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Measuring the Circularity and Impact Reduction Potential of Post-Industrial and Post-Consumer Recycled Plastics

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Abstract: Post-industrial recycling (PIR) and post-consumer recycling (PCR) are measures used to sustain resources by improving material circularity and sustainability. Currently, circularity is mainly measured as the degree of reutilization of a material from 0 to 100% at the product or company level. This measure fails to assess the resource usage over multiple product life cycles. Therefore, we propose to assess circularity as (i) the frequency of resource use in products (effective circularity, eC), and as (ii) a vehicle to reduce environmental impacts (environmentally efficient circularity, eeC). Additionally, to compare the environmental impacts of using recycled materials from PIR or PCR, we analyze their impact reduction potential (IRP), indicating the environmental benefits of recycling in relation to virgin material submitted to the market. We demonstrate the suggested indicators for a case study material: polypropylene. For this polymer type, the eC ranges between 0.93 and 9.08 uses of the resource, on average, depending on collection, sorting, and recycling rates. Likewise, the eeC ranges between 0.31 and 1.50 uses per kg of CO_2 equivalents emitted. PCR has a higher IRP regarding climate change impacts than PIR in all analyzed scenarios. The results reveal the relevance of PCR and PIR beyond the product life cycle. Finally, we discuss possible embeddings of the indicators in the assessment of climate policy and environmental protection measures, such as strengthening the use of PCR in contrast to PIR materials.

Keywords: life cycle assessment; circular economy; polypropylene; global warming impact; circularity assessment; environmental efficiency; post-industrial recycling; post-consumer recycling

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1. Introduction

As society and industry move toward strategies of sustainable development, the circular economy concept has been proposed to overcome the growing dependency on resource demand and depletion, while minimizing emission levels [1–3]. Economic growth should be decoupled from the consumption of finite resources and negative impacts on the environment by preserving raw materials, components, and products at their highest possible value and utility [4]. Implementing circular economy strategies and business models is seen as a key to accelerating this transition and supporting sustainable development, which is widely highlighted in political frameworks, such as the European Circular Economy Action Plan [5], and relevant scientific literature [6–8].

Plastics are materials of particular interest in current circular economy debates [9–12]. More than 57.2 million tons of plastics were produced in EU27+3 countries in 2021, while only 5.5 million tons were recycled to replace virgin material [13]. Forecasts of the global plastic production show a strong growth, anticipating a doubling of global plastic demand by 2050 [14]. Strategies fostering the circular economy concept are widely known as 'R-strategies' [15]. This study focuses on plastic recycling as one particular R-strategy, which can be implemented in products using two core principles: The use of recycled materials in products and a fully recyclable product after its use [16], with a circular product system requiring both principles.

1.1. Difference between Post-Industrial Recycling and Post-Consumer Recycling

An important distinction in the use of recycled materials in products is the difference between materials from post-industrial recycling (PIR) and post-consumer recycling (PCR). PIR material is made of post-industrial waste (PIW), sometimes referred to as pre-consumer waste. PIW refers to waste that is obtained during production and manufacturing and thus, before use. It typically consists of uncontaminated mono-materials, or at least of a well-known composition, resulting in minor losses in recycling and a high quality of the recyclate, as demonstrated in a case study comparing the quality of recycled non-food pouches from PIR and PCR [17]. PIR does not include the reuse of materials from reworking, regrinding, or scrap from a technical procedure that is reused in the same process [18]. In contrast, PCR uses post-consumer waste (PCW) that originates from products after use, i.e., in households or commercial and industrial facilities [18]. Plastic PCW is often collected as part of a mixed waste stream, together with other materials and contaminants. PCR usually includes higher impurities and losses during collection, separation, and recycling, thus resulting in a lower quality compared to PIR [19].

PIW is often not referred to as waste, but rather as a by-product of joint production, especially if it has a positive economic value [20]. The amount of PIW available on the market is limited by plastic manufacturing processes that are optimized regarding the efficient usage of their main (virgin) plastic material. Since PIR uses a by-product as the feedstock from production before use, it does not close the loop, but preserves material that cannot be reused in the same process. In contrast, PCR and the use of PCR granulate in products closes the loop at a products' end of life (EoL), thus allowing materials to be recycled multiple times. Therefore, a decoupling of virgin resource extraction from economic growth and environmental damage might only be realized by a combination of PIR and PCR. The potential of PIR to contribute to the CE, however, is low compared to that of PCR.

1.2. Measuring Circularity

Circularity can be measured by indicators, but these indicators have not yet been used in the scientific literature to compare the contribution of PIR and PCR to circularity. Recent publications present comprehensive overviews of existing indicators to measure circularity [1,6,21–37]. However, these reviews lack indicators to compare the circularity of PIR and PCR. The missing capability to analyze the circularity of PIR and PCR might be due to the prevailing understanding of material circularity as a degree or percentage of closing the loop ranging from 0 to 100%. A case study measuring the circularity in terms of mass and quality conservation as a percentage of recycled plastic made of PIR and PCR mentioned the different waste origins as a main limitation for the comparability of results [17]. Most indicators fail to point out the dependence and fixed ratio between virgin and PIR production and do not quantify this relation to the frequency of times PCR materials can be recycled. In existing studies, the perspective is often set to a single product life cycle, neglecting to consider multiple recycling loops and the intrinsic differences between PIR and PCR. For example, the widely applied material circularity indicator (MCI) does not distinguish between recycled materials from PIW and PCW and only accounts for PCR [38]. Most studies addressing circularity from recycling focus either on PIR only [39] or PCR only [40]. Neither is sufficient to assess the specific relevance of PIR and PCR materials in a circular economy, as addressed above.

A radically different perspective on material circularity can be employed based on the path length of a resource, which was first proposed by Bailey et al. [41]. This idea has been transferred to a metric defining circularity as the average number of product life cycles in which a material is involved before it leaves the system as waste [42]. According to Figge et al. [42], a circularity of 1 describes a linear system; a circularity of infinity represents a fully circular product system. The indicator captures resource circularity from its first use—defined as initial use of the material—to its last use, when the initial amount of material is lost due to dissipative losses. Lost material is described as anything that cannot be preserved in the value chain as recycled material [42], such as material that is not collected for recycling, or remelting losses in the recycling process. This definition does not limit material circularity to a single product life cycle, but rather calculates the circularity of the material over several product applications. The indicator has been demonstrated on the closed-loop remanufacturing of medical products [17] and used for the assessment of the copper value chain as an open-loop system [43]. However, it has not been applied to compare PIR and PCR.

Circularity and sustainability are closely linked but can also contradict each other [7]. Pauliuk [44] mentioned the need for circularity indicators in combination with life cycle sustainability indicators. When assessing circularity, the focus can be on (i) increasing the frequency of resource use, or (ii) using circularity as a vehicle to reduce virgin resource use and environmental impacts. The former might ignore the fact that recycling activities also require resources and cause emissions. The latter assesses the material circularity in relation to environmental impacts caused. Ever since the assessment of processes began, effectiveness and efficiency have been widely regarded as two important but separate metrics, which are sometimes confused. The present paper follows the well-known definition: "Efficiency is concerned with doing things right. Effectiveness is doing the right things" [45]. Effectiveness is usually driven by a specific goal to be achieved, regardless of the effort it takes and the impacts it causes. Regarding circularity as the goal, a recycling activity is effective if the circularity is increased, without considering resources required and emissions generated.

We suggest measuring the frequency that resources are used in the product systems (i) by the effective circularity (eC) and the result of using circularity as a vehicle to reduce environmental impacts and (ii) by the environmentally efficient circularity (eeC). The eeC is in line with the well-established concept of "eco-efficiency", which aims to use fewer resources while generating the same, or a greater, amount of economic activity [46]. Eco-efficiency is measured in sustainability analysis and development [47,48]. Analogously, the eeC can be used to compare circularity measures for minimizing virgin resource extraction, while generating fewer environmental impacts. Thus, eeC sets the obtained eC in relation to the environmental impacts. Moreover, to compare the environmental impacts of using recycled materials from PIR or PCR, the impact reduction potential (IPR) is proposed to analyze the environmental benefits of recycling in relation to the virgin material submitted to the market. In contrast to existing metrics, the IPR considers the availability of PIR and PCR material per kg of initial virgin resource input. It addresses the proportionality and fixed quantities of virgin, PIR, and PCR granulate to be used in products.

This study assesses circularity in terms of effectiveness and environmental efficiency, comparing recycled resources from PIW and PCW. Additionally, we identify the IRP of PIR and PCR material compared to that of virgin plastic use. In the process, we measure the path length of an initial resource input, including all product life cycles in which it is used. A case study is conducted on polypropylene (PP), focusing on the PP packaging loop. The eC, the eeC, and the IPR are demonstrated in different scenarios.

2. Materials and Methods

Section 2.1 introduces the concept and calculation of the eC to assess the frequency a resource is used, on average, in a product system. Afterwards, in Section 2.2, the combination of the eC and the environmental impact assessment is explained to obtain the eeC and the IRP. In Section 2.3, the application of the proposed indicators to a case study of PP is outlined to answer the research question regarding how the circularity of plastic can be measured for PIR and PCR, also considering environmental impacts.

2.1. Effective Circularity

For the purpose of this study, the indicator proposed by Figge et al. [42] is modified to consider the different contributions of a resource being used in a product system as virgin, PIR, and PCR material. The original indicator sums up three different contributions to circularity: *initial use*, *refurbishment*, and *recycling* [42]. For the initial use, Figge et al. propose setting the contribution of virgin resource use to 1, which means that the virgin material is always used once [42]. Setting the initial use of a resource to 1 neglects loss during production, i.e., material that is processed but never enters the use phase, including PIW that is not collected for recycling. However, these lost resources should be considered when measuring the eC. We propose to divide the *initial use* into contributions of both virgin production and PIR. Both virgin and PIR material are used in products for the first time, thus representing the initial use of the material. Their contributions should be calculated separately (eC_{vir} and eC_{PIR}). Ideally, the sum of eC_{vir} and eC_{PIR} can have a maximum value of 1, if the PIW is fully collected, recycled and processed into products (without dissipative loss before use). For this study, contributions from *refurbishment* are neglected, as the focus is on recycling. Here, the contribution of *recycling* is defined as material used in products made of PCR granulate. The eC is determined by eC_{total}, according to Equation (1), by adding the three contributions from virgin (eC_{vir}), PIR (eC_{PIR}), and PCR material (eC_{PCR}) along the value chain.

$$eC_{total} = eC_{vir} + eC_{PIR} + eC_{PCR} \tag{1}$$

All three contributions to eC_{total} reflect the nubmer of average uses of the material per virgin resource input. The higher the eC, the more effectively the resource is used. Ideally, eC_{total} would be infinite. In practice, dissipative losses of uncollected material, material that is sorted out, or rejects from recycling occur, which is why eC_{total} aims for a quantifiable value. This indicator provides the relationship between the use of the material in virgin, PIR, and PCR product systems, starting from an initial and fixed input quantity of virgin resource input (m_{vir}) until the material is lost. The eC of virgin products (eC_{vir}) equals the virgin production rate (PR_{vir}) multiplied by m_{vir} (see Equation (2)).

$$eC_{vir} = m_{vir} PR_{vir} \; with \; PR_{vir} = 1 - p_{PIW} \tag{2}$$

In line with the work of Figge et al. [24], we suggest setting m_{vir} to 1 kg to obtain the frequency with which a resource is used, on average, per kg. This way, the results can be interpreted based on 1 kg of virgin material put on the market. If the parameter is set to another specific input value, eC_{total} is calculated for this specific value, which must be communicated in the interpretation. The input of virgin material is multiplied by the percentage of the material that is processed into a final virgin product (PR_{vir}) in order to consider losses in virgin production. Since the focus is on the circularity of the material, this metric does not consider a specific target product and production rate. Nevertheless, the losses along the value chain must be captured holistically. Accordingly, an average production rate from the pre-processing and virgin product manufacturing of a material should be considered, since only the material used in products on the market contributes to eC. The value for PR_{vir} can be determined based on average market data that represents a specific value chain for a resource and a market under study, such as the overall plastic pre-processing and production in a specific country. In Section 2.3, this is further explained using a case study on PP used for lightweight packaging (LP) in Germany.

All losses during pre-processing and virgin product manufacturing serve as a potential feedstock for PIR and equal the share of PIW based on m_{vir} (p_{PIW}). The eC of PIR (eC_{PIR}) is calculated according to Equation (3).

$$eC_{PIR} = m_{vir} p_{PIW} CR_{PIW} RR_{PIW} PR_{PIR} \tag{3}$$

To obtain eC_{PIR}, m_{vir} and p_{PIW} are multiplied with the collection rate of PIW (CR_{PIW}), the recycling rate of PIW (RR_{PIW}), and the production rate of PIR granulate into products (PR_{PIR}). CR_{PIW} is defined as the share of the PIW collected for recycling compared to the total amount of PIW accumulated during virgin production. For PIW, sorting often plays a minor role, since most PIW is collected as mono-material waste at industrial production locations. Therefore, losses in the sorting of PIW are neglected in Equation (3). RR_{PIW} is defined as the material share preserved in the recycling process (outgoing recycled material per ingoing material). Analogously to virgin production, PR_{PIR} is defined as the losses in the processing and production of the recycled material into a final product.

To determine the eC of PCR material (eC_{PCR}), it is necessary to calculate the maximum amount of material accumulated as PCW after the first use ($p_{PCW,1}$), according to Equation (4).

$$p_{PCW,1} = eC_{vir} + eC_{PIR} \tag{4}$$

The subscripted index of 1 reflects the first time PCW is collected after use. $p_{PCW,1}$ is used to calculate the contribution of PCR to eC_{total} by considering that some of the material will be recycled several times, which is depicted in Equation (5).

$$eC_{PCR} = \sum_{i=1}^{n} \left[p_{PCW,1} \left(\prod_{j=1}^{i} CR_{PCW,i} SR_{PCW,i} RR_{PCW,i} PR_{PCR,i} \right) \right] \tag{5}$$

The variable n shows the total number of PCR loops until the initial input of virgin material is lost. The more frequently the material is recycled as PCR granulate on average, the more often it can be used to replace virgin material. For each loop i, the amount of material that passes through each loop preceding and including loop *i* must be considered. The accumulating PCW after first use ($p_{PCW,1}$) is multiplied and summed up with the series of all further loops. This is obtained by multiplying the percentages of the PCW that is collected (CR_{PCW}), sorted (SR_{PCW}), recycled into granulate (RR_{PCW}), and processed into a final product made of PCR (PR_{PCR}) for all loops i. The index j is used to add up the amount of material that has reached each loop i. The PCW collection rate (CR_{PCW}) reflects the waste share that is disposed of correctly into the waste stream and collected for sorting and recycling based on the virgin and PIR material submitted into the market. The PCW sorting rate (SR_{PCW}) corresponds to the waste share that is sorted correctly and separated into the desired fraction, such as by polymer type. For PCW plastics, this point is often measured as the output of a sorting plant [20]. Losses from additional pretreatment steps at the recycler can be attributed to either sorting or recycling. In any case, it is important to capture losses holistically and identify the reference points. After recycling, the material is again processed into products for another use. Losses during production refer to material that is processed and cannot be reused internally. This material should be referred to as PIW, as it occurs before use. However, this material has been used and recycled from PCW. It can contain impurities and, therefore, contributes to eC_{PCR}. The recycling of this waste share is theoretically possible, but can often be neglected in calculations, as most recycled plastics from PCW are used in products that can internally reuse generated waste. In most cases, PR_{PCR} shall be set to 1 and therefore, be excluded from Equation (5). For the calculation of eC_{PCR} in Equation (5), the variables are illustrated in Figure 1.

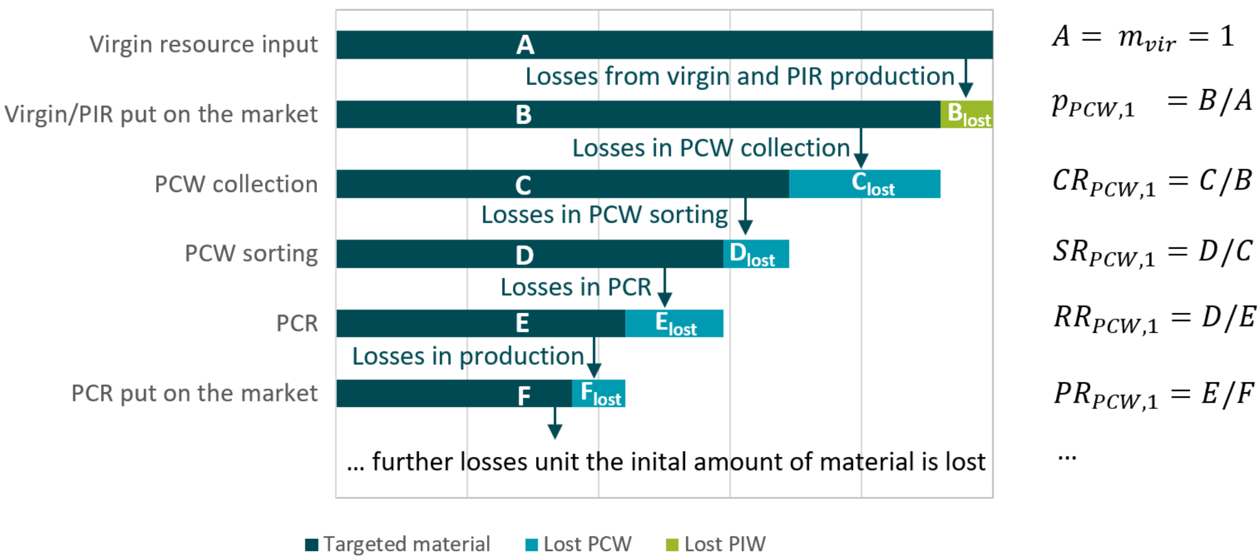

Figure 1. Simplified collection, sorting, and recycling scheme of targeted PCW material to be recycled (authors' own chart, with PCW: post-consumer recycling, and PIW: post-industrial waste).

In Figure 1, m_{vir} is split into a share of virgin and PIR material put on the market (B) and the losses of PIW that are not collected for recycling or that occur during the PIR process (B_{lost}). This material share does not enter the market and therefore, cannot be collected as PCW. During PCW collection, a certain share of the virgin and PIR material used in products on the market is disposed of correctly into the waste stream and collected for sorting and recycling (C). The remaining share of virgin and PIR material used in products on the market is lost (C_{lost}). Likewise, during PCW sorting and recycling, a certain waste share is sorted correctly (D), recycled to granulate (E), and processed into products from PCR granulate (F). The remainder of these are lost (D_{lost}, E_{lost}, and F_{lost}). The share of PCW that is preserved in each subsequent loop i is calculated and added up until the entire amount of m_{vir} is lost. Regarding Figure 1, this corresponds to the point where the targeted material reaches zero.

Whereas PIW is always recycled in an open-loop recycling system, which is described by recycled material cascading into another product system, PCW can be recycled via an open- or closed-loop recycling system. The original indicator proposed by Figge et al. [42] only extends to activities which companies can control. In the context of recycling activities, this can often only be realized in closed-loop systems which aim to return products to the original manufacturer that are used again to produce new products of the same type [4]. Since most PCW plastics are collected, sorted, and recycled as lightweight packaging (LP) waste from household and commercial use, we extend the terminology for open- and closed-loop recycling and briefly define it in the context of this study. Open-loop recycling is described as follows: products, components, or materials are reused or recycled (which can be cascaded) generally among unspecified organizations, into alternative products, components or materials [49]. PCW can be recycled via a product-specific return system in regards to the original manufacturer to be used again in new products of the same type (closed-loop) or recycled into alternative products, which is in line with the definition of open-loop recycling given above.

Closed-loop recycling of PCW can often only be realized for products that remain in the company's ownership or are returned to the company after use, requiring broad infrastructure. For instance, PP recycling of fruit and vegetable crates or PET bottle-to-bottle recycling are well established closed-loop systems [50–52]. However, a product-specific take-back system might not be purposeful regarding the variety of plastic products in household and commercial waste. If companies each manage their own collection and recycling activities, this could indeed be much more resource-intensive compared to an open-loop system for household and commercial waste. This is supported by the British standard, which states that "a closed-loop system cannot generally be advocated over an open-loop system" [49]. Therefore, the definition of closed- and open-loop recycling is extended to include the following:

- Level 1: Closed-loop recycling of a product into an identical production application.
- Level 2: Quasi-closed-loop recycling, with restricted but defined reuse in products that are managed by the same recycling system.
- Level 3: Open-loop recycling, with reuse in alternative products that might be further managed by another recycling system (also referred to as a recycling cascade).

The conventional understanding of closed-loop recycling (level 1) is complemented in this study by quasi-closed-loop recycling (level 2). The re-granulate of quasi-closed-loop recycling can fully replace corresponding virgin material in some applications, such as plant pots, non-food pouches, or pipes, without compromising the quality and longevity of the products compared to those of the virgin material. However, in contrast to virgin material, its use is limited in terms of color or food contact. For open-loop recycling (level 3), the collection, sorting, and recycling rates in Equation (5) must be set separately for each loop, as the rates can vary for different open-loop recycling systems. In line with the assumptions of Figge et al. [42], some simplifications can be made for the variables used in Equation (5) with an index higher than 1, if a closed or quasi-closed-loop system can be assumed: all variables in Equation (5) for each loop i are assumed to equal those of the first loop, and thus follow Equations (6a)–(6d).

$$CR_{PCW,1} = CR_{PCW,i,}\ whatever\ i(i = 1, \ldots n) \tag{6a}$$

$$SR_{PCW,1} = SR_{PCW,i}\ whatever\ i(i = 1, \ldots n) \tag{6b}$$

$$RR_{PCW,1} = RR_{PCW,i}\ whatever\ i(i = 1, \ldots n) \tag{6c}$$

$$PR_{PCR,1} = PR_{PCR,i}\ whatever\ i(i = 1, \ldots n) \tag{6d}$$

Thus, eC_{total} reflects the frequency with which a resource is used, on average, in a product system, but focuses on the contributions of virgin, PIR, and PCR materials. Applying the assumptions discussed, (i) setting m_{vir} to 1, (ii) excluding production losses for products made of PIR and PCR materials (PR_{PIR} = PR_{PCR} = 1), as well as assuming a closed- or quasi-closed-loop recycling (simplification according to Equations (6a)–(6d)), a simpler formula is presented in Equation (7) to determine eC_{total}.

$$\begin{cases} eC_{total} = eC_{vir} + eC_{PIR} + eC_{PCR} \\ \quad eC_{vir} = 1 - p_{PIW} \\ \quad eC_{PIR} = p_{PIW} CR_{PIW} RR_{PIW} \\ \quad eC_{PCR} = p_{PCW,1} (CR_{PCW} SR_{PCW} RR_{PCW}) \left[\frac{1-(CR_{PCW} SR_{PCW} RR_{PCW})^n}{1-(CR_{PCW} SR_{PCW} RR_{PCW})} \right] \end{cases} \tag{7}$$

If a value chain is linear (i.e., without considering PCW recycling), eC_{total} can be lower than 1, if the virgin and PIR material is not completely processed into products, and a share of it never enters the market. With PCR, circularity increases depending on the loss of resources being wasted. As a result, an ever-decreasing fraction of the resources re-enters each cycle until the material is lost completely. We note that this metric does not consider quality or lifetime restrictions. Both must be taken into account regarding a specific product or product group after manufacturing.

2.2. Combining Effective Circularity and Environmental Impact Assessment

In Section 2.2.1, the eC is set in relation to the environmental impacts caused over the value chain to assess the environmental efficiency resulting from circularity as eeC. In Section 2.2.2, the IRP (introduced above as impact reduction potential) of PIR and PCR is determined.

2.2.1. Environmentally Efficient Circularity

Factors enhancing the eC, such as increasing the recycling rate, might have a negative environmental impact because collection, sorting, and recycling require resources and produce emissions. To consider this, we developed the indicator called environmentally efficient circularity (eeC), indicating the relationship between the eC and environmental impacts. To obtain eeC_{total}, eC_{total} is measured as a function of the environmental consequences from providing, recycling, and treating the virgin resource input (m_{vir}) from its first to its last use, according to Equation (8):

$$eeC_{total} = \frac{eC_{total}}{E_{Total}} \tag{8}$$

E_{total} reflects the environmental impacts of a material over the entire path until m_{vir} is lost. Environmental impact assessment, which is also referred to as life cycle assessment (LCA), is a widely accepted method to assess environmental impacts over a product's life cycle from raw material extraction to the EoL. A product LCA is defined by DIN ISO standards 14040/44 and typically focuses on a single product life cycle [53,54]. Therefore, its ability to provide information for decision making is often limited to the life cycle phases of the product. However, environmental impacts can also be determined beyond a product life cycle. In the LCA context, this is often referred to as system expansion. We use this term to state that the environmental impacts of a material over the entire value chain are captured. In particular, an investigated product system from virgin material is expanded from one product life cycle to cover additional product systems. The aim is to capture the environmental impacts associated with m_{vir} over all product life cycles in which it is used, including its virgin provision, PIR, and PCR, as well as its final treatment as waste. Calculating eeC_{total}, each impact category of the LCA methods can be selected for E_{total}, as further elaborated in the case study included in Section 2.3.2. The calculation of E_{total} for a respective impact category is described by Equation (9) and illustrated in Figure 2.

$$E_{total} = E_{vir} * eC_{vir} + E_{PIR} * eC_{PIR} + E_{PCR} * eC_{PCR} + +E_{EoL} - E_{credits} \tag{9}$$

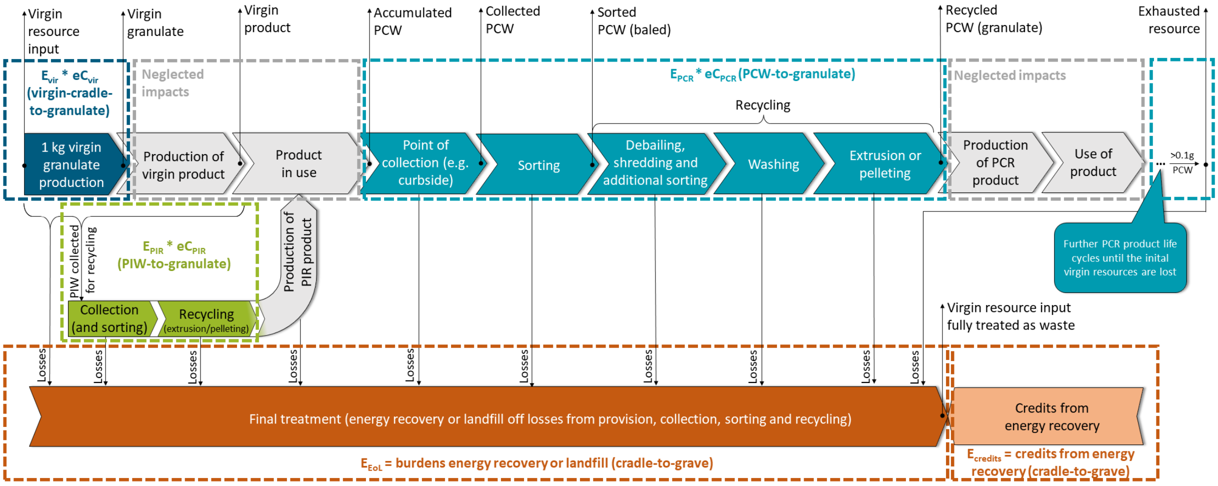

Figure 2. Entire path of 1 kg of virgin resource input used in multiple product systems until the material is lost, including the environmental impacts associated with the material (PCW: post-consumer recycling, PIW: post-industrial waste, PCR: post-industrial recycling, and PIR: post-industrial recycling).

E_{vir} reflects all impacts of providing virgin plastic granulate to be further manufactured into a product from cradle-to-granulate per kg of virgin granulate. In Equation (9), E_{vir} is multiplied with the eC of the virgin material (eC_{vir}). E_{PIR} corresponds to the impacts of PIW-to-granulate per kg of PIR granulate, which is then multiplied by eC_{PIR}. Analogously, E_{PCR} describes the impacts of the PCR granulate from PCW-to-granulate and is multiplied by eC_{PCR}. The environmental impacts of the manufacturing step, from granulate into an end-product, e.g., injection molding or thermoforming, as well as the environmental impacts of the use phase, are not considered in our study (see Figure 2). Such impacts are related to a specific product instead of the material and are therefore neglected in regards to the aim stated above. The material entering the market can be partially collected, sorted, and recycled into PIR and PCR granulate. The collected PCW can be recycled again and again until the material is lost. By multiplying E_{PCR} by eC_{PCR} and adding them in Equation (9), the environmental impacts of recycling PCW and providing re-granulate over multiple loops are added up, as eC_{PCR} indicates the frequency of the average applications of m_{vir} recycled as PCW.

Note that for E_{PIR} and E_{PCR}, the burdens associated with collection, sorting, and recycling are exclusively accounted for. The burdens of the treatment of residues are attributed to the last treatment activity to avoid double counting. The material lost along the value chain that is not collected for recycling or accumulates as residue is treated as waste via thermal treatment or landfill. This does not contribute to eC_{total}, but causes environmental impacts that are associated with the material and therefore, must be added to E_{total}.

Consequently, E_{EoL} reflects the burdens arising from thermal treatment (e.g., municipal incineration) and from the landfill of lost waste. Regardless of the frequency with which the resource is recycled after use, the amount of virgin resource input (m_{vir}) must finally be treated as waste via energy recovery or landfill. If m_{vir} is set to 1 kg as the suggested input value (see Section 2.1), 1 kg is fully treated as waste after a certain number of times that the resource has been recycled. In this study, in Equation (9), the last variable $E_{credits}$ accounts for environmental benefits that are only considered for thermal treatment processes.

If waste is incinerated, the waste heat is usually transformed into heat and electricity to be used in other product systems that might exist outside the value chain under investigation. For eeC, we need to consider how to account for the environmental impacts of energy recovery processes that provide a benefit for other product systems in which the recovered energy could be used, but which may be outside the investigated material's path. There is a long running debate in LCA regarding how to assign the impacts of EoL processes if they provide valuable resources to be used in other product systems, as is the case for recycling and energy recovery [15,55,56]. Any benefits of recycling and energy recovery are always shared between two product systems—one producing the waste, and another using the recycled material or recovered energy [15,55]. DIN ISO 14044 defines a hierarchical procedure for handling such multi-functional processes [54]. The preferred options are subdivision, by means of dividing the multi-functional process into sub-processes, or system expansion. A subdivision is not possible for recycling and energy recovery processes, as the waste is treated, and resources (materials or energy) are provided simultaneously. As explained above, recycling is modeled by system expansion in this study, as every subsequent product system in which the material is used, is added into the system boundaries until the material is completely lost. Nonetheless, system expansion is not applied to energy recovery processes. The eeC aims to investigate the environmental impacts associated with the material. Recovered heat and electricity are used in other product systems that are out of the scope of this study. Therefore, substitution is applied, awarding credits for recovered energy to account for the benefit of recovered energy. This is often referred to as avoided burdens [57]. The secondary use of recovered energy in other product systems is substituted. Here, the environmental impacts of heat and electricity mixtures provided to the market under study can be avoided and should be included in Equation (9) ($E_{credits}$).

2.2.2. Impact Reduction Potential of Using Recycled Granulate

To compare the potential of PIR and PCR for the CE, we have developed the indicator impact reduction potential (IRP), which depends on the eC and the environmental impact assessment. In contrast to eeC, the IPR focuses on decreasing environmental impacts and is analyzed for the use of recycled materials (here PIR and PCR granulate) to replace virgin granulate. The IRP of recycled granulates is often calculated for the use of 1 kg of PIR or PCR granulate to replace 1 kg of virgin granulate, as applied in LCA studies on plastics [58,59]. However, this neglects the fact that PIR and PCR granulate are not available in unlimited quantities. The amount of available PIR granulate dependents directly on the amount of virgin granulate processed; more precisely, its share that cannot be used internally. PCR granulate cannot be used infinitely and independently from virgin granulate provision due to dissipative losses along the value chain that must be compensated for by bringing new material into the loop.

To quantify the IRP of PIR and PCR in this study, eC_{total} is linked to the environmental benefits of 1 kg re-granulate replacing 1 kg virgin granulate, based on a fixed virgin resource input (m_{vir}) to create a value chain perspective. This maps the proportionality and resource availability of virgin, PIR, and PCR granulate to be used in products. The law of leverage is used to explain this in a simplified manner. The law states that the longer the lever, the greater the force, which is said to provide leverage. The environmental benefits of replacing 1 kg of virgin granulate with 1 kg of PIR and PCR granulate, respectively, are set as weights, and the eCs of PIR and PCR describe the levers of a seesaw (see Figure 3).

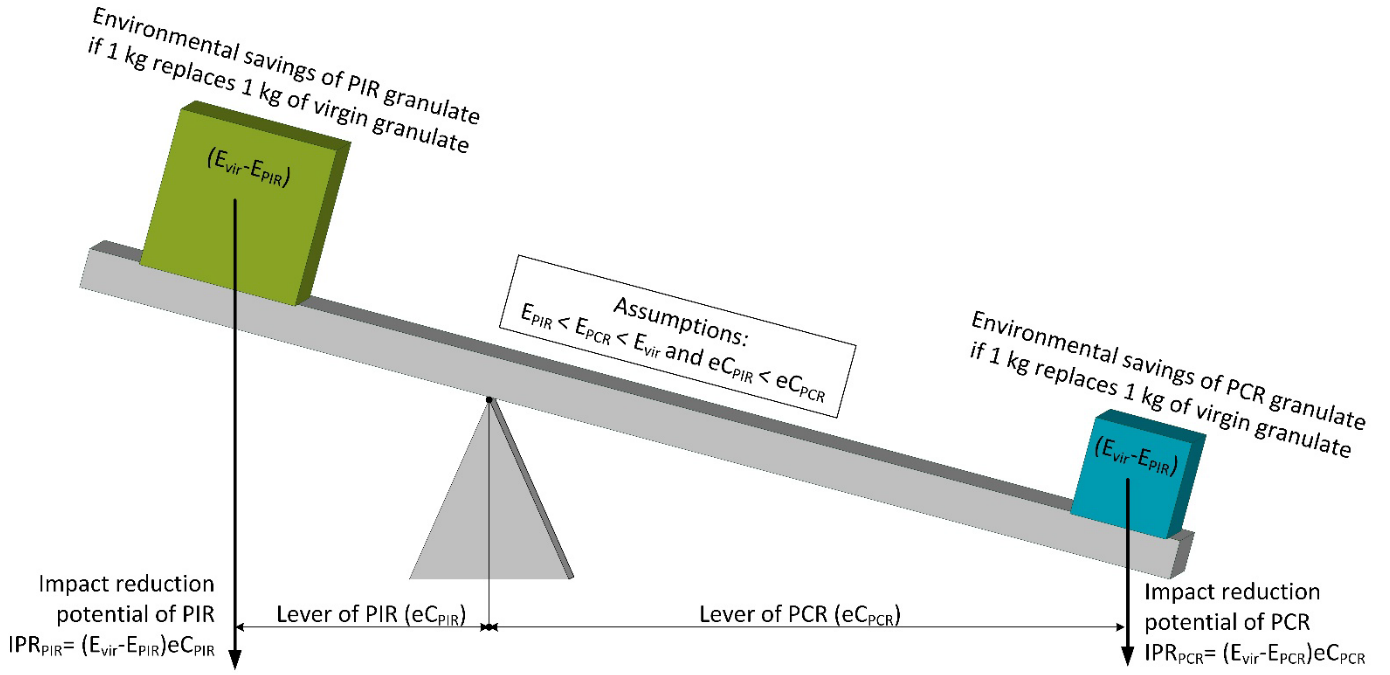

Figure 3. Schematic example of the impact reduction potential (IRP) of post-industrial recycling (PIR) and post-consumer recycling (PCR). Here, PIR granulate causes fewer environmental impacts than does PCR granulate ($E_{PIR} < E_{PCR}$), and both have fewer impacts than does virgin granulate provision (E_{vir}).

The environmental benefits of using 1 kg PIR and PCR granulate to replace 1 kg of virgin granulate are calculated as the difference between the re-granulate and virgin granulate (see the size of the weights on both sides of the seesaw in Figure 3). It is expected that E_{PIR} is lower compared to E_{PCR} because the collected PIW often consists of minor impurities, resulting in high recycling rates, and both have a lower impact than does virgin granulate provision per kg ($E_{PIR} < E_{PCR} < E_{vir}$). Thus, the weight of the seesaw on the left side ($E_{vir} - E_{PIR}$) is depicted to be heavier than the weight on the right side ($E_{vir} - E_{PCR}$). The bigger the difference between the impact of producing 1 kg of virgin granulate and 1 kg of PIR or PCR granulate, the heavier the weights on the seesaw. As can be seen in Figure 3, eC_{PIR} and eC_{PCR} are considered to be the levers indicating the amount of PIR and PCR granulate available per kg of virgin resource input (m_{vir}). The weights can each be multiplied by the respective eC of PIR and PCR (eC_{PIR} and eC_{PCR}) to determine the force providing the leverage, defined as IPR_{PIR} and IPR_{PCR}, based on the principle that the force equals the weight times the lever, as described by Equation (10).

$$IRP_{PIR} = (E_{vir} - E_{PIR})eC_{PIR} \quad \text{and} \quad IRP_{PCR} = (E_{vir} - E_{PIR})eC_{PCR} \tag{10}$$

2.3. Transfer to the Case Study Example of Polypropylene Used for Packaging

The proposed indicators eC, eeC, and IRP are demonstrated using the value chain of PP, which currently exhibits the highest market share (approximately 20% of all polymers processed in Germany and worldwide) [13,60]. Since the largest area of application for PP is packaging [13], the study explicitly considers the packaging loop of virgin, PIR, or PCR materials. The geographic scope of the study focuses on German market conditions, as the data were mostly obtained for PP processed, collected, sorted, and recycled in Germany. Here, most packaging materials are collected as LP (introduced as lightweight packaging above) and recycled via the dual system in the so-called yellow bin or yellow bag in Germany [61]. Like many other countries, Germany imports and exports waste and recycled materials. For the sake of simplicity, imported and exported waste and recycled materials are excluded from the system boundaries, which means that plastic packaging consumption equals the amount of accumulating plastic packaging waste. Therefore, the analyzed PP LP value chain can be understood as a theoretical path of virgin PP, whose waste is (partly) processed into subsequent packaging materials made of PIR and PCR.

We note that the recycled material made of PIR and PCR might not be used for all packaging applications, especially due to regulations for food contact materials. However, since the recycled material from PCW can be used to manufacture products of restricted, but defined, applicability and quality that can be recycled again via LP recycling, the value chain can be considered a quasi-closed-loop recycling (level 2) method. This means that the case study results cannot be interpreted in the context of all PP packaging, but only PP packaging for non-food applications that can be made (partly) of recycled PCW. Although no particular product application is considered here, we assess an existing value chain. There are products made of recycled PP (both from PIR and PCR), which can be collected, properly sorted, and recycled via an LP recycling system to be used again in goods, regardless of the form and function of the product. Secondary data from the literature, as well as primary data from a plastic processor (Pöppelmann GmbH & Co. KG Kunst-stoffwerk-Werkzeugbau, Lohne, Germany) who produces PP plant pots from both PIR and PCR materials are used. PP plant pots can be considered as a reference product in this study because they are currently available on the market and are made of 100% PIR and PCR plastic.

To determine the eC, the eeC, and the IRP, a scenario analysis is conducted. Two linear scenarios are investigated in which PP LP waste is not recycled at the EoL, but incinerated. In the first linear scenario, *virgin only*, only virgin material is processed, without the recycling of PIW and PCW. In the *vir + PIR* scenario, in addition to virgin material, PIW is partially collected and recycled. The linear scenarios do not reflect the prevailing situation of LP recycling of PP in Germany, but are used for comparison. Both scenarios reflect virgin PP and PIR material processed into non-recyclable products that are not collected or cannot be sorted for PCR and are thus fully lost after their first use. Additionally, four circular scenarios are analyzed including PCR. As the collection and recycling rates of PCW plastics have increased in recent years, and are expected to further increase due to recycling targets of the EU [10], four circular scenarios are investigated with varying collection, sorting, and recycling rates of PCW. Such scenarios are based on conservative, realistic, optimistic, and ideal assumptions and are therefore called *conservative*, *realistic*, *optimistic*, and *ideal* scenarios that are further explained below.

2.3.1. Effective Circularity

The scenario *virgin only* is only determined by eC_{vir}. According to suggestions of researchers, the virgin resource input (m_{vir}) is set to 1 kg. The *virgin + PIR* scenario is determined by the sum of eC_{vir} and eC_{PIR}. The value of p_{PIW} is used as a starting point to calculate eC_{PIR}. All parameters needed to calculate eC_{vir} and eC_{PIR} are assumed to remain unchanged in the future because the processing of virgin and PIR materials is already considered to be optimized for the efficient usage of the virgin material, and therefore, it is assumed to be constant in all analyzed scenarios. For the circular scenarios (*conservative*, *realistic*, *optimistic*, and *ideal)*, eC_{total} is calculated as a sum of all three contributions (eC_{vir}, eC_{PIR}, and eC_{PCR}), assuming different collection, sorting, and recycling rates. Since a quasi-closed-loop recycling of PP is investigated for PCW in this study (level 2), the mentioned simplifications for calculating eC_{total} are employed, following Equation (7) in Section 2.1. According to the manufacturer, production rates of both PIR and PCR (PR_{PIR} and PR_{PCR}) can be assumed to be 100%, since any significant waste produced is reused internally in the production process for our case study product.

Table 1 summarizes the values used to calculate eC_{vir}, eC_{PIR}, and eC_{PCR} in each scenario. The sources and calculation of the assumed values are explained in detail in Appendix A. For some values, the specific data for PP and/or (PP) packaging was unavailable. Therefore, the literature data for plastics in general are used. In Table 1, the values for PR_{PIR}, PR_{PCR}, and m_{vir} are not shown because they do not influence the eC. The values for p_{PIW}, CR_{PIW}, RR_{PIW}, and p_{PCW} are explained above and do not change across the scenarios. Since the collection and sorting of LP is mostly reported as an aggregated value, CR_{PCW} and SR_{PCW} are summarized as an aggregated value and further referred to as CSR_{PCW}.

Table 1. Investigated scenarios and corresponding values to calculate the eC.

Scenario		p_{PIW}	CR_{PIW}	RR_{PIW}	$p_{PCW,1}$	CSR_{PCW}	RR_{PCW}
Linear scenarios	*Virgin only*	7.6% [b] [60]	0%	0%	92.4% [b] [60]	0%	0%
	Virgin + PIR	7.6% [b] [60]	89.1% [b] [60]	96% [a]	99% [b]	0%	0%
Circular scenarios	*Conservative*					38.9% [b] [60]	65% [c]
	Realistic					55.5% [b] [49]	75% [c]
	Optimistic					75% [c]	85% [c]
	Ideal					99% [c]	90% [c]

[a]: primary data based on PP provided by Pöppelmann GmbH & Co. KG Kunststoffwerk-Werkzeugbau, Germany, Lohne. [b]: literature values based on plastics. [c]: estimation based on different literature values (explained in Appendix A).

2.3.2. Environmentally Efficient Circularity and Impact Reduction Potential

The aim here is to measure the eeC of the PP LP value chain to analyze the eC and the IRP in relation to the environmental impacts caused from its first use to its final treatment. Every environmental impact category typically calculated in LCA methods can be used in relation to the eC. In this study, we focus on the climate change (CC) impacts, according to the impact assessment method of the sixth IPCC assessment report as the exemplary impact category [62]. Therefore, the CC impact, measured in terms of the CO_2 equivalents (CO_2eq) of a material over the entire path, is calculated for E_{total}, according to Section 2.2.1. The scope and system boundaries to be assessed for E_{total} contain the investigated life cycle stages, according to Equation (9) and Figure 2, related to the material. This includes the provision of virgin PP, as well as recycled PP from PIR and PCR, and of its final treatment activity. If the PP packaging waste is not collected for recycling, it is assumed to be incinerated, including energy recovery in this study only, since landfill no longer plays a significant role in Germany [13].

The life cycle inventory of the modeled foreground system of this study can be found in the Supplementary Materials. The data for E_{total} are obtained by modeling the life cycle inventory and conducting the impact assessment using the Sphera database and software version 10.6.2.9. The CC impacts of providing PP granulates (E_{vir}, E_{PIR} or E_{PCR}) are calculated based on 1 kg of PP granulate that can be used in products within the system boundaries. $\mathrm{E_{vir}}$ is modeled using an existing European dataset for PP granulate from the Sphera database. E_{PIR} is modeled from PIW-to-granulate, based on data for mechanical recycling provided by the company Pöppelmann. For E_{PCR}, data for PP recycling from PCW-to-granulate are collected from the literature. A fully reproducible life cycle inventory is found in the literature regarding PCW recycling of PP in North America. As the geographic scope of this study focuses on German market conditions, the background data are updated to representative datasets for the market under study. Transport processes are modeled using a dataset representing truck-trailer transport (Euro 6, 34–40 t gross). The incineration is modeled using a dataset for PP in a municipal waste incineration plant (E_{EoL}) with energy recovery ($E_{credits}$). The European district heat mix is used to credit recovered heat. The electricity demand and credits are modeled using the German electricity grid mix.

To determine the IRP of PP packaging using PIR or PCR granulate to replace virgin granulate, the values required for Equation (10) can be taken from previous descriptions of this case study.

3. Results and Discussion

The results are presented in four sections: the eC (Section 3.1), the eeC (Section 3.2), and the IPR (Section 3.3), followed by a discussion of the indicators in terms of applicability to other studies and limitations (Section 3.4).

3.1. Effective Circularity

Figure 4 shows the results for the eC of the linear and circular scenarios. The number at the top of each bar indicates the eC. The number inside or next to the bars, as well as the color legend, indicate the contribution of the virgin (eC_{vir}), PIR (eC_{PIR}), and PCR product system (eC_{PCR}) to eC_{total}, based on 1 kg of virgin resource input.

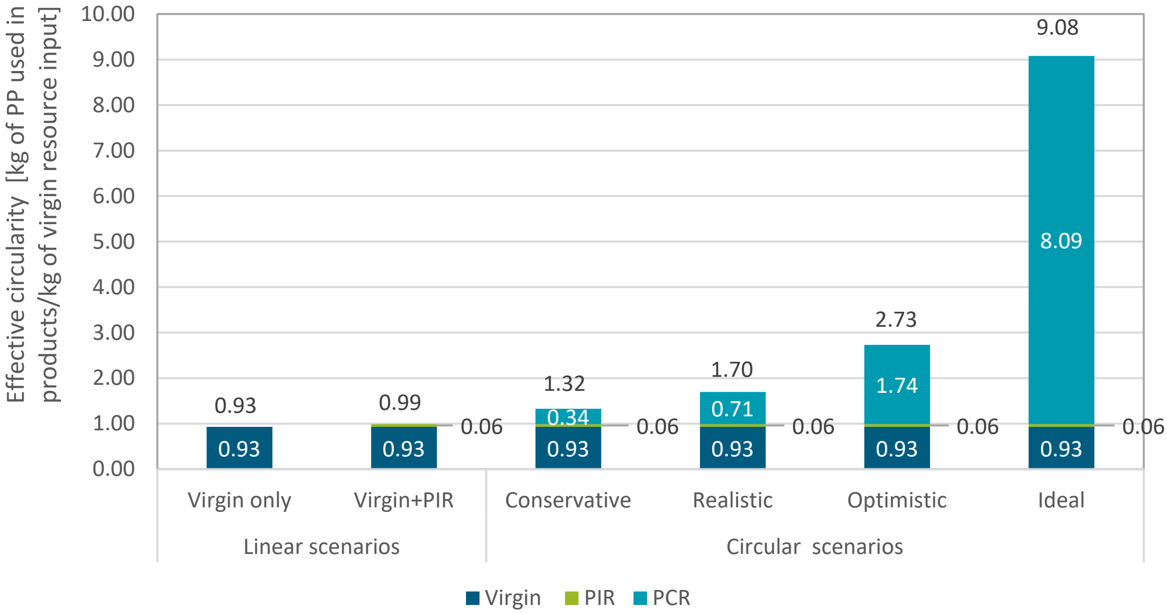

Figure 4. The total effective circularity (eC) of PP for the linear and circular scenarios.

The first two bars in Figure 4 represent the two linear scenarios. The *virgin only* scenario results in an eC of 0.93. In the *virgin + PIR* scenario, the eC cumulates to a value of 0.99. Comparing both linear scenarios, the PIR increases the eC by 6.5%. The eC is understood as the frequency of the average uses per kg of virgin resource input. However, the results can also be interpreted as kg of material used in products, on average, per kg of virgin resource input. Thus, including PIR in the *virgin + PIR* scenario, in addition to the 0.93 kg of virgin material used in the products, 0.06 kg PIR material per kg of virgin resource input can be preserved and additionally processed into products. Ideally, the sum of eC_{vir} and eC_{PIR} could have a maximum value of 1. However, 0.01 kg of the initial virgin PP granulate is lost due to some PIW not collected for recycling and minor losses in the recycling of PIW. The ratio of PIW per kg of virgin material processed may be different for a specific process, but it can be assumed that virgin production is always optimized towards the main product, which is the virgin product.

The last four bars in Figure 4 show the circular scenarios, including PCR, from conservative to ideal assumptions. The four scenarios vary in the values for CSR_{PCW} and RR_{PCW} to demonstrate the influence of dissipative losses in the collection, sorting, and recycling of PCW. While the absolute contribution of virgin and PIR to the eC does not change, the contribution of PCR (eC_{PCR}) increases from the conservative to the ideal scenario. In principle, the larger the share of the PCW collected, sorted, and recycled, the more often the initial virgin input of 1 kg virgin granulate is preserved and recycled into PCR material that can be used in products.

In the conservative scenario, 1 kg of virgin input (PP) is used 1.28 times, on average, in product systems. Thereof, 0.93 kg is used in virgin products, 0.06 kg is used in PIR products, and 0.34 kg is recycled at least once and used in PCR products. Even in the conservative scenario, PCR contributes more than four times the PIR to the eC. Although PIW has a higher collection and recycling rate than PCW, the contribution of PIR is limited by two factors: firstly, the size of the remaining fraction of virgin production that is not reused in the virgin production process onsite, and secondly, the fact that a material can only be considered PIR material once, but be part of the PCR multiple times. About 0.09 kg are recycled more than once in the conservative scenario, and eC_{PCR} increases exponentially in the subsequent scenarios, with increasing CSR_{PCW} and RR_{PCW}.

Regarding the realistic scenario, PCR can preserve 0.71 kg of PP used in products per kg of virgin input. This means that 0.71 kg of PCR is generated and can be used in products per kg of virgin input over several loops. The relative contributions of virgin, and PIR, materials to the eC (eC_{vir} and eC_{PIR}) decrease, while the relative contribution of PCR materials (eC_{PCR}) increases from the conservative to the ideal scenario. The more PCR granulate is maintained in the loop, the more often the PP material is recycled and used in PCR products on average, and the less significant eC_{vir} and eC_{PIR} will be in the overall PP value chain.

The relationship between the collection, sorting, and recycling rate of PCR and the obtained eC_{PCR} is exponential (see Equation (5) in Section 2.1). This becomes visible if looking at the optimistic and ideal scenario. In an optimistic scenario, 1.74 kg of PCR granulate can be produced from 1 kg of virgin input, resulting in an eC of 2.73. In the ideal scenario, PCR material is recycled and used more than eight times, resulting in 8.09 kg of PCR material used in products. Thereof, 7.21 kg are recycled more than once. As a result, the initial virgin resource input of 1 kg PP granulate is used 9.08 times on average, referring to kg available material used in products.

Figure 5 shows a Sankey diagram for the realistic and the ideal scenario up to the 10th use of the material. It depicts the amount of material that passes each loop i from use to use (with a number indicating the use phase) and reflects the remaining fraction of the initial virgin input that is used in the product system. The upper Sankey diagram shows the realistic scenario, while the lower diagram represents the ideal scenario.

(**a**)

(**b**)

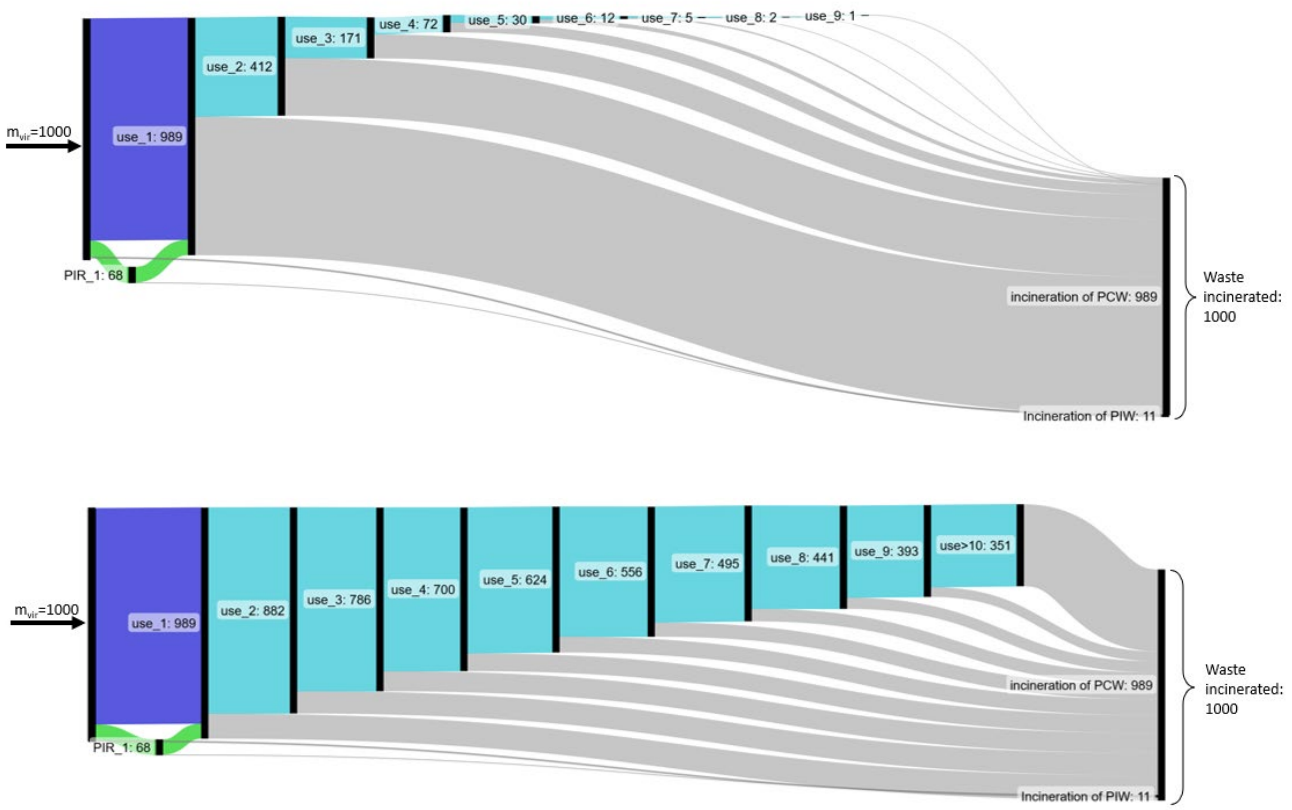

Figure 5. Sankey diagram of 1 kg of virgin PP input up to the 10th use of a material, including contributions from virgin (dark blue), PIR (green), and PCR (light blue): (**a**) realistic scenario; (**b**) ideal scenario.

In both scenarios in Figure 5, about 11 g of 1 kg of virgin input do not reach the first use phase due to uncollected PIW or losses during the mechanical recycling of PIW (which corresponds to the sum of eC_{vir} and eC_{PIR} of 0.99). At the end of the value chain, the virgin input of 1 kg is fully incinerated (11 g PIW and 989 g PCW). The two scenarios differ between the first use and the final treatment (incineration). In the realistic scenario, a larger proportion of material is unpreserved and sent to incineration in each loop i, resulting in the virgin resource input being lost after seven uses of the material. No significant amount of the material from the initial PP virgin input reaches an 8th use phase. In the ideal scenario, about 351 g of the initial 1 kg is still in the loop after the 10th use phase. Additional loops are not shown. After the 67th loop, the initial virgin input is fully lost in the ideal scenario. The more PCW is collected and recycled, the more significant the PCR in terms of its contribution to eC_{total} and the more often materials are used in product systems, on average. Figure 5 visualizes the delayed incineration of the initial virgin input in the ideal scenario compared to the realistic one, as the material remains in the value chain over more loops, resulting in an increased average frequency of use. However, the eC does not indicate whether the collection and recycling of PCW also lead to lower environmental impacts. Therefore, the eeC is calculated and discussed in the next section.

3.2. *Environmentally Efficient Circularity*

For the eeC of the linear and circular scenarios, the eC is employed in relation to the CC impact to obtain the eeC, which is shown in Figure 6.

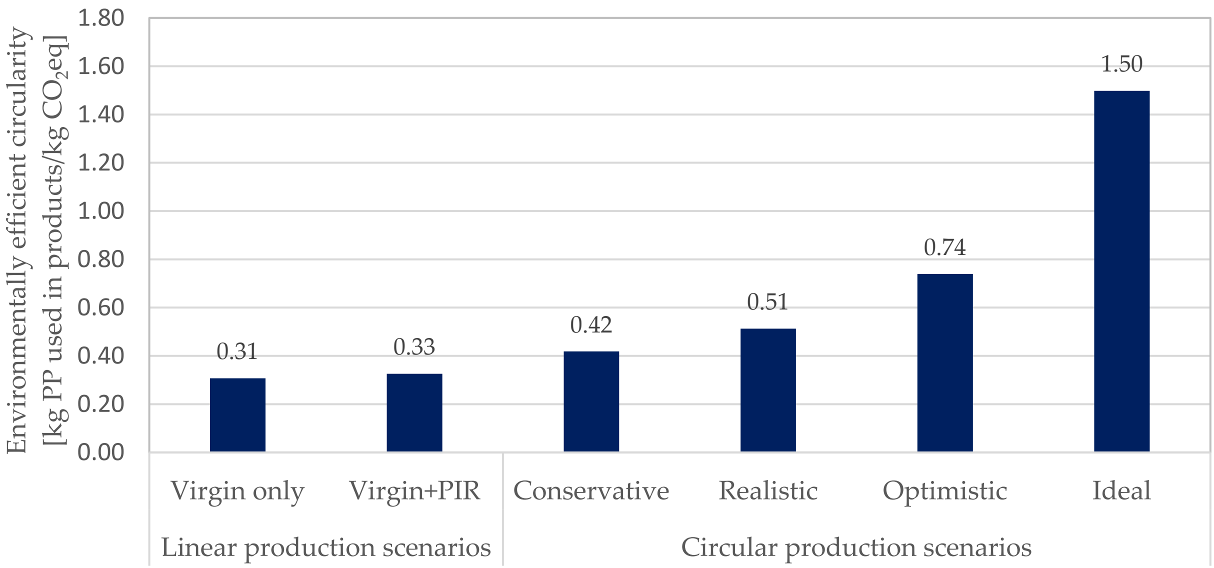

Figure 6. The environmentally efficient circularity (eeC) calculated for the linear and circular scenarios per CC impact.

The eeC here assesses the efficiency of the effective resource use in relation to the CC impact. Thus, eeC indicates the average uses of a material per kg of CO_2eq emitted. Since m_{vir} has been set to 1 kg, the eeC can also be interpreted as kg of PP to be used in the LP packaging loop per kg of CO_2eq emitted. This means that here, 1 kg of CO_2eq is used as a reference unit to depict the climate efficiency of the different scenarios, with or without including PIR and PCR. In the *virgin only* scenario, the eeC is determined to be 0.31 kg PP used in the LP packaging loop per kg CO_2eq. In the *virgin + PIR* linear scenario, the eeC barely increases compared to that of the *virgin only* scenario, from 0.31 to 0.33 kg PP used in products per kg CO_2eq. By taking PCR into account in the circular scenarios, the eeC increases significantly from the conservative to the ideal scenario, reaching 1.50 kg PP used in the packaging loop per kg CO_2eq in the ideal scenario. It follows that PCR contributes to the eeC to a greater extent than does PIR. PCR more often preserves the initial virgin resource in the value chain, while maintaining the same emission level (per kg of CO_2eq).

To better understand the eeC in terms of CC, the CC impact of providing 1 kg virgin, PIR, and PCR granulate, as well as the burdens and benefits from the energy recovery of 1 kg of PP, are shown in Figure 7. All values shown are used to calculate the CC impact of the overall PP value chain (E_{total}), according to Equation (9).

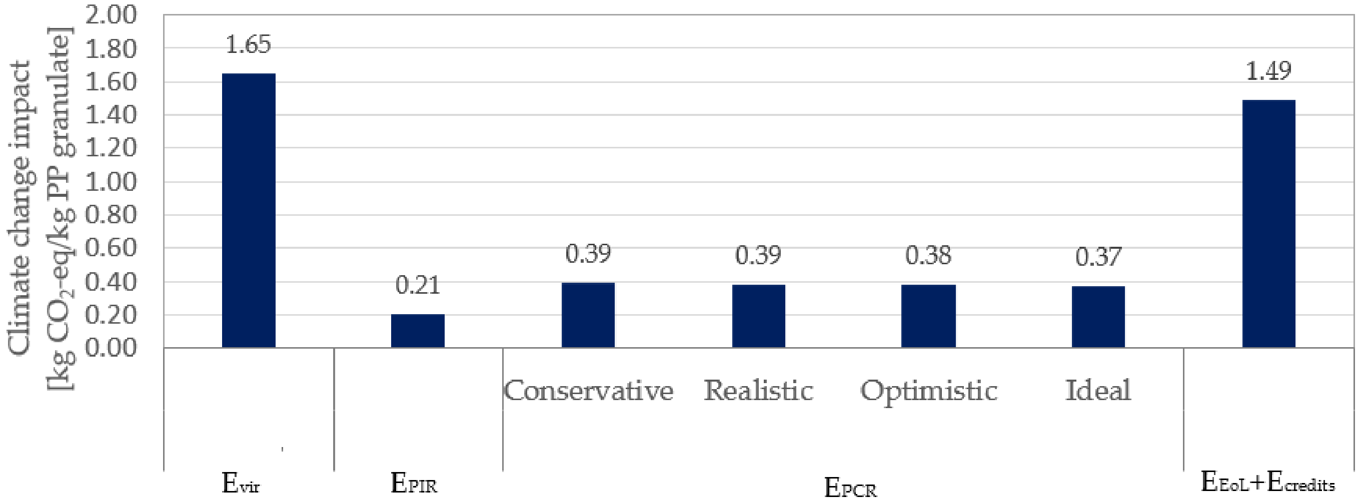

Figure 7. Climate change (CC) impact per kg of polypropylene (PP) from virgin granulate provision (E_{vir}), post-industrial recycling (E_{PIR}), and post-consumer recycling (E_{PCR}), as well as the aggregated burdens and benefits of incineration and energy recovery of 1 kg PP (E_{EoL}+$E_{credits}$).

The provision of PP granulate from virgin material has a higher impact on CC per kg of PP granulate (E_{vir}: 1.65 kg CO_2eq/kg) than granulate produced via PIR (E_{PIR}: 0.21 kg CO_2eq/kg) or PCR (E_{PCR} ranging from 0.41 to 0.37 kg CO_2eq/kg, depending on the scenario). As the collection, sorting, and recycling rates for PCR increase from the conservative to the ideal scenario, less PCW needs to be collected and transported in these scenarios to provide 1 kg of recycled PP granulate. Since the CC impact of the modeled transport processes depends on the quantity and distance transported, the CC impact per kg PP granulate decrease. All other inputs into the collection, sorting, and recycling processes, such as required energy, are constant for all scenarios. With increasing collection, sorting, and recycling rates, the quality of the PCW stream might increase, which could result in a lower energy and resource consumption per kg of recycled granulate. This would probably also decrease the CC impact, but this has not been considered here. The impacts caused per kg of PP granulate (E_{vir}, E_{PIR}, and E_{PCR}) are each multiplied with the respective eC_{vir}, eC_{PIR}, and eC_{PCR} to obtain the CC impact per kg of virgin resource input. This expresses the proportionality between the virgin PIR and PCR loops. The last bar in Figure 7 shows the burdens and benefits of 1 kg of PP incinerated, including energy recovery. As already demonstrated in the Sankey diagrams in Figure 5, 1 kg of PP is always sent to incineration after becoming a dissipative loss during sorting or recycling. Since the sum of the burdens and credits from energy recovery of 1 kg of PP is positive, the thermal treatment of PP leads to a net burden.

The more frequently the material is recycled and used in the LP packaging loop, the higher the eC, but also the environmental impacts (E_{total}). If the eC and the environmental impacts are used in relation to each other, the eeC indicates the extent to which the additional eC is also environmentally worthwhile. Only if the eC in relation to the environmental impacts (here, the exemplary CC impact) is higher, do we speak of an environmentally and circularly efficient value chain. Since PCR causes a more significant increase in the eC than PIR, the eeC increases to a greater extent for the circular scenarios compared to the linear scenarios (although E_{PIR} < E_{PCR}).

3.3. Impact Reduction Potential

Based on the findings of the previous section, we conclude that PIR and PCR both have a potential to reduce the CC impact when replacing virgin PP granulate in regards to the CC impact ($E_{PIR} < E_{PCR} < E_{vir}$). If 1 kg of PIR granulate replaces 1 kg of virgin granulate, 1.44 kg CO_2eq/kg is saved. In contrast, using 1 kg of PCR granulate to replace 1 kg of virgin granulate saves between 1.24 and 1.28 kg CO_2eq/kg, depending on the scenario. As described above, this neglects the fact that PIR and PCR granulates are not available in unlimited quantities. PIR directly depends on the virgin input, but PCR is not completely used infinitely and independently from the virgin production, due to the need to compensate for dissipative losses. To consider the availability of PIR and PCR granulates, we employed the picture of the seesaw in Section 2.2.2. IRP indicates the benefits (here, regarding the CC impact) per kg of PIR and PCR per kg of virgin resource input (see Figure 8).

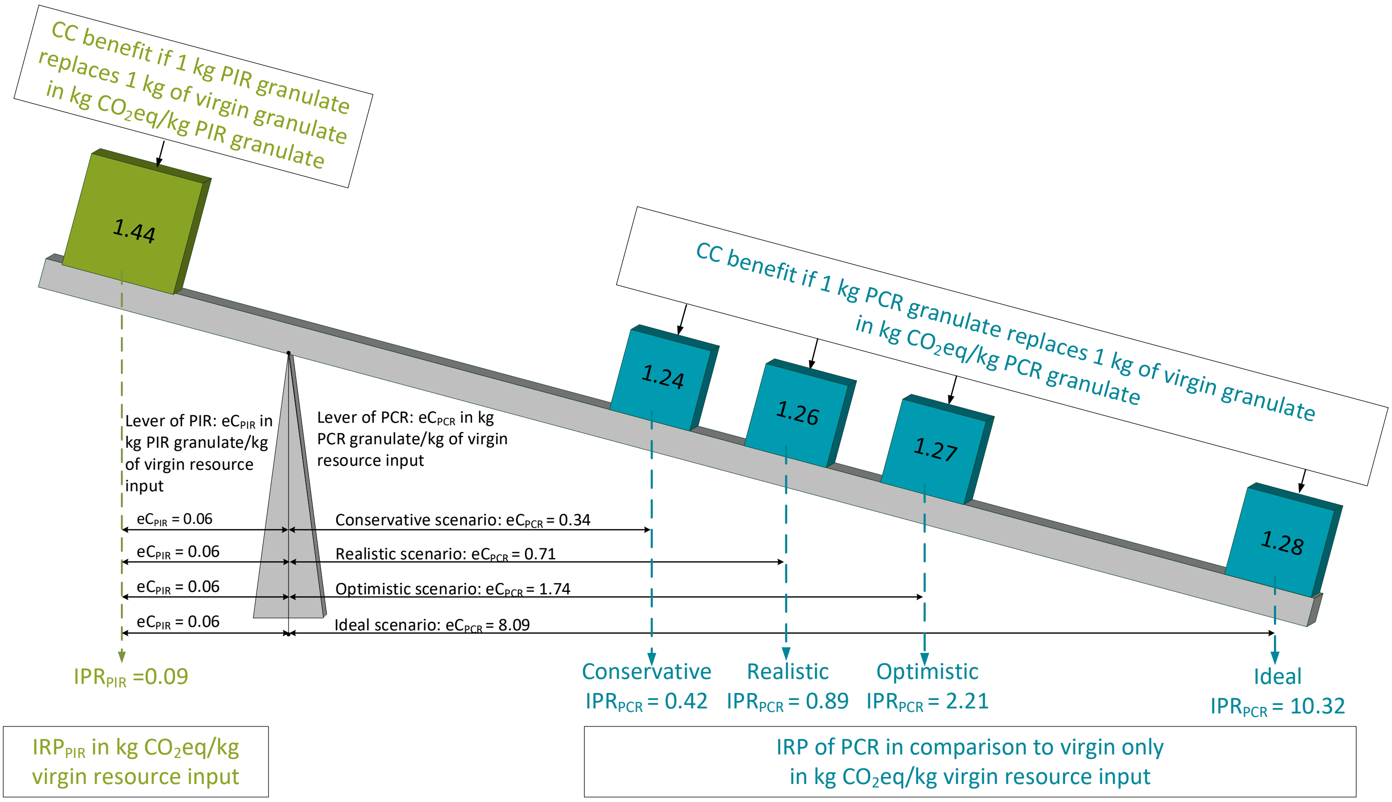

Figure 8. The IRP of PP PIR compared to PP PCR (CC: climate change, IPR: impact reduction potential, eC: effective circularity, PIR: post-industrial recycling, and PCR: post-consumer recycling).

On the left side, the IRP of the PP PIR granulate is shown (IRP_{PIR}). The benefits of CO_2eq emissions of 1 kg PIR re-granulate replacing 1 kg of virgin material (the weight on the left side) is multiplied by eC_{PIR} (the lever on the left side). As a result, 0.09 kg CO_2eq per kg of virgin input can be saved by the PIR granulate, considering its availability per the virgin input. In contrast, the IPR of PCR (IRP_{PCR}) is shown on the right side, depicting all four circular scenarios from conservative to ideal assumptions. In all scenarios, the benefits of CO_2eq of 1 kg PCR re-granulate replacing 1 kg of virgin granulate do not vary significantly (the weights on the right side), because the collection, sorting, and recycling rates vary, but not the processes themselves. Only the transport-dependent climate emissions cause a slight increase of the weights on the seesaw because they directly depend on the dissipative losses from PCW-to-granulate. All other inputs of energy and materials are the same per kg of the provided re-granulate in all scenarios. In principle, we expect that energy and resource input per kg of generated re-granulate would decrease with increasing collection, sorting, and recycling rates for the optimistic and ideal scenario, if this accompanies an increase in PCW quality. This would further increase the weight, and thus, the IPR of PCR.

On the contrary, eC_{PCR}, defined as the lever, varies with the scenarios. In the conservative scenario, the IPR of PCR equals 0.42 kg CO_2eq per kg of virgin PP input that can be saved by the PCR granulate. Even in this scenario, the combination of the weight (the CC benefit) and the lever (the eC) of the PCR outweighs those of the PIR. In subsequent scenarios, in which the PCW is kept in the loop even more often, the IPR of PCR increases, mainly because the lever becomes larger. The increase in weight on the seesaw plays a minor role here because the process inputs are kept constant. For the case study, PP from PCR has a higher IRP than PIR. For other value chains and materials, however, the seesaw can tip to the other side, i.e., if the collection and sorting rates for PCR are lower or the environmental impacts to recycle the PCW are relatively high. This might be the case for plastic PCW that is currently minimally recycled, such as plastics in the waste of electrical and electronic equipment. Here, the plastics are mostly incinerated as residual fractions because the energy and resources required to obtain valuable recycled plastics by mechanical separation and recycling processes are often too high to be recycled in an environmentally and economically reasonable way. Additionally, the seesaw could tip for other environmental impact categories that have not been analyzed here.

3.4. Applicability, Limitations, and Recommendations

The eC can be used to quantify material circularity, regardless of additional resources used or environmental impacts caused when increasing material circularity. A recycling activity is effective if the frequency of uses increases, regardless of the effort it takes. Looking at the path of a resource from its first to its last use, the relevance of PIR in contrast to PCR can be investigated as the eC. The eC serves as the basis for the combination of circularity and environmental assessment to calculate the eeC and the IPR, but could also be used as a single metric to rate and compare the circularity of different value chains. Moraga et al. [23] define three scopes of circularity indicators, including those that measure:

i. The physical properties of technological cycles, such as a recycling rate;
ii. The physical properties of technological cycles, with full or partial life cycle approaches, such as the eC or the MCI [38]; and
iii. The effects (burdens/benefits) of technological cycles such as eeC or the circular economy performance indicator (CPI) proposed by Huysman et al. [39].

Table 2 provides an overview of the indicators eC and eeC regarding their scopes, applicability, and limitations compared to two existing indicators of the same scopes.

Neither of the existing indicators (MCI and CPI) has the ability to compare PIR and PCR. The MCI is considered to capture PCR only, while the CPI has only been described for and applied to PIR. However, both existing indicators address quality constraints, which are currently not captured by the eC and the eeC. Additionally, the MCI addresses lifetime and usability constraints. The integration and influence of strategies to extend the use stage or quality aspects are beyond the scope of this work but might be interesting for future research. Two previous studies can serve as starting points here: the first has already addressed measuring strategies to extend the use stage following the philosophy of assessing circularity as the frequency of uses [63]; the second measures quality conservation for recycled plastics [17].

In principle, the provided indicators are applicable to all types of waste and materials. Thus, they are not limited to the assessment of recycled plastics. This study focuses on recycled plastics because the differing potential of PIR and PCR for the CE is mainly discussed for plastics. The PCR of mixed plastic waste often creates higher environmental impacts and suffers from downcycling effects compared to the characteristics of PIR, from a product perspective. Due to the material perspective, which covers multiple uses of a material, the proposed indicators of this study are primarily relevant for strategic decision makers at the company and policy level. The indicators might also be used by companies that face decisions of whether to use PIR or PCR materials. If companies stick solely to product LCAs, they might conclude that the environmental impacts of a product are lower when using PIR material compared to PCR material. However, to contribute to closing the loop at the EoL, companies also need other methods and indicators to quantify the environmental advantages along the value chain, including multiple material uses. A particularly suitable area of application in industries can also be the monitoring and assessment of closed-loop systems in cases where companies can control the recycling system, which is supported by Figge et al. [42].

Table 2. Overview of the proposed circularity indicators of this study in comparison with two existing indicators.

	Effective Circularity (eC)	**Material Circularity Indicator (MCI) [38]**	**Environmental Efficient Circularity (eeC)**	**Circular Economy Performance Indicator (CPI) [39]**
Scope	(ii) Technological cycles with full or partial life cycle approaches		(iii) Effects (burdens/benefits) of technological cycles	
Perspective	Material perspective	Product perspective	Material perspective	Product perspective
Unit	Frequency of uses	Degree or rate from 0 to 1	Frequency of uses in relation to environmental impacts associated with the material	Environmental impacts per functional unit, such as extracted cumulative exergy from natural environment per 1 kg of plastic waste
Number of material uses considered	Multiple	Single	Multiple	Single
Life cycle stages	Provision of the material and its recycling	Feedstock provision (reuse and recycled content), use stage (lifespan and utility), destination after use (reuse, recycling)	Provision of the material and its EoL (recycling, recovery, and landfill)	EoL (recycling, recovery, and landfill)
Information needed	Production, collection, sorting, and recycling rates of PIW and PCW	Recycled and reused content, recycling efficiency for recycled feedstock provision and for destination after use; lifespan, utility, and material fraction for reuse and recycling after use	eC and the environmental impacts associated with the material (virgin provision, PIR and PCR, and EoL)	Avoided impacts of the virgin production (material or energy), percentage of substitutable virgin material, recycling rate, environmental impact of the recycling process
Ability to compare PIR and PCR	Yes	No (intended for PCR)	Yes	No (only for PIR)

Both the eeC and IPR are useful for interpreting the link between environmental impact assessment and material circularity, but with different focuses. In the context of planetary boundaries [64], the eeC can be used to measure the environmental efficiency of circularity measures, such as PIR and PCR. LCA approaches set the focus on decreasing environmental impacts while providing the same function (defined by the so-called functional unit in each LCA) and only consider a single product life cycle. In contrast, the eeC is calculated the other way around. The focus is set on increasing circularity while causing the same environmental impact. With regard to the CC impact, this could be used, for instance, to assess climate policy and protection measures. For CC impacts, the so-called CO_2-budget, also known as the carbon budget, is often discussed. It refers to the total amount of CC emissions from anthropogenic sources that may be emitted as a maximum if global warming beyond a defined limit is to be avoided with a certain probability [65]. Studies report a relationship between the cumulative total amount of CO_2eq emitted and the resulting temperature increase [66,67]. Therefore, the cumulative amount of CC emissions must be limited by climate-efficient measures, including PIR and PCR. Nonetheless, if the assessment focus is always set to a product level, as in conventional LCA, environmental advantages that play out along the value chain might be neglected. Thus, the eeC can contribute to the discussion of CO_2-budgets, but also planetary boundaries related to other environmental issues related to LCA impact categories.

The IRP can help determine whether PIR or PCR leads to greater overall environmental benefits. Again, if the impact assessment is always limited to a product level, as in product LCA standards, environmental advantages along the value chain are neglected. Especially for products that can be made of PIR or PCR, without restrictions regarding quality and applicability, this study reveals that companies should choose PP from PCR to support overall climate protection goals. Focusing on the existing system boundaries of a product life cycle, the use of PIR materials in products will often lead to lower impacts because the availability of recycled material is not considered. Both PIR and PCR limit CC impact compared to virgin PP production across the PP value chain of packaging materials. Nonetheless, PCR has the greater leverage compared to PIR in all scenarios. The more PCR material is collected and recycled from the conservative to the ideal scenario, the higher the amount of PCR material that can be used in products replacing virgin material, which will lead to overall benefits along the value chain. It follows that the more PCR material is looped in the value chain, the higher the share of PCR products on the market and thus, the greater the influence of PCR on the eeC and the IRP. By broadening the perspective from the product to material level, the significance of PCR becomes visible.

Looking at the current LCAs of plastics at the product level, existing standards recommend distinguishing between modeling PIR and PCR granulate [20]. According to such standards, if PIW has a positive economic value (market price above 0) at the point of occurrence (i.e., excluding any storage, transport, additional processing, etc.), it shall be modeled as any other by-product in LCA [20]. Thus, PIW should include the impacts of its (virgin) pre-chain, which are often allocated based on economic distribution factors between a virgin PP product and the PIW. Since the PIW in our study has a monetary value, which is, however, low compared to the main product of the pre-chain, the PIR granulate would carry only minor impacts of the virgin pre-chain. Our research regarding prices of different pre-chains producing PP PIW indicate an allocatable share of the pre-chain between 0.94% and 4.62%, depending on the volatile prices provided by a plastics manufacturer (further information can be found in the Supplementary Materials). Even if the calculated CC impact of providing 1 kg of PIR granulate (E_{PIR} = 0.21 kg CO_2eq/kg PP) would additionally carry the highest identified economic share of 4.62% from the CC impact of virgin PP granulate provision (E_{vir} = 1.65 kg CO_2eq/kg PP), it would result in 0.28 kg CO_2eq/kg PP. This is lower than the calculated CC impact of 1 kg PCR granulate calculated in this study (E_{PCR} is between 0.37 and 0.39 kg CO_2eq/kg PP). Since the PCR granulate would reveal a higher CC impact compared to the PIR granulate, based on economic allocation, as suggested in product LCA standards, this might not be sufficient to identify the CC benefits that are provided along the value chain.

Furthermore, the common product LCA standards often refer to avoided burdens for the recycled material replacing virgin material at the EoL [20]. Avoided burden approaches have been criticized for claiming environmental impacts that are credited to a product system with a negative sign that "do not physically occur" [57]. This can challenge the interpretation of the results. In our case, energy can clearly be used 1:1 in the form of generated heating value or kilowatt hour of electricity in every arbitrary product system, replacing heat and electricity mixes of an area under study. Contrarily, recycled material can only be used in combination with a substitution rate that must be defined regarding a specific product. Currently, recycled plastics from PCW can fully replace corresponding virgin material in some applications, such as thick-walled injection molding products, but not for food contact materials. Thus, the definition of the avoided burdens caused by recycled materials is sometimes challenging or very case specific. By using system expansion to include the whole value chain of a material, as with the eeC and the IPR, avoided burdens for the materials are not considered, improving the interpretability of the results.

Regarding the limitations of this study, it should be noted that the case study should be seen as a first example to demonstrate the indicators. Most limitations for interpreting the results are a consequence of available data sources. Especially regarding PCR, more updated data for the German market would help to create a reliable dataset regarding the value chain under study. As reported for the case study, there was no consistent data available to calculate the eC for PP packaging. Data for plastic packaging or even plastic products in general had to be used. Existing data sources usually group plastics together, so there are scarcely any separate rates according to polymer type. The results serve as a first and rough estimation regarding the eC of PP packaging and reflect high uncertainties, which propagate with the eeC and the IPR. The reproducibility of the results in an experimental study cannot be fully predicted. To capture loss rates over multiple loops in an experimental setup, a tracer or maker system, with in-depth digitalization of monitoring activities, would be necessary to track a virgin resource input over serval recycling loops. A first starting point might be the investigation of closed-loop recycling systems with a closed and fixed material amount. As mentioned, the influence of longevity or quality due to recycling has not been considered in this study. This would require considering lifetime restrictions or downcycling effects, such as mechanical, processability, or aesthetic properties. Figge et al. [42] proposed another indicator for considering the service life and limitations due to quality, resulting in a decreased longevity of a product. This indicator was not examined here, since service life and quality must always be considered with a specific product. For instance, it is noted that the ideal scenario represents a hypothetical scenario of a closed-loop system, regardless of quality losses that might influence recyclability and the processability into specific products made of PCR granulates. Studies have reported that PP suffers quality losses, such as a decreasing melt flow index, after five extrusion cycles in a closed system [68]. Specifically, the results for the eC presented for the ideal scenario need to be confirmed in practice. The dissipative losses per loop in collection and recycling have to be compensated for by bringing new material into the system, which can improve the material properties because it rejuvenates the average age of the materials in the loop.

4. Conclusions and Outlook

This study proposes indicators to answer the question regarding how plastic circularity can be measured for PIR and PCR, also considering environmental impacts. First, we suggest measuring circularity as the frequency with which resources are used in product systems using the effective circularity (eC). This is obtained from the first to the last product system in which a material is used, on average, and is subdivided into contributions from virgin, PIR, and PCR product systems. Second, circularity is regarded as a vehicle to reduce environmental impacts using the environmentally efficient circularity (eeC). Third, the impact reduction potential (IPR) is calculated, measuring environmental benefits if recycled material (PIR or PCR) replaces virgin material but considering the resource availability of PIR and PCR per kg of virgin resource input. The indicators are demonstrated in a case study of PP packaging.

The proposed indicators help to explain the relevance of PIR and PCR in the context of minimizing virgin resource use and closing the loop, while reducing emission levels from a material perspective. Most indicators concerning circularity and LCA are developed in the context of a product level. Thus, they are applicable at a product perspective because they aim to isolate a single product life cycle. Comparing the product and material perspective, the material perspective captures the whole value chain, from virgin production to the final treatment activity of a resource. The case study results reveal that the eC of the PP packaging loop increases significantly the more it is collected, sorted, and recycled. An initial virgin PP granulate can be used, on average, more than nine times in an ideal scenario aiming for a closed loop. Additionally, the eeC and the IPR comparing the PIR and PCR of PP show better results for PCR, although PCR has a higher CC impact per kg of PP granulate than does PIR. In summary, the assessment of multiple material uses is currently underrepresented in the current literature. The fundamental differences between PIR and PCR require a reasonable decision at the material level. To achieve science-based targets for reducing primary resource extraction and environmental impacts and increasing the use of recycled materials, the proposed indicators can strengthen the use of recycled materials. Assessing the whole value of a material from its first to its last use in a product system is currently not established, and companies often optimize their goods at the product level. In the future, the proposed indicators could be used to assess circularity and environmental benefits at a material level. Environmental decisions for a sustainable material should be made on material level, looking beyond a product life cycle. Future research should focus on how to integrate the proposed indicators (eC, eeC, and IPR) into existing assessment methods and reporting obligations or environmental policy. The indicators eC, eeC, and IPR may be incorporated into policies and strategic decision-making processes to complement current environmental assessment methods that focus mainly on the product level. The use of PCR materials should be prioritized if their use leads to lower environmental impacts in the long term, considering all material uses. The assessment of multiple material uses as a mere frequency should be complemented with assessing the consequences of the deterioration of the physical properties due to downcycling. The focus should be on preserving materials at their highest possible value and utility for as long as possible, instead of just closing the loop at the product level. The assessment of the impacts of all loops in which a material is used provides a more long-term perspective on the use of recycled materials and can foster the use of PCR materials. The proposed indicators can also be used to measure progress towards policy targets, such as the use of ten million tons of recycled plastics by 2025. Alternatively, these indicators might be used to create incentives for companies using PCR materials, especially in cases where the product level is not sufficient to prove the benefits of PCR materials.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151612242/s1, Table S1: Collection and mechanical recycling of PIW-to-granulate; Table S2: LCI of PCW collection and sorting; Table S3: LCI of PCW recycling; Table S4: Quantities and prices to calculate economic allocation factors between PIW and the main virgin product. Reference [69] was cited in the Supplementary Materials.

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Data Availability Statement: This study includes licensed data from the company Sphera, which is taken from the LCA for Experts (formerly GaBi) database version 10.6.2.9. The used datasets are listed in the Supplementary Materials. The data is processed and provided according to the Sphera data processing and publication policy available at https://scn.spherasolutions.com/client/tc/Sphera-GaBi-Software-Special-Terms-and-Conditions.pdf (accessed on 5 June 2023), as well as in line with the MDPI Research Data Policies found at https://www.mdpi.com/ethics (accessed on 5 June 2023).

Conflicts of Interest: The method was jointly developed by Fraunhofer UMSICHT and Pöppelmann GmbH & Co. KG Kunststoffwerk-Werkzeugbau. The co-author B.K. is an employee of the company Pöppelmann GmbH & Co. KG Kunststoffwerk-Werkzeugbau, which partially financed the project and provided primary data to fill existing data gaps regarding post-industrial recycling. The authors have no competing interests and declare no conflicts. Fraunhofer UMSICHT exclusively performed the calculations, analysis, and interpretation of data to ensure scientific independence.

Appendix A

Here, the values listed in Table 1 which are assumed to calculate the eC of the case study example are explained for all scenarios. For the linear scenarios of the eC, the production rate of virgin material (PR_{vir}) is calculated based on the share of accumulated PIW per processed virgin plastic (p_{PIW}) in Germany (see Equation (2)). p_{PIW} is obtained using plastic flow data for Germany by dividing the total amount of PIW from plastic producers and processers (0.95 million tonnes) by the total amount of virgin plastics processed in the same year (12.61 million tonnes) [60]. The amount of virgin plastics processed in Germany is determined by subtracting the processed recycled materials from PIR and PCR (0.95 million tonnes from PIR and 0.05 million tonnes from PCR) from the total amount of all plastics processed (14.37 million tonnes). Data specifically for PP and/or (PP) packaging were unavailable. As a result, p_{PIW} is set to 7.6%, and consequently, PR_{vir} equals 92.4%. The detailed calculation can be found in the Supplementary Materials. For eC_{PIR}, according to Equation (3), CR_{PIW} is assumed to be 89.1%, based on the same material flow data for plastics used for p_{PIW} in Germany [60]. Out of 0.95 million tonnes of accumulating PIW, 0.85 million tonnes are used in PIR. Values for the recycling rate of PIR are obtained from the manufacturer of plant pots providing the primary data for PIR (see Table 1).

As a starting value for eC_{PCR}, $p_{PCW,1}$ is calculated to be 99% for all scenarios. Regarding the values for CR_{PCW}, SR_{PCW}, and RR_{PCW} needed to calculate eC_{PCR} for the circular scenarios, different reference points for LP packaging are reported in the literature. For the collection and sorting of LP, most data are currently available as output of collected waste for recycling at the sorting plant. Hence, CR_{PCW} and SR_{PCW} are summarized as an aggregated value and further referred to as CSR_{PCW}. In this study, losses from additional pre-treatment steps at the recycler are captured as losses during recycling, starting with debailing at the recycler. Further losses in recycling occur during shredding, washing, additional sorting, and extrusion or palletization. According to the revised reference point of the EU-2019/665 [70], the amount of PCW that is recycled is measured in reference to the amount of plastic that has been separated by polymer type during the previous sorting processes and does not undergo any further pre-processing before being used in a pelleting, extrusion, or molding process. At the time of data collection for this study, most available data were calculated according to the previous method, considering the amount of PCW that is sent to the recycler according to the EU Packaging Directive 94/62/EC and EU-2005/270/EC [70,71]. However, the change in the reference points for the recycled quantities has no influence on eC_{total} because with both reference points, losses are captured over the entire recycling chain. The shift in reference points affects the quotas to which the losses are assigned, but not the losses in total. In any case, it is important to holistically capture all relevant sources of dissipative losses along the value chain, according to available and reported data.

In the conservative scenario, CSR_{PCW} is based on data for plastic products in general, which is assumed to be lower than the CSR_{PCW} for PP plastic packaging because of the existing collection and sorting capacities for LP waste. Therefore, CSR_{PCW} for the realistic scenario is derived from data for plastic packaging waste in Germany for the year 2019 [72]. This value represents plastic packaging only, and it is therefore more realistic for the case study. The optimistic value for CSR_{PCW} entails a future assumption that 75% of PP LP is disposed of and sorted correctly by the user in the LP waste stream. The ideal scenario could represent, e.g., a product-specific take-back system in which 99% of a specific product waste is recollected and sorted, e.g., for plant pots that are re-collected, assuming that only 1% of the waste is lost in collection.

For RR_{PCW}, different literature values were collected for mechanical recycling, ranging from 66%, as the suggested status-quo for PP PCR in the EU [73], to 93% for the closed-loop recycling of PP plastic crates [74]. Again, we present scenarios with lower and higher recycling rates to analyze different scenarios. We rounded the values found in the literature and selected 65% as a conservative assumption for RR_{PCW} in Germany, based on the median of eight recycling plants in the EU [73]. For the realistic scenario, the RR_{PCW} is set to 75%, based on findings by Antonopoulus et al. [73] (71%) and Schwarz et al. [75] (74% for open-loop mechanical recycling, and 80% for closed-loop mechanical recycling). For the optimistic RR_{PCW}, the future target of 85% suggested by Antonopoulos et al. [73] is employed. For the ideal scenario, the RR_{PCW} is set to 90%. The RR_{PCW} can be assumed to be lower than the RR_{PIR} (96%) because of contamination with organic and other impurities after use. Since we consider PP packaging as end-consumer products, a slightly lower rate

(RR_{PCW}) of 90% is assumed as compared to the 93% for plastic crates that are mainly used in the B2B sector [74].

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