Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 140 (2026) 940–945

www.elsevier.com/locate/procedia

33rd CIRP Conference on Life Cycle Engineering (LCE 2026)

# Circular Footprint Formula: Challenges and Opportunities in Assessing the Circularity of Post-Consumer Recycled Materials for Automotive Panels

Vineet Shah*[a], Carsten Asshoff[a], Nina Ritter[a], Dirk Berthold[a]

[a] *Fraunhofer WKI,Riedenkamp 3, 38108 Braunschweig, Germany*

* Corresponding author. Tel.: +49 511 3532 4815; *E-mail address:* vineet.shailesh.shah@wki.fraunhofer.de

**Abstract**

The automotive industry, at 9.7 %, drives the third largest demand for virgin plastics after the packaging and construction industries in Europe. While increasing the recycling rates for the end of life (EoL) of vehicles is important, it is also imperative to close the loop by increasing the use of post-consumer recycled (PCR) plastics. The utilization of PCR materials remains largely constrained due to olfactory limitations in interior applications and due to technical and surface performance limitations in exterior applications. Novel and scalable manufacturing technologies like co-injection molding and in-label molding can improve the surface performance whilst increasing the share of PCR materials. This also addresses the new draft on EU-Regulation on circularity requirements for vehicle design which is expected to come into effect by the year 2032. The use of PCR materials, however, creates the issue of EoL allocation in the life cycle assessment of the primary and the recycled materials between their consecutive life cycles. There are multiple EoL allocation approaches like the cut-off approach, the avoided burdens approach, the Nordic LCA guidelines recommended 50/50 approaches, the EU-JRC PEF recommended circular footprint formula, and other market-price based allocation approaches. These approaches allocate the burdens of recycling and disposal of the materials differently between its consecutive lifecycles, thus affecting the overall LCA results for the recycled material. PCR polypropylene used to manufacture automotive carrosserie, specifically the bumpers, is used as a case-study to demonstrate how value choices in the selection of EoL approach can affect the overall life cycle assessment results. Results indicate that using disparate allocation approaches could potentially yield divergent outcomes, i.e., the inconsistent use of allocation approaches in different life cycles of materials might lead to double counting or complete avoidance of environmental impacts.

© 2026 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer review under the responsibility of the scientific committee of 33rd CIRP Conference on Life Cycle Engineering

*Keywords:* Life cycle assessment; Allocation; End-of-life; Circular Footprint Formula; Post-consumer recycling, Exterior automotive panels

## 1. Introduction

The automotive industry is the third largest consumer of virgin plastics in Europe, driving a total of 9.7% demand [1]. In addition to their substantial environmental impact, plastics are also subject to critical discourse owing to the significant amounts of generated waste. Presently, there is a paucity of infrastructure to facilitate End-of-Life (EoL) recycling in the automotive sector. As part of the European Green Deal, a new draft of the EoL of vehicles, which aims to improve circularity, mandates a minimum of 25% of post-consumer recycled (PCR) plastic content in all vehicles registered after 2030, of which 25% must originate from a closed-loop cycle [2]. From the standpoint of life cycle assessment this engenders a three-fold allocation predicament for the environmental burdens, namely virgin materials, recycling, and disposal between life cycles.

2212-8271 © 2026 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer review under the responsibility of the scientific committee of 33rd CIRP Conference on Life Cycle Engineering
10.1016/j.procir.2026.05.158

These issues are addressed using the 'pcrExteriA – Post-Consumer Recycled Plastics for Exterior in Automotive' project as a case study. The objective of the project is to increase the PCR content in the exterior body panels to comply with the new draft of the EoL vehicles directive. Life cycle assessment (LCA), as delineated in the ISO 14040/44 standards [3, 4], is chosen as the methodological framework to evaluate the environmental impacts. As the focus is on PCR materials, different EoL allocation approaches including the cut-off, system expansion, 50/50, circular footprint formula (CFF), and market-price based approaches are systematically evaluated and compared.

## 2. Methods

Inventory modelling and impact assessment have been performed using the Sphera LCA for Experts (version 10) software. Figure 1 illustrates the system boundaries and the consecutive life cycles of the material with the life cycle ($L_2$) representing the evaluated life cycle. Given the emphasis on allocation of the environmental impacts of material extraction, recycling, and disposal between the distinct life cycles, the manufacture and use phases are explicitly excluded. The objective is to evaluate and demonstrate the differences that value choices, through the use of different EoL allocation approaches, engender in LCA.

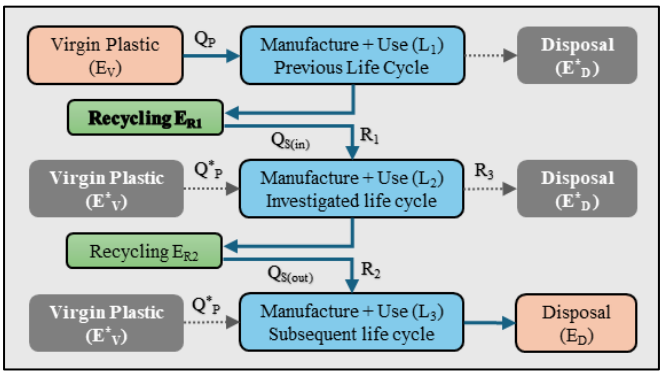


Figure 1 different life cycles that share the burdens and benefits of recycling

### *2.1. Product System – PCR Polypropylene*

The product system for the post-consumer mechanical recycling of Polypropylene comprises of six sequential steps as illustrated in Figure 2, viz., collection, transportation, sorting, shredding, washing, drying, and in most cases, extrusion and granulation. For the time being, the inventory for collection, transportation, shredding, washing, and drying have been derived from literature [5] and the inventory for extrusion and granulation have been derived from Sphera managed life cycle content (MLC). It is, however, planned to capture primary data for all these steps to make the inventory modelling more representative of the actual technologies used. Although the inventory data pertains to the mechanical recycling of polypropylene (PP), there may be other plastics in the mixture due to the limitations of the sorting technologies [5]. The functional unit is 1 kg of PCR-PP which is of sufficient quality to increase the proportion of PCR plastics in exterior body panels in the automotive industry. For now, the additional functions are not taken into consideration.

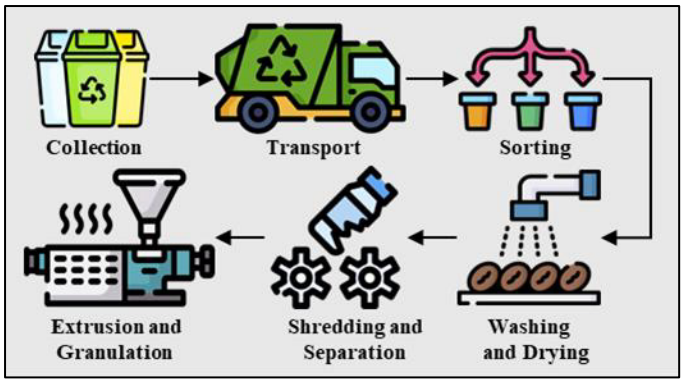


Figure 2 post-consumer mechanical recycling of plastics

Figure 3 shows the PCR-PP flakes on the left half of the image, which are extruded and granulated to obtain PCR-PP granules, shown in the right half of the image.

Figure 3 post-consumer recycled polypropylene

Currently, the inventory is modelled using the attributional framework. Since the case-study potentially represents a sector-based change, it can be argued that the consequential framework aligns better with the decision context. Thus, the EoL allocation approaches are also analysed based on their alignment with consequential and attributional inventory modelling frameworks.

### *2.2. Different EoL Allocation Approaches*

The evaluated EoL allocation approaches and their mathematical expressions are described in the following sections and Table 1 describes the variables used in the mathematical expressions. The notations of the variables have been adapted for uniformity and for comparability of different approaches, as also illustrated in Figure 1.

Table 1 Description of variables used in Mathematical expressions

| Variable | Description |
|---|---|
| $E$ | Environmental impacts per FU of the recycled material used in the investigated product system |
| $E_V$ | Environmental impacts per FU of the virgin material that is used in the previous life cycle ($L_1$) |
| $E^*_V$ | Environmental impacts per FU of the virgin material assumed to be replaced in the investigated life cycle ($L_2$) |
| $E_D$ | Environmental impacts per FU of waste disposal without energy recovery in the investigated life cycle ($L_2$) |

| | |
|---|---|
| $E^*_D$ | Environmental impacts per FU of the avoided waste disposal without energy recovery in the investigated life cycle ($L_2$) |
| $E_{R1}$ | Environmental impacts per FU of the recycling process between the previous ($L_1$) and the investigated life cycles ($L_2$) |
| $E_{R2}$ | Environmental impacts per FU of the recycling process at the end of the investigated life cycle ($L_2$) |
| $E_{ER}$ | Environmental impacts per FU of energy recovery during disposal of material in the investigated life cycle ($L_2$) |
| $E_{SE,heat}$ $E_{SE,elec}$ | Specific Environmental impacts per FU associated with the substituted energy sources, heat and electricity |
| $R_1$ | [Dimensionless] proportion of recycled material input in the investigated life cycle ($0 \leq R_1 \leq 1$) |
| $R_2$ | [Dimensionless] proportion of material that will be recycled for a subsequent life cycle ($0 \leq R_2 \leq 1$) |
| $R_3$ | [Dimensionless] proportion of material used for energy recovery after the investigated life cycle ($L_2$) |
| $Q_S$ | Quality indicator for the recycled secondary material |
| $Q_P$ | Quality indicator for the substituted material |
| $Q^*_P$ | Quality indicator for the avoided virgin material |
| A | [Dimensionless] allocation factor between the supplier and the user of recycled materials |
| $A_1$ | [Dimensionless] market-price based allocation factor between the supplier and the user of recycled materials in the investigated life cycle ($L_2$) |
| $A_2$ | [Dimensionless] market-price based allocation factor between supplier and user of recycled materials in the subsequent life cycle ($L_3$) |
| B | [Dimensionless] allocation factor for energy recovery |
| $X_{SE,heat}$ $X_{SE,elec}$ | Efficiency of the energy recovery process for heat and electricity respectively |
| LHV | Lower heating value of the material in the product that is used for energy recovery |

*2.2.1. The 100/0 Approach*

The 100/0 approach, also called the recycled content approach or the simple cut-off approach, is defined in the GHG Protocol, PAS 2050, and the ISO 14067 standards [6–8]. Allocating the environmental burdens using this approach incentivizes the use of recycled materials as long as the recycling process has lower impacts than the production of virgin materials. However, this approach disincentivizes material recycling when the burdens of recycling are higher than those of disposal [9]. The mathematical expression is shown in equation (1).

$$E = (1 - R_1)E_V + R_1 E_{R1} + (1 - R_2)\, E_D \quad (1)$$

*2.2.2. The 0/100 Approach*

The 0/100 approach, also called the allocation to material losses or the closed-loop substitution approach or the EoL approach, is defined in the GHG Protocol, PAS 2050, and the ISO 14067 standards [6–8]. Allocating the environmental burdens using this approach does not incentivize the use of recycled material irrespective of the burdens of recycling compared to those of the virgin material production. However, it does incentivize recycling in the investigated system if the burdens of recycling are lower than those of disposal [9]. This approach can be used with and without credits for avoided production of virgin materials. The mathematical expressions for the 0/100 approach without and with credits for avoided virgin material production are shown in equations (2) and (3) respectively.

$$E = E_V + R_2 E_{R2} + (1 - R_2)\, E_D \quad (2)$$

$$E = E_V + R_2 \left(E_{R2} - E_V^* \times \frac{Q_S}{Q_P}\right) + (1 - R_2)\, E_D \quad (3)$$

*2.2.3. The 50/50 Approach*

The 50/50 approach is described in the Nordic guidelines on LCA [10], where the environmental impacts of the recycling processes are divided equally between the life cycles. This approach can be used with and without credits for the avoided production of virgin materials. The mathematical expressions without and with credit for the avoided production of virgin material are shown in equations (4) and (5) respectively.

$$E = (1 - R_1)E_V + \frac{R_1}{2} E_{R1} + \frac{R_2}{2} E_{R2} + (1 - R_2)\, E_D \quad (4)$$

$$E = (1 - R_1)E_V + \frac{R_1}{2} E_{R1} + \frac{R_2}{2}\left(E_{R2} - E_V^* \times \frac{Q_S}{Q_P}\right) + (1 - R_2)\, E_D \quad (5)$$

The 50/50 approach with credits for avoided production of virgin material has been excluded here since it assumes a closed loop approach, which is not applicable to PCR materials. While the 50/50 approach tries to solve the incentive issue that persists with the 0/100 and the 100/0 approaches, it doesn't accurately represent the material quality loss in the recycling process. To account for this, a quality adjusted 50/50 approach is proposed [11], which is based on the approach proposed by German Federal Environmental Agency (Umweltbundesamt) for life cycle assessment of beverages [12] and recommended by the French standard for LCA [13]. The Umweltbundesamt still recommends a similar approach to allocate the burdens of open-loop recycling in the life cycle assessment of beverage packaging [14]. The mathematical expression for the quality adjusted 50/50 approach is shown in equation (6).

$$E = \left(1 - \frac{R_1}{2}\right) E_V + \frac{R_1}{2} E_{R1} + \frac{R_2}{2}\left(E_{R2} - E_V^* \times \frac{Q_S}{Q_P}\right) + \left(1 - \frac{R_1}{2} - \frac{R_2}{2}\right) E_D \quad (6)$$

*2.2.4. The Circular Footprint Formula (CFF)*

The quality adjusted 50/50 approach was later refined into the CFF by the Joint Research Centre of the European Union (EU-JRC) as part of the PEF methodology. The CFF tries to allocate more accurately the environmental burdens of virgin and recycled materials as well as the burdens of recycling and disposal processes, including energy recovery, between the consecutive life cycles of products or materials. The CFF also takes into consideration the material and quality losses between consecutive life cycles through the quality ratios for the recycled materials coming in and going out of the investigated life cycle [15]. The mathematical expressions to calculate the life cycle environmental impacts of the recycled materials are shown in equations (7), (8), (9), and (10) respectively.

$$E = material\ (m) + energy\ (e) + disposal\ (d) \quad (7)$$

$$\mathrm{m} = (1-R_1)E_V + R_1 \times \left(AE_{R1} + (1-A)E_V \frac{Q_{S_{in}}}{Q_p}\right) + (1-A)R_2 \times \left(E_{R2} - E_V^* \frac{Q_{S_{out}}}{Q_p}\right) \quad (8)$$

$$e = (1-B)R_3 \left(E_{ER} - \left(LHV \times X_{ER,heat} \times E_{SE,heat}\right) - \left(LHV \times X_{ER,elec} \times E_{SE,elec}\right)\right) \quad (9)$$

$$d = (1-R_2-R_3)E_D \quad (10)$$

*2.2.5. The Market-Price based Allocation*

The market-price based allocation is defined in the ISO 14067 standard [8] and is based on an open-loop approach, i.e., the material is recycled into another product system whilst undergoing inherent change in its physical properties. Similar to the CFF, this approach also works with an allocation factor, $A_1$ in this case, which is the ratio between the global market value of the recycled material and the global market value of the virgin material. The mathematical expression is shown in equation 11.

$$E = E_V(A_1(R_1-R_2)+1-R_1) + R_1E_{R1} + E_D(1-R_2) \quad (11)$$

*2.2.6. The Market-Price based Substitution*

The market-price based substitution [16] combines the approach of ISO 14067 and the CFF by using two different allocation factors, $A_1$ and $A_2$. The allocation factor $A_1$ is the same as for market-price based allocation approach. The allocation factor $A_2$ is the ratio of the global market value of the material recycled from the investigated life cycle for use in a subsequent life cycle to that of the virgin material assumed to be avoided in the subsequent life cycle. The mathematical expression is shown in equation 12.

$$E = E_V\left(1 - R_1\left(1 - \frac{Q_{S_{in}}}{Q_p}\right)\right) + E_D - (1-A_1)R_1\left(E_V\frac{Q_{S_{in}}}{Q_p} + E_D^* - E_{R1}\right) - A_2R_2\left(E_V^*\frac{Q_{S_{out}}}{Q_P^*} + E_D - E_{R2}\right) \quad (12)$$

*2.3. EoL Allocation Approaches in Consequential Modelling*

The 0/100 and the 100/0 approaches do not align with the consequential framework for inventory modelling since they do not take into consideration the substitution of virgin materials [8]. The 50/50 approaches, while they try to allocate the burdens of recycling equally between the consecutive lifecycles, they do not account for quality or the substitution of materials and thus also do not align with the consequential framework. The CFF tries to address all these issues and aligns relatively well with the consequential framework since it takes into consideration the substitution of avoided materials. But the CFF does not take into consideration avoided disposal so it does not align perfectly with the consequential framework [17]. The market-price based allocation does not take avoided processes into consideration so it does not align with the consequential framework. The market-price based substitution takes into consideration the avoided disposal as well as avoided production of virgin materials and thus aligns well with the consequential framework.

## 3. Results and Discussions

PCR PP partly replaces virgin PP in the manufacturing of exterior automotive panels, with the aim of collecting, dismantling, and recycling the automotive carrosserie at EoL. The default assumption when modelling the inventory using the different EoL allocation approaches is that the newly developed automotive panels will be manufactured such that they contain a minimum of (R1=) 40 % PCR PP. It is also assumed that almost 95 % of the automotive panels will be recycled at EoL which is in line with the new proposal for the EoL of vehicles directive [2]. Thus, a recycling rate of (R2=) 75% is assumed after accounting for losses during the use of the product as well as the recycling losses. Further, it is also assumed that the material losses during recycling, i.e., the wastes from the recycling processes are incinerated, which is in line with the current German disposal situation, i.e., 99 % of plastic waste is incinerated, as recommended in the Annex C of the EU-PEF methodology [15]. Thus, a disposal rate of (R3=) 20 % is assumed.

Since a PCR material is investigated, $E_V$ in this case reflects the environmental impacts per FU of virgin plastics in the ratio that reflects the average PCR mixed-plastic waste stream, i.e., 60 % Polyethylene Terephthalate, 32 % High-density Polyethylene, and 8 % PP [5]. This is so because it is difficult to determine the exact environmental impacts of the virgin material from a previous life cycle. The results are calculated using the EF 3.1 impact assessment method.

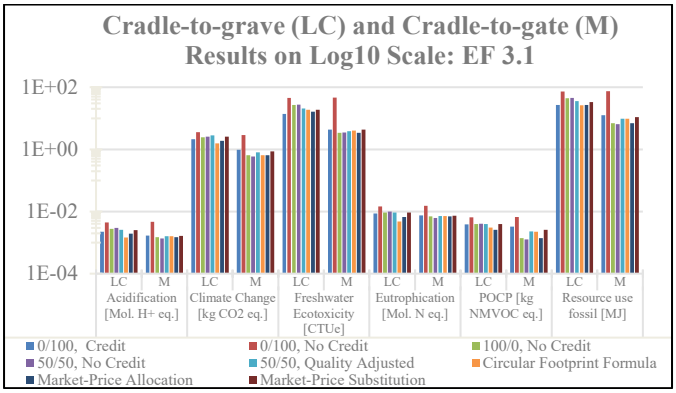

Figure 4 Comparison of the different allocation approaches

Selected LCIA results per kg of PCR-PP for the evaluated EoL allocation approaches are shown in Figure 4. Different EoL approaches are color-coded as seen in the legend. The Y-axis is in the scale of $\log_{10}$. The X-axis shows the six relevant impact categories and their respective units. The results for each impact category are subdivided into different system boundaries, cradle-to-gate (denoted by M) and the cradle-to-grave (denoted by LC). The cradle-to-gate results includes only

the allocated impacts of the virgin material and the recycling process before the investigated life cycle, while cradle-to-grave also includes the allocated impacts of the recycling and disposal at the end of the investigated life cycle. Both the 0/100 and the 100/0 approaches provide, as expected, drastically different results in most impact categories as seen in Figure 4. The climate change impact calculated using the 0/100 approach is 0.97 kg $CO_2$ eq./kg PCR-PP whereas that calculated using the 100/0 approach is comparatively lower at 0.64 kg $CO_2$ eq./kg PCR-PP. This can be explained by the fact that these approaches allocate the burdens of recycling to the previous ($L_1$) and the current ($L_2$) life cycle of the material respectively.

The current case study, especially taking into account the new proposal to the EoL of vehicles directive, reflects a sectoral change in the decision context. Hence, the consequential inventory modelling framework aligns better with the decision context of the LCA, which makes the CFF or the market-price based substitution approaches more suitable. The downside to using the market-price based substitution approach in this case is that the use phase of the product in consideration is rather long, extending up to 20 years [18], making it difficult to determine the price-based allocation factor ($A_2$) which is the ratio of the global market price of the material recycled at the EoL to that of the virgin material assumed to be substituted in a subsequent life cycle.

Thus, it is reasonable to employ market-constraint-based allocation factor, which can be determined with more certainty than price-based allocation factors, which is why, the CFF is deemed more suitable. To analyze the possible future situations and use-cases of PCR-PP, scenarios are developed through expert consultation and based on best-case and worst-case outcomes whilst reflecting the possible effects of the new draft of the EoL of vehicles directive. These scenarios are transferred into the context of the CFF and are outlined in Table 2.

Table 2 best-case and worst-case scenario for CFF implementation

| Name | Scenario | CFF Variables |
|---|---|---|
| Status Quo | Things progress as they are. Business as usual. | A=0.5; R1=0.4; R2=0.75; R3=0.2 |
| LS-HD | Low supply and high demand of recycled material | A=0.2; R1=0.4; R2=0.75; R3=0.2 |
| HS-LD | High supply and low demand of recycled material | A=0.8; R1=0.4; R2=0.75; R3=0.2 |
| LRR | Low recycling rates after the investigated lifecycle | A=0.2; R1=0.4; R2=0.5; R3=0.4 |
| HRR | High recycling rates after the investigated lifecycle | A=0.8; R1=0.4; R2=0.9; R3=0.1 |

The cradle-to-gate LCIA results for the relevant impact categories for the scenarios described Table 2 in are shown in Figure 5. Scenarios are color-coded as shown in the legend. The Y-axis shows the six relevant impact categories and the respective units and the X-axis is in the scale of $\log_{10}$. It can be deduced from Figure 5 that the results are sensitive to changes in allocation factor (A) as well as to changes in the recycling rates ($R_1$, $R_2$, and $R_3$). The results for the scenarios LS-HD and the HS-LD, i.e., the low supply and high demand of PCR materials and the low demand and high supply of PCR materials respectively, are counter-intuitive since the potential environmental impacts for most impact categories are lower for low supply coupled with high demand of the PCR materials and vice versa. This can be explained by the fact that the allocation factor A allocates the burdens of recycling and disposal to reflect the market constrains of demand and supply. Another interesting observation is that the potential environmental impacts for most impact categories are higher when the EoL recycling rates are lower, implying that the CFF provides an incentive for recycling at EoL since a higher rate of recycling reduces the environmental impacts allocated to the material in the investigated life cycle.

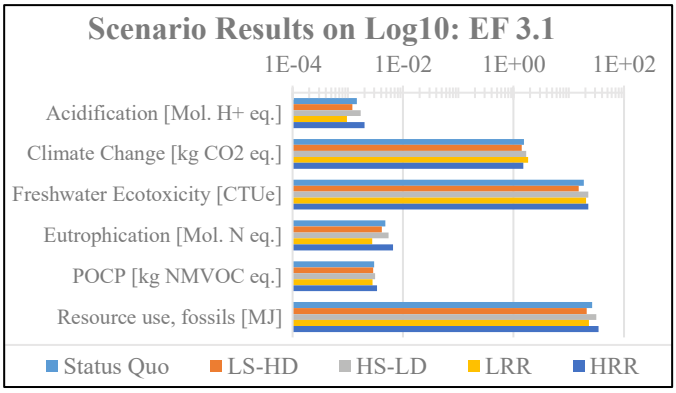


Figure 5 CFF EF 3.1 lifecycle LCIA results for Scenarios

## 4. Conclusions

The 0/100 and the 100/0 allocation approaches provide counter-incentives for recycling and disposal in the consecutive life cycles. Thus, if these approaches are used incoherently to assess the consecutive life cycles, it may lead to double counting or complete exclusion of the environmental impacts associated with recycling and disposal. The 50/50 approach tries to solve the counter-incentive issue by distributing the burdens of recycling and the production of virgin material between the consecutive life cycles equally. However, the 50/50 approach does not take into account the changes in the quality of the recycled materials. The quality-adjusted 50/50 approach takes into account the change in quality of the recycled materials but leads to double counting of certain impacts owing to its inherent mathematical asymmetry [9].

The CFF takes into consideration the quality losses as well as the substitution of virgin materials in the consecutive life cycles whilst solving the inherent mathematical asymmetry issue of the quality adjusted 50/50 approach. However, it comes with its own set of challenges. For instance, allocation factor A, which determines the allocations of the burdens between the different life cycles, also reflects the demand-supply situation in the market. The PEF guidance [5] recommends (A = 0.5) for PCR plastics, which indicates a demand-supply equilibrium in the market. The changes proposed by the new draft of the EoL of vehicles directive will likely alter the market demand-supply relationship for PCR plastics, thus A = 0.5 may no longer hold true. Even Factor B, which determines the allocation of energy burdens and credits, takes the default value B = 0 to prevent double counting. This is equivalent to assuming that the quantity of incinerated waste depends on quantity of waste generated [19]. Thus, recycling is only incentivized over incineration only when the energy mix which is replaced by energy recovery from disposal has lower environmental impacts than the production of virgin plastics.

The market-price based allocation, as opposed to the CFF, does not take into account the quality factors, but rather bases the allocation factor ($A_1$) on economic relationships of recycled materials. The market-price based substitution approach goes one step further by using two price-based allocation factors ($A_1$ & $A_2$) to represent better the two market constraints, viz., sourcing a recycled material as well as EoL recycling. Thus, in most cases, the market-price based substitution allocates the potential environmental impacts of recycling and disposal more accurately followed closely by the CFF. But both these EoL allocations approaches are not as easy to implement within inventory modelling as the 0/100, 100/0, and the 50/50 EoL allocation approaches.

## Next Steps

The next step is to evaluate the circularity of the concept by employing the Material Circularity Indicator (MCI) methodology developed by the Ellen McArthur Foundation in collaboration with Granta Design (now Ansys) [20] using the free excel-based assessment tool made available by thinkstep Pty Ltd (Australia). The MCI results combined with the LCA results will give a comprehensive overview of sustainability of the entire concept as opposed to the LCA results alone.

## Acknowledgements

The research is performed as part of the pcrExteriA project at the Fraunhofer WKI. The project is carried out jointly between Audi AG, OPmobility GmbH, KomRec-ReCond GmbH, Neue Materialien Bayreuth GmbH, and the Fraunhofer WKI. The project is funded by the BMWE – Bundesministerium für Wirtschaft und Energie – The German Federal Ministry for Economic Affairs and Energy and managed by the TÜV Rheinland project management agency (Funding code: 19S24002B). Moritz Micke-Camuz, Dr. Dirk Berthold, and Dr. Nina Ritter (Fraunhofer WKI) worked on developing the project and acquiring the funding. Carsten Asshoff (Fraunhofer WKI) works on the mechanical and technical aspects of PCR materials and Venkateshwaran Venkatachalam (Institute of Plastics and Circular Economy at the Leibniz University Hannover) helped proofread the paper. Angela Scherer and Fabian Groh (Audi AG) provided valuable insights on the paper. Vineet Shah developed the idea for, wrote, and edited the paper, in addition to performing the LCA.

Supported by:

on the basis of a decision
by the German Bundestag

## References

[1] Baldassarre, B., Maury, T., Tazi, N., Mathieux, F. et al., 2025. Increasing plastic circularity in the automotive sector: Supply chain analysis and policy options from the European Union (EU) 218, p. 108216.

[2] European Commission, 2023. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on circularity requirements for vehicle design and on management of end-of-life vehicles, amending Regulations (EU) 2018/858 and 2019/1020 and repealing Directives 2000/53/EC and 2005/64/EC: Document 02000L0053-20230330.

[3] ISO International Organization for Standardization. ISO 14044:2006/Amd 2:2020: Environmental management — Life cycle assessment — Requirements and guidelines, 2nd edn. 13.020.10 13.020.60, 2020(14044). https://www.iso.org/standard/76122.html.

[4] ISO International Organization for Standardization. ISO 14040:2006/Amd 2:2020: Environmental management — Life cycle assessment — Requirements and guidelines, 2nd edn. 13.020.10; 13.020.60, 2020(14040). https://www.iso.org/standard/76121.html.

[5] Franklin Associates, 2018. Life cycle impacts for postconsumer recycled resins: PET, HDPE, and PP: Submitted to the Association of Plastic Recyclers by Franklin Associates, a division of Eastern Research Group (ERG).

[6] World Resources Institute and World Business Council for Sustainable Development. GHG Protocol: Product Standard: The Product Life Cycle Accounting and Reporting Standard, 1st edn., 2001(GHG Protocol). https://ghgprotocol.org/product-standard.

[7] BSI. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services: PAS 2050, 1st edn. British Standards Institution 13.020.40, 2011(PAS 2050). ISBN 9780580713828

[8] ISO International Organization for Standardization. ISO 14067:2018: Environmental management — Life cycle assessment — Requirements and guidelines, 1st edn. 13.020.40, 2018(14067). https://www.iso.org/standard/71206.html.

[9] Ekvall, T., Björklund, A., Sandin, G., Jelse, K., Lagergren, J., Rydberg, T., 2020. Modeling recycling in life cycle assessment, 2018th edn., Gothenburg.

[10] Finnveden, G., Lindfors, L.-G., 1996. On the nordic guidelines for life cycle assessment 1, p. 45.

[11] Allacker, K., Mathieux, F., Pennington, D., Pant, R., 2017. The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative 22, p. 1441.

[12] Plinke, E., Schonert, M., Meckel, H., Detzel, A., Giegrich, J., Fehrenbach, H., Ostermayer, A., Schorb, A., Heinisch, J., Luxenhofer, K., Schmitz, S., 2000. Ökobilanz für Getränkeverpackungen II, 1st edn., Berlin.

[13] AFNOR - National standards and national normative documents. General principles for an environmental communication on mass market products, 2011(BP X30-323-0:2011).

[14] Hauschke, F., Zimmermann, T., Kauertz, B., Dittrich, M., Drescher, A., Busch, M., Schüler, Kurz, Caye, Nicolas, Leighty, A., Ritthoff, M., Wulf, L., Wilts, H., 2024. Ökobilanzielle Analyse von Optimierungspotentialen bei Getränkeverpackungen, Dessau-Roßlau.

[15] EU-PEF, 2021. COMMISSION RECOMMENDATION (EU) 2021/2279 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations: EU-PEF.

[16] Schrijvers, D.L., Loubet, P., Sonnemann, G., 2016. Developing a systematic framework for consistent allocation in LCA 21, p. 976.

[17] Schrijvers, D.L., Loubet, P., Weidema, B.P., 2021. To what extent is the Circular Footprint Formula of the Product Environmental Footprint Guide consequential? 320, p. 128800.

[18] Negri, M., Bieker, G., 2025. Life-cycle greenhouse gas emissions from passenger cars in the European Union: A 2025 update and key factors to consider, Washington.

[19] Ekvall, T., Gottfridsson, M., Nilsson, J., Nellström, M., Rydber, M., Rydberg, T., 2021. Factor B in the Circular Footprint Formula.

[20] Herrmann, S., Goddin, J., Marshall, K., Pariera, A., 2019. Material Circularity Indicator Methodology: An approach to measuring circularity.