reversal of the results, the statement that the CL recycling of the PRS leads to an ecological surplus benefit compared to the OL recycling can be regarded as certain.

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