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Operational Framework to Quantify "Quality of Recycling" across Different Material Types

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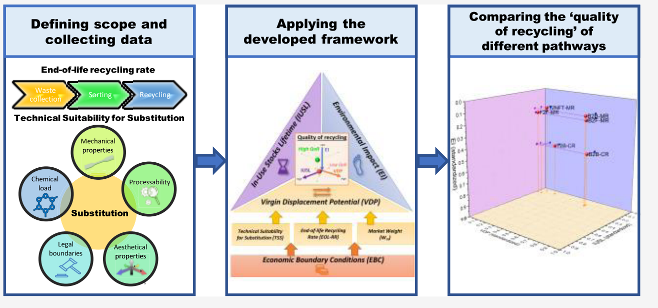
ABSTRACT: Many pledges and laws are setting recycling targets without clearly defining quality of recycling. Striving to close this gap, this study presents an operational framework to quantify quality of recycling. The framework comprises three dimensions: the Virgin Displacement Potential (VDP); In-Use Stocks Lifetime (IUSL); and Environmental Impact (EI). The VDP indicates to what extent a secondary material can be used as a substitute for virgin material; the IUSL indicates how much of a certain material is still functional in society over a given time frame, and the EI is a measure of the environmental impact of a recycling process. The three dimensions are aggregated by plotting them in a distance-to-target graph. Two example calculations are included on poly(ethylene terephthalate) (PET) and glass. The results indicate that the recycling of bottle and container glass collected via a deposit−refund system has the lowest distance-to-target, at 1.05, and, thus, the highest quality of recycling. For PET bottles, the highest quality of recycling is achieved in closed-loop mechanical recycling of bottles (distance to optimal quality of 0.96). Furthermore, sensitivity analysis indicates that certain parameters, e.g., the collection rate for PET bottles, can reduce the distance-to-target to 0.75 when all bottles are collected for recycling.



KEYWORDS: *recycling, secondary materials, decision-making, substitutability, circular economy*

1. INTRODUCTION

The transition to a more circular economy is an urgent challenge to mitigate climate change and natural resource depletion. Indeed, using recycled (secondary) materials to manufacture new products typically decreases life cycle greenhouse gas emissions thanks to energy savings from avoiding resource extraction and/or processing of primary (virgin) materials.[1] However, the waste management landscape is complex, with heterogeneous feedstocks and variations in extended producer responsibility (EPR) schemes on one hand and an increasingly diverse arsenal of emerging sorting and recycling technologies on the other.[2−4] Moreover, certain attempts to close material loops may not always be effective, or even desirable, owing to the spatiotemporal dimensions of environmental risk from materials and global policies' variability.[5] Thus, it is challenging to make decisions regarding optimal waste management, taking into account different aspects, e.g., technical limitations, economic balance, and waste management processes' environmental impact.

The European Commission's Circular Economy Action Plan indicates the importance of ensuring "high-quality recycling" to achieve a more circular economy. The plan acknowledges that improving quality of recycling is essential to increasing the amount of recycled materials that can be used in new products.[6] Several aspects are important in optimizing quality of recycling, including consumer behavior and collection efficiencies, as well as technical properties (i.e., properties that give materials the ability to fulfill certain functions[7]) of secondary materials (i.e., recyclates) produced from heterogeneous waste fractions. To be used in a certain market, the technical properties of products produced from recycled materials should be in line with the technical properties of products produced from virgin materials to be accepted by production companies and, ultimately, consumers. If a secondary material's inherent technical properties differ from those of the primary material from which it was obtained in a way so that the secondary material is only usable for other products that require different and often less-demanding technical properties, then additional production of primary materials is unavoidable to fulfill the initial product's functions. When a given material cannot be used in the economy anymore, "dissipative flows" (i.e., flows to sinks or stocks that are not accessible to future users due to different constraints)

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occur.[8,9] This prevents humans from using the function(s) that the resources could provide in the technosphere.[10] To compensate for dissipative flows, virgin materials and resources continue to be consumed.

Zeng and Li[11] stated that a sustainable material economy will be based on a closed loop of materials, which, as much as possible, are free from quantitative and qualitative losses in the technosphere. However, even for metals, as an example, open-loop recycling is more common than closed-loop recycling due to degradation of quality in the end-of-life phase, among other factors.[12] Thus, to meet the target product's quality requirements, dilution of the secondary material by adding high-purity materials is required.[13]

To improve recycling, a clear definition of quality of recycling is required. In this respect, Grant et al.[14] served as a major stepping stone, providing an operational definition, namely, "the extent to which, through the recycling chain, the distinct characteristics of the material are preserved or recovered so as to maximize their potential to be reused in the circular economy." Furthermore, extensive research and development in the life cycle assessment (LCA) field concerning substitutability (i.e., the degree to which a secondary material can replace a primary one; notably by Vadenbo et al.[15] and Rigamonti et al.[16]) most certainly has led to important insights related to quality of recycling.[14] Furthermore, several authors have published important stepping stones toward effective quantification of quality of recycling. For example, Zeng and Li[17] established mathematical models to measure e-waste recyclability by defining rules for determining various materials' grades. Uekert et al.[18] analyzed technical, economic, and environmental metrics for closed-loop polymer recycling technologies through a multi-criteria decision analysis, which is a systematic technique for evaluating and ranking options across priorities that can enable visualization of different recycling options' overarching performance. Ghosh et al.[19] developed a versatile tool that can simulate material flows of plastic resins and products through the economy, and they linked this to the assessment of a variety of sustainability metrics, circularity metrics, and techno-economic parameters. Various other studies[20−24] have proposed individual indicators that reflect quality of recycling.

Thus, various approaches clearly exist to assess quality of recycling; however, a more streamlined and operational framework is needed to quantify quality of recycling across different material types, as Tonini et al.[7] stressed recently. Therefore, the present study's main objective is to develop an operational framework that can quantify quality of recycling based on different aspects, e.g., substitutability, recycling efficiencies, and the recycling chain's environmental performance. Instead of proposing a completely new approach, this work builds and capitalizes on elements from existing studies—e.g., those that Grant et al.,[14] Tonini et al.,[7] and others proposed—and focuses on taking an approach that is operational, practical, and applicable across different sectors. We also demonstrate the framework's functionality using case studies on PET recycling (provided in Section 3) and glass recycling (provided in the Supporting Information).

2. GENERAL INTRODUCTION TO THE FRAMEWORK

We include different aspects—or so-called dimensions—that are relevant in the quality of recycling in a mathematical framework. Very relevant is the preservation of the functionality of materials (i.e., the quantity of material that is "actually" useful to displace virgin production) as it allows achieving a maximum of substitutions across the multiple markets where the material can possibly be applied at a certain point in time.[7] This is in our work included by the first dimension, called the Virgin Displacement Potential (VDP). Also important is the environmental dimension of quality of recycling. Recycling processes producing high-quality recyclates may be associated with higher impacts than processes with lower-quality outputs, due to energy/resource consumption or material losses.[7,25] Therefore, our framework includes an additional dimension on the environmental performance of the recycling process, namely, the Environmental Impact (EI). Both the VDP and EI reflect on the current state of a recycling process. Quality of recycling can also be viewed as the path that ensures the longest durability of the material in the economy.[26] Therefore, we include the In-Use Stocks Lifetime (IUSL) dimension. This dimension shows how much of a certain material is still functional in society over a given time frame, and is thus a more prospective aspect of the quality of recycling.

A schematic overview of the three main "dimensions" of the proposed quality of recycling framework is presented in Figure 1: the VDP (expressed in %); IUSL (expressed in ton-years);

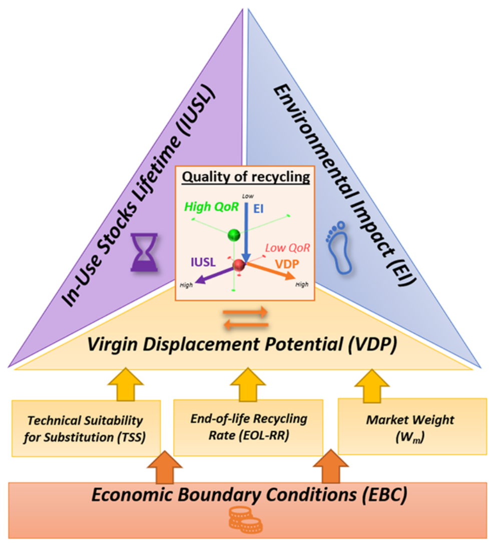

Figure 1. Schematic representation of the proposed quality of recycling framework. Based on the three dimensions—In-Use Stocks Lifetime (IUSL), Environmental Impact (EI), and Virgin Displacement Potential (VDP)—quality of recycling can be evaluated quantitatively.

and EI (which can have different units depending on the impact category). Each dimension provides additional information relevant to quality of recycling. Generally, the higher the VDP and IUSL, and the lower the EI of a certain recycling pathway, the higher the quality of recycling. We have oriented the direction of the three axis in such a way that all desired values are far from the origin (so this corresponds to the best quality of recycling) and all undesired values are near to the origin (so this corresponds to the lowest quality of recycling).

2.1. Virgin Displacement Potential (VDP).

The first dimension of the framework, VDP, indicates to what extent a secondary material can be used to substitute primary materials. This dimension builds on Vadenbo et al.[15] who proposed a

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similar indicator—the substitution potential (SP) (γ)—which is based on four main determining factors—technical properties of secondary materials ($\alpha^{rec/disp}$), overall recycling efficiency (η^{rec}), amount of material in a waste stream that can be used as secondary material (U^{rec}), and the impact on the market in which the secondary materials are used (π^{disp})—as can be seen in eq 1 (adopted from ref 15)

$$\gamma = U^{rec}\cdot\eta^{rec}\cdot\alpha^{rec/disp}\cdot\pi^{disp} \quad (1)$$

In the current framework, the impact on the market in which the secondary materials are used is omitted for simplicity reasons. Thus, our proposed VDP depends on four different "indicators": technical suitability for substitution (TSS, which is somewhat equivalent to what Vadenbo et al.[15] proposed earlier, but that we have elaborated on further so that it can be calculated systematically); End-of-Life Recycling Rate (EOL-RR, which is the fraction of material in discarded products that is reused so that their functional properties are maintained entirely or to a certain extent); Market Weight (W_m, which is based on a given application's market share in a certain market); and Economic Boundary Conditions (EBCs, which indicate whether the recycling process is feasible economically). The VDP combines these four indicators by means of following eq 2, which is proposed in this study as

$$\mathrm{VDP}_j = \sum_{i=1}^{n} (\mathrm{TSS} \times W_m \times \mathrm{EOL{-}RR} \times \mathrm{EBCs})_i \quad (2)$$

with VDP_j the Virgin Displacement Potential of a secondary material j (e.g., end-of-life PET) to substitute primary materials for a number of applications i (e.g., bottles, trays, fibers, etc.), where n is the upper bound of the summation (here the number of applications in which the secondary material can be used, e.g., bottles, trays, and fibers). A concrete example of applying eq 2 is provided in Table 1.

2.1.1. Technical Suitability for Substitution (TSS). TSS reflects the extent to which the technical properties of a secondary material j are suited for substitution of primary materials in a given application i, which is based on a set of properties. We link this indicator to the definition of substitutability that Vadenbo et al.[15] proposed, i.e., the ratio of a secondary material's end-use-specific functionality over the functionality of the potentially displaced alternative products. However, our frame is developed at the (sub)application level, e.g., beverage bottles, building sector piping, etc.

A TSS of zero indicates that the technical properties do not allow for any substitution of virgin material in that application, and a TSS of one indicates that virgin material can be fully substituted by a secondary material in that application. If blending the secondary material with virgin material would yield a blend with the required technical properties, a score between 0 and 1 could be provided based on the ratio of the amount of a secondary material that is used to the total amount of material needed to manufacture a given application in a certain market (i.e., the sum of primary and secondary materials).

A wide range of properties can be assessed, and the key properties are, to some extent, material- and application-dependent.[27] However, regarding the framework presented in this work, five aspects are distinguished in the assessment of technical properties that in general should be evaluated for a given secondary material, as presented in Figure 2, namely, the mechanical properties, processability, aesthetic properties,

Table 1. Calculations of the VDP of Different PET Recycling Pathways by Determining TSS, W_m, EOL-RR, and EBC[a]

recycling from		bottle								tray								fiber							
recycling path		mechanical				hydrolysis				mechanical				hydrolysis				mechanical				hydrolysis			
recycling to	market weight (%)	EOL-RR (%)	TSS	EBC	VDP (%)	EOL-RR (%)	TSS	EBC	VDP (%)	EOL-RR (%)	TSS	EBC	VDP (%)	EOL-RR (%)	TSS	EBC	VDP (%)	EOL-RR (%)	TSS	EBC	VDP (%)	EOL-RR (%)	TSS	EBC	VDP (%)
bottle	39	66	0.89	1	24	59	1	1	24	19	0	1	0	17	1	1	7	7	0	1	0	6	1	1	2
food tray	10	66	0.89	1	6	59	1	1	6	19	0	1	0	17	1	1	2	7	0	1	0	6	1	1	1
nonfood tray	1	66	0.89	1	1	59	1	1	1	19	0.8	1	0	17	1	1	0	7	0	1	0	6	1	1	0
fiber	44	66	0.89	1	28	59	1	1	28	19	0.8	1	7	17	1	1	8	7	0.89	1	3	6	1	1	3
sum	94	sum			59	sum			59	sum			7	sum			17	sum			3	sum			6

[a]The VDP is the sum of the substitution potential (SP) of each waste product (in the table indicated by the row "recycling from"). For mechanical recycling of bottles, the VDP is calculated using the following equation: (39% × 66% × 0.89 × 1)/94% + (10% × 66% × 0.89 × 1)/94% + (1% × 66% × 0.89 × 1)/94% + (44% × 66% × 0.89 × 1)/94% = 59%.

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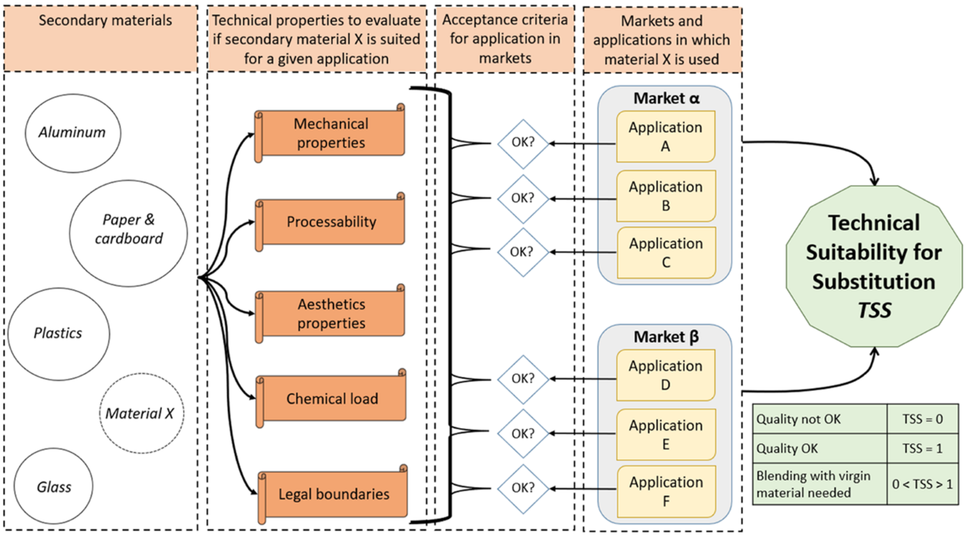

Figure 2. Theoretical framework for determining technical suitability for substitution (TSS).

chemical load, and legal boundaries. The requirements—together with their definitions and some illustrative aspects that influence these requirements for plastics, glass, paper and cardboard, and aluminum—are presented in Section S1 and Table S1, Supporting Information. Slight adaptations or additions might be needed in consultation with stakeholders about certain material groups, but this framework is meant to be followed across material groups. In some material groups, certain indicators might not be relevant (e.g., odor for metals), in which case, this indicator might be omitted from the assessment.

2.1.2. Market Weight (W_m). TSS does not implicitly indicate "how much" substitution is possible. The larger the market is covered by a secondary material, the better. For this purpose, W_m is incorporated, inspired by the work of Eriksen et al.[23] W_m represents the market share of a given application i (e.g., bottles) in the market of the corresponding material j (e.g., PET), as eq 3 proposed. Thus, W_m weighs TSS toward how important that substitution is in the total market on a mass basis.

$$W_{\mathrm{mi},j} = \frac{\text{total production of a specific application } i}{\text{total production of a material } j} \times 100\% \tag{3}$$

Ideally, the sum of the applications in which secondary materials can be used covers the size of the total market for that material. If this is not the case—and, thus, the end-use market in which secondary materials could be used is smaller—then virgin materials still are required.[28]

2.1.3. End-of-Life Recycling Rate (EOL-RR). A third indicator to consider in the VDP dimension is EOL-RR, which focuses on how efficient recycling industries and recycling pathways are, as it captures the amount of secondary material j recovered and recycled at end-of-life compared with overall waste quantities generated (see eq 4, adopted from 29).[29] Thus, it accounts for overall losses in recovery processes until the point of substitution.

$$\mathrm{EOL-RR} = \frac{m_{\text{secondary material } j \text{ functionally recycled}}}{m_{\text{generated waste of material } j}} \times 100\% \tag{4}$$

Applying the EOL-RR allows us to conform to recycling rate definitions, as the European Commission[30] proposed, thereby building on the United Nations Environment Program's status report on metals' recycling rates.[31] Creating recycling outputs in which the technical properties allow for use in high-end applications can affect, in some cases, the EOL-RR negatively and, thus, dissipative flows. In waste management, this is known as the quality−quantity trade-off.[32,33] Thus, more compensatory virgin material is needed to replace physical losses that occur in the recycling chain.

2.1.4. Economic Boundary Conditions (EBCs). EBCs implicitly incorporate an economic dimension into the VDP, which is needed because an input's suitability to produce secondary raw materials with adequate technical properties is dependent on the recycling plant's financial resources. Measures proposed to improve technical properties may impact processing costs, output revenues, and disposal costs that occur at a plant, which can affect the recycling pathway's industrial feasibility.[14] Recycling pathways need to meet an economic condition: The price of recyclates (which their technical properties influence) should cover the recycling pathway's costs. However, there also can be a "willingness to pay" (WTP) in a particular material's circular economy, which comes back, e.g., in EPR fees that producers pay at the end-of-life stage of their products brought to market. If recyclate and WTP revenue cannot cover recycling pathway costs, the pathway is not economically feasible.

In the current framework, the EBC assesses the recycling pathway's economic feasibility by assigning a score of zero to the EBC if the pathway incurs overly high costs to make it profitable, resulting in a VDP value of zero. Thus, if the revenue recyclates + WTP_j > cost of recycling chain, then the EBC = 1, and if the revenue recyclates + $\mathrm{WTP}_j \leq$ cost of recycling chain, then the EBC = 0.

2.2. In-Use Stocks Lifetime (IUSL). In a circular economy, waste disposal is replaced by strategies that aim to maintain and recover resources in production and consumption for as long as possible.[34] Material resources' inaccessibility is caused by anthropogenic compromising actions related to exploration, environmental dissipation, hibernation, and in-use occupation.[35] Moraga et al.[26] indicated that the concept of in-use occupation is of particular interest,

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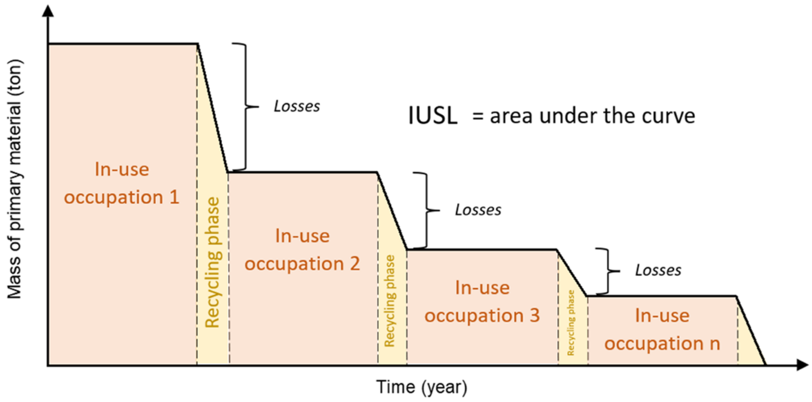

Figure 3. Area chart conceptualizing the occupation phases and the IUSL dimension used in quality of recycling framework, adopted from Moraga et al.[26]

as the purpose of any extracted resource is to remain in a useful state. The authors stated that the time dimension is a key parameter for the circular economy; however, this aspect often is disregarded in many circularity indicators. To account for this, an indicator was adopted from Moraga et al.[26]—the In-Use Stocks Lifetime (IUSL, similar to the long-term in-use occupation, as referred to by Moraga et al.[26])—which is defined as the mass of material kept in the material loop over time. Mathematically, this can be described through eq 5 (based on ref 26).

$$\mathrm{IUSL} = \int_{T_0}^{T_1} M(t)\,\mathrm{d}t \tag{5}$$

in which $M(t)$ is the function that describes the relationship between time and a given material's mass, and T_0 and T_1 denote the upper and lower bound constants of integration, respectively (T_0 equals zero years, and T_1 is viewed as the number of years it takes to have a residual mass of the material of less than 1 mass %). By plotting the mass of material as a function of time, the IUSL is represented visually by the area under the curve (see Figure 3), which can be calculated using statistical analysis software (see Figure S1). In the present study, data and graph processing, including integration of the IUSL, were performed using OriginPro 2016 software (OriginLab). However, care should be taken when using this indicator to compare sectors that have inherent shorter use with sectors that have inherent longer use (e.g., the building and construction sector). Proper use of this indicator also can support policy decisions related to other circular economy strategies, e.g., reused or refurbished models, or increased product durability. Furthermore, it could provide an indication of the secondary resources effect that one sector produced being transferred to another sector.

2.3. Environmental Impact (EI). The third dimension of the proposed recycling framework is the environmental impact of the recycling process. The recycling chain should be designed to ensure minimal negative consequences on public health and the environment; therefore, in the current framework, the recycling chain's environmental impact should be minimized and evaluated through environmental footprint calculations to guide the waste management sector and develop meaningful policies.

For this purpose, one can build on recent standardization works, notably the Product Environmental Footprint (PEF)[36] proposed by the European Commission, as common ways of measuring a product's potential life cycle environmental impact. However, considering that we are examining waste treatment technologies or pathways' environmental performance (e.g., recycling), and not products specifically, it has been suggested to follow the principles described by the ISO 14040:2006 framework for LCA, or the extensive literature on waste-oriented LCA.[37−39] As many standardization efforts have been performed and remain ongoing, also related to circular economy "measurements", more elaboration on this indicator lies beyond this paper's scope. In the examples presented in Section 3, we limited ourselves to the Carbon Footprint impact category for the sake of simplicity.

2.4. Calculating Distance-to-Target. To determine the recycling pathway with the highest quality of recycling for a certain product (e.g., a PET bottle), the VDP, IUSL, and EI are included as separated axes in a three-dimensional (3D) scatter plot that comprises each recycling pathway as an individual coordinate. Graedel et al.[40,41] presented and discussed a similar approach, in which certain parameters are plotted in a 3D plot to quantify certain metals and metalloids' degree of criticality. The authors stated that the 3D framework's main advantage is that it provides user flexibility. Moreover, specific indicators can be deleted or added as desired and weighted as the user deems appropriate.[40]

In the present study's framework, we (initially) give equal weight to each of the three dimensions to determine quality of recycling. Thus, a normalization is applied, using eq 6, to avoid one of the three dimensions making a more significant impact due to the difference in scale, resulting in a value between zero and one for each dimension.

$$r_{\mathrm{normalized}} = \frac{r - r_{\min}}{r_{\max} - r_{\min}} \tag{6}$$

Based on the recycling pathways' Cartesian coordinates included in the 3D graph, the Euclidean distance between each point of the analyzed recycling pathways (as standardized values) and the optimal/targeted quality of recycling are calculated using eq 7, with d the distance-to-target, r the coordinates that represent a given recycling pathway, and o the coordinates of the target quality of recycling.

$$d(r, o) = \sqrt{(r_{\mathrm{VDP}} - o_{\mathrm{VDP}})^2 + (r_{\mathrm{IUSL}} - o_{\mathrm{IUSL}})^2 + (r_{\mathrm{EI}} - o_{\mathrm{EI}})^2} \tag{7}$$

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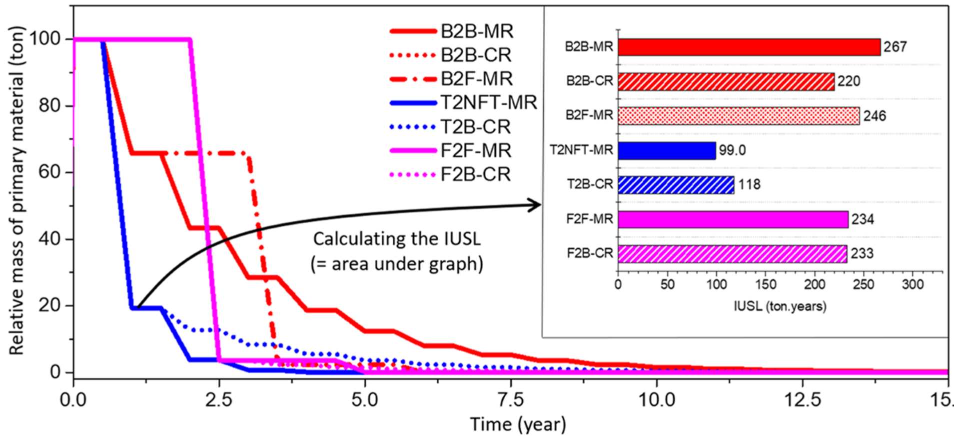


Figure 4. Analyzed PET recycling pathways' IUSLs, visualized by plotting the mass of raw material (ton) as a function of time (year).

The closer the recycling pathway is located to the "optimal quality of recycling point", the lower the distance-to-target and, thus, the better the quality of recycling.

3. APPLICATION OF THE FRAMEWORK

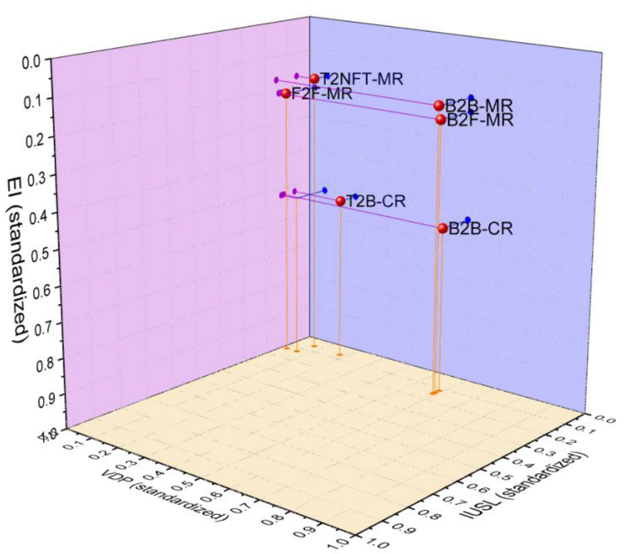
3.1. PET Recycling. To demonstrate the framework's functionality to quantify quality of recycling, an initial example is elaborated regarding PET recycling. Several recycling technologies exist for PET. Conventional extrusion-based mechanical recycling is implemented most widely. An alternative to mechanical recycling of PET is chemical recycling, which can be conducted through different pathways—including hydrolysis, glycolysis, and methanolysis—to depolymerize PET into its monomers. These monomers can be purified, e.g., by distillation or crystallization, then reintroduced into virgin polyesters' polymerization processes.[42] Furthermore, PET waste can have different origins and destinations, including bottles, trays, films, and textiles as their main markets.[43] Data on PET market share are adopted from refs 43−45 and are valid for the EU28+2 (defined as the European Union with Norway and Switzerland). In the current assessment, which excluded the other 6% of diverse applications of PET, it is assumed that bottle recyclates from mechanical recycling can be used in all included applications (i.e., bottles, trays, and fibers). As for mechanical recycling of PET trays, several barriers—e.g., the complex composition that includes the presence of multilayers, inks, glues, absorbent, pads, etc.—prevent full circularity in this product application.[44,46] Therefore, it is assumed in the current analysis that PET trays can be recycled mechanically only into nonfood PET trays.[44] Textile fibers generally can be recycled mechanically (or reused) in textile applications, but not into bottles or trays to date. In the case of chemical recycling, it is assumed that the monomers have sufficiently qualitative technical properties, i.e., they can be repolymerized to serve all market applications regardless of the waste's origin.

As a first step, the framework's first dimension, the VDP, is calculated for recycling PET from bottles, trays, and fibers as to-be-recycled material *j* in product *i*. TSS is determined first here based on the acceptance criteria that are valid for the applications in which the secondary materials will be used. A detailed description of the determination of TSS can be found in Section S2, Supporting Information. Following the TSS, the market weight and EOL-RR are determined based on previous studies.[43−45,47,48] A detailed overview of the data used and corresponding references related to market weight and EOL-RR can be found in Tables S3 and S4, respectively, which consider West-European collection systems' efficiencies, the pretreatment chain (including sorting, washing, float-sink separation, and drying), and the effective recycling process itself. For each of the performed steps, physical losses occur, resulting in an overall EOL-RR of 66% for PET bottles and 19% for PET trays when they are recycled mechanically. However, textiles are only recycled/reused to a limited extent, at a global EOL-RR of 6%, which mostly concerns applications, e.g., insulation material or mattress stuffing, all of which are currently difficult to recapture and, therefore, likely constitute final use. The EBC always has been viewed as one, i.e., all chains are assumed to be economically feasible. The calculations of the VDP of different PET recycling pathways by determining the TSS, Wm, EOL-RR, and EBC can be found in Table 1.

As reported in Table 1, both the mechanical and chemical recycling pathways for bottles have the highest VDP, at 59%, i.e., 1 kg of recycled PET bottle waste has the potential to substitute (or supply) 0.59 kg of virgin-like material to the PET applications market (here comprising bottles, trays, and fibers). Chemically recycled trays and fibers have a higher TSS compared with mechanically recycled trays and fibers, resulting in a higher VDP for these applications.

As a next step, the second dimension of the recycling framework, the IUSL, is determined for seven scenarios: (1) mechanical recycling of PET bottles into PET bottles (B2B-MR); (2) chemical recycling of PET bottles into PET bottles (B2B-CR); (3) mechanical recycling of PET bottles into PET fibers (B2F-MR); (4) mechanical recycling of PET trays into nonfood PET trays (T2NFT-MR); (5) chemical recycling of PET trays into PET bottles (T2B-CR); (6) mechanical recycling of PET fibers into PET fibers (F2F-MR); and (7) chemical recycling of PET fibers into PET bottles (F2B-CR). In addition to the EOL-RR, the various products' lifespans are needed to calculate the IUSL. Based on the literature, PET bottle and PET tray lifespans are assumed to be 0.5 years, and textile applications, 2 years (see Table S5).[49,50] Figure 4 presents the IUSLs of the investigated PET recycling scenarios by plotting the relative mass of the material as a function of time. It can be observed that the type of recycling and the application in which the material is recycled affect the area under the curves (i.e., the IUSL). For instance, the IUSL corresponds to 267 ton-years for the B2B-MR pathway,

(A)



(B)

Recycling pathway	IUSL (standardized)	VDP (standardized)	EI (standardized)	Distance-to-target
B2B-MR	0.15	0.59	0.17	0.96
B2B-CR	0.12	0.59	0.52	1.10
B2F-MR	0.14	0.59	0.21	0.98
T2NFT-MR	0.06	0.07	0.17	1.34
T2B-CR	0.07	0.18	0.52	1.35
F2F-MR	0.13	0.02	0.21	1.33
F2B-CR	0.13	0.06	0.52	1.38

Figure 5. Overview of the framework applied to the seven analyzed PET recycling scenarios. (A) 3D graph that indicated the analyzed scenarios. (B) Distance-to-target calculated to the "point of highest quality of recycling." B2B-MR: mechanical recycling of PET bottles into PET bottles, B2B-CR: chemical recycling of PET bottles into PET bottles, B2F-MR: mechanical recycling of PET bottles into PET fibers, T2NFT: mechanical recycling of PET tray into a nonfood PET tray, T2B-CR: chemical recycling of PET trays into PET bottles, F2F-MR: mechanical recycling of PET fibers into PET fibers, F2B-CR: chemical recycling of PET fiber into PET bottles.

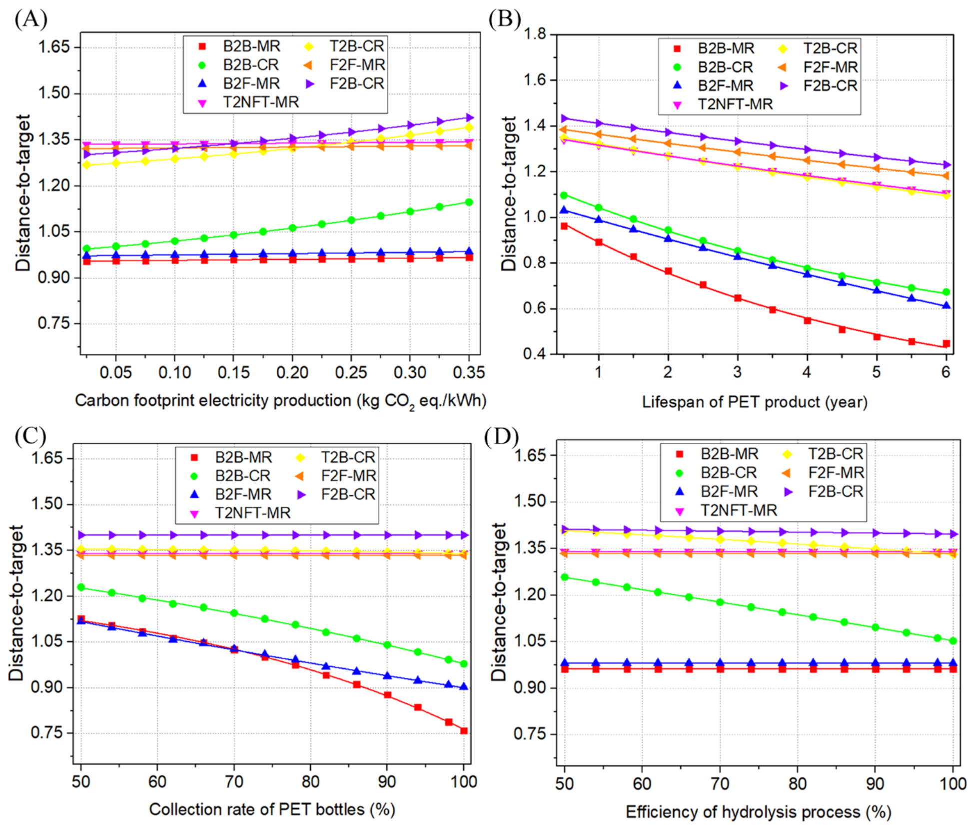


Figure 6. Impact on quality of recycling expressed by the distance-to-target of a change in (A) the carbon footprint of electricity production, (B) PET products' life span, (C) the collection rate for PET bottles, and (D) the efficiency of the PET hydrolysis process.

whereas for the B2F-MR pathway, the IUSL is only 246 ton-years. Thus, by recycling PET bottles again into new bottles, the IUSL is higher compared with recycling PET bottles into textile applications. For PET trays, chemical recycling results in a higher IUSL (118 ton-years) than mechanical recycling (99 ton-years).

The third dimension of the framework concerns EI calculations. For the illustrative example in this study, the EI is based on the literature,[51] in which a "cradle-to-gate" LCA of

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two PET bottle recycling pathways was carried out, namely, the production of 1 kg of post-consumer mechanically recycled PET through a bottle-to-bottle recycling process and the production of 1 kg of recycled PET fiber through a bottle-to-fiber recycling process. For the PET fiber-to-fiber recycling process, data were adopted from ref 51. For the chemical recycling of PET packaging, the carbon footprint analysis of Ügdüler et al.[42] was adopted. An overview of the carbon footprint and references used in this case study can be found in Table S6.

Prior to calculating the distance-to-target score, the minimum and maximum values for each dimension are defined—and needed for normalization. In the current recycling analysis, we apply the minimum and maximum values, as depicted in Table S7. Recycling of materials ideally should create environmental benefits; therefore, the maximum value in terms of environmental impact is viewed as incineration of PET, followed by the production of virgin PET to replace the incinerated PET, resulting in a carbon footprint of 5.7 kg CO_2-equiv/kg waste, whereas for minimum value, a carbon footprint of 0.0 kg CO_2-equiv/kg waste is selected, which should be viewed as an ideal target.

The distance-to-target from each of the seven recycling pathways is calculated and visualized in Figure 5. Notably, for the recycling of PET bottles, mechanical recycling has the lowest distance-to-target (0.96) and, thus, the highest quality of recycling compared with chemical recycling into bottles (1.10). For PET trays, mechanical recycling from tray into nonfood tray and chemical recycling from tray into bottle resulted in an almost equal distance-to-target of 1.34 and 1.35, respectively. Thus, in terms of quality of recycling, both chemical and mechanical recycling of PET trays might be a good option. For PET fibers, the distance-to-target was slightly lower with mechanical recycling (1.33) than with chemical recycling (1.38).

3.2. Potential Prospective Quality of Recycling Scenarios. Several factors can influence distance-to-target, including changes in EPR schemes, electricity production, waste management technologies, etc. Thus, good data collection is key in assessing quality of recycling, which might involve certain assumptions. In this light, sensitivity analysis can help determine how different values of a certain variable (e.g., collection rate or product lifespan) affect quality of recycling. Moreover, by varying a certain variable's values, potential future changes' impact can be modeled and assessed. Therefore, we have simulated the impact of varying the carbon footprint of electricity production, PET products' lifespan, PET bottles' collection rate, and the efficiency of the PET hydrolysis process. The results are presented in Figure 6. It can be seen that a decrease in the carbon footprint of electricity production makes a more pronounced impact on chemical recycling than on mechanical recycling. However, even with increased quality of recycling due to the expected improved carbon footprint, mechanical recycling remains the preferred recycling pathway for PET bottles. However, for PET trays, the threshold at which chemical recycling becomes more favorable than mechanical recycling is situated around 0.24 kg CO_2-equiv/kWh. In the baseline scenario, we used a value of 0.26 CO_2-equiv/kWh based on the process used in the ecoinvent database (Tuchschmid, M., Frischknecht, R., electricity, production mix BE, ecoinvent database version 2.2). However, the European Environment Agency expects greenhouse gas emissions from electricity generation to decrease to around 0.115 kg CO_2-equiv/kWh by 2030 in Europe, which would influence distance-to-target of chemical recycling of PET trays positively, rendering this recycling method more favorable than mechanical recycling of PET trays, considering that mechanical recycling only can recycle PET trays into nonfood PET trays, as assumed in the baseline scenario.

As for PET products' life spans, it can be seen that distance-to-target decreases for each recycling pathway with an increase in lifespan. For instance, when textiles' life span increases from 1 to 7 years, the distance-to-target will decrease from 1.37 to 1.16 with mechanical recycling of PET fibers into fibers, and from 1.42 to 1.23 with chemical recycling of PET fibers into bottles. One of the points related to the IUSL that should be monitored is the material's "hibernation phase", During hibernation, products are not in use, but are awaiting end-of-life treatment.[26] Examples of the hibernation phase include a PET bottle between discard (into a trash bin) and collection for either final disposal or recycling (in a new supply phase), or a PET sweater between the last time it was worn and the collection phase. Future research ideally should focus on how to calculate the useful state of different types of products to calculate IUSL values more accurately.

Figure 6C indicates that increasing the collection rate of PET bottles positively impacts distance-to-target for the recycling pathways B2B-MR (from 1.13 to 0.76), B2B-CR (from 1.23 to 0.98), and B2F-MR (from 1.12 to 0.90). Thus, collecting more PET bottles, particularly the mechanical recycling of bottles into bottles, becomes more favorable than the other studied recycling pathways. Increasing the efficiency of chemical recycling processes strongly impacts the chemical recycling of PET bottles into bottles, as Figure 6D indicates. However, even with an assumed efficiency of 100%, mechanical recycling of PET bottles still has a lower distance-to-target.

3.3. Glass Recycling. As a second example, quality of recycling for various glass products (i.e., bottle and container glass, flat glass, mineral wool, and domestic glass) is calculated. A full description of the calculations and visualization of the results are presented in Section S3, Supporting Information. However, in this section, a comprehensive summary of the approach and results is provided. First, the VDP is calculated for each of the analyzed glass products. The highest VDP, at 61%, is achieved by recycling bottles and containers collected via a deposit−refund system, followed by recycling of domestic glass (VDP of 33%). As a next step, the IUSLs are determined for five scenarios: (1) re-melting bottle and container glass into bottle and container glass (BC2BC-R); (2) washing of bottle and container glass collected through a deposit−refund system and reusing it as bottle and container glass (BC2BC-W); (3) re-melting domestic glass into domestic glass (D2D); (4) re-melting flat glass into flat glass (F2F); and (5) re-melting flat glass into mineral wool (F2M). The results indicate that the application in which the material is recycled significantly impacts the IUSL—even more than for PET recycling—due to the more pronounced differences in various glass applications' life spans, e.g., bottle and container re-melting results in an IUSL of 345 ton-years, whereas processing glass in vehicles and buildings as flat glass has an IUSL of 2520 ton-years. The third dimension of the quality framework concerns the EI calculations, which were adopted from the ecoinvent database (Hischier R., glass cullets, sorted, at sorting plant, ecoinvent database version 2.2), and from Tua et al.[52]

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Based on the three dimensions, distance-to-target is calculated using eq 7, indicating that for bottle and container glass, the highest distance-to-target (1.24) and, thus, the lowest quality of recycling are achieved by re-melting, while the lowest distance-to-target (1.05) and, thus, the highest quality of recycling are achieved for bottles and containers collected via a deposit−refund system. Comparing recycling of flat glass into flat glass (distance-to-target: 1.08) with the recycling of flat glass into mineral wool (distance-to-target: 1.04) demonstrates that the latter recycling pathway is the most favorable option and can be attributed to the higher VDP of mineral wool compared with that of flat glass.

4. DISCUSSION AND OUTLOOK

4.1. Novelty of the Framework. Recycling is key for improving resource efficiency and is well embedded in, e.g., the Circular Economy Action Plan of Europe. However, definitions of quality of recycling are scarce, and a widely supported framework to quantify quality of recycling has not been established yet, hampering policymaking. In this study, an operational framework is described and demonstrated in two case studies: PET and glass recycling. Making a framework operational to assess quality of recycling is a crucial step forward for industry, policymakers, and researchers to steer development in the circular economy.

Previous efforts to quantify quality of recycling provided either general qualitative definitions or strategies reflecting quality of recycling, or focused on single issues within the broader field of quality. However, the present study goes beyond these efforts by addressing quality of recycling within a comprehensive framework, making all aspects related to quality of recycling quantifiable and aggregable in a single-score value. This is encouraged by industry and policymakers to allow for the assessment of different recycling strategies in an objective and holistic way.[7] The framework includes three relevant recycling dimensions—VDP, IUSL, and EI—which consider not only technical properties related to virgin displacement in applications (e.g., mechanical properties, aesthetics, and processability) but also the time dimension of maintaining materials in the economy, as well as the environmental impact of such processes. Furthermore, dimensions are integrated with a distance-to-target approach, which is, to the best of the authors' knowledge, a holistic quality quantification approach that has not been presented yet at the same granular level as in this study.

4.2. Value for Policymaking and the EU Green Deal's Objective. The European Commission has adopted a set of proposals to make the EU's climate, energy, transport, and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared with 1990 levels.[53] For plastics, the EU Green Deal specifically aims to achieve the following three objectives: (1) prevent the generation of packaging waste; (2) reduce the need for primary natural resources by creating a well-functioning market for secondary raw materials, including increased use of recycled plastics in packaging through mandatory targets; and (3) boost "high-quality" recycling by making all packaging on the EU market recyclable in an economically viable way by 2030. Focusing on European acquis, a clear definition of quality of recycling is missing, even though the term "high-quality recycling" often is mentioned. Likewise, quantitative methods provide value to quality of recycling. Legislative efforts historically have focused on increasing collection and recycling rates, i.e., the quantity of waste material recovered. Moreover, recycling metrics, e.g., recycling targets, generally are defined for large material groups (e.g., plastics, glass, etc.), whereas further specification of recycling metrics at the level of specific material subgroups (e.g., PET bottles, flat glass, etc.) is advised in our framework, which would allow for a more detailed and technically valid comparison in terms of quality of recycling. However, recovering material in large quantities is not sufficient to close material loops, as the material might not necessarily have the adequate technical properties to replace primary (virgin) materials, which is the goal of circular economy-oriented recycling. However, suboptimal market applications are often an inevitable consequence of low-quality recycling, incurring virgin material demand for given market applications that require highly qualitative technical properties. The main value of developing an improved definition of quality of recycling, as well as methods to quantify it, would move beyond quantity-based recycling rates and similar indicators, thereby providing a sound basis on which to support recycling pathways and technologies that elicit the most value in terms of the circular economy. The developed framework's main advantage is the ability to quantify and compare quality of recycling for different options based on a scoring system(s). This is required due to policymakers' need to steer recycling developments by instituting certain economical instruments or laws that promote recycling pathways to ensure the highest quality of recycling. For instance, the "plastic tax," which obligates EU Member States to contribute 0.80 EUR per kilogram of nonrecycled plastic packaging waste to the EU, could be employed to stimulate (financially) recycling pathways that have a high quality of recycling.

4.3. Functionality across Different Material Types. Performing two case studies on different materials (PET and glass recycling) illustrated the framework's functionality. For PET recycling, seven recycling pathways have been evaluated: (1) mechanical recycling of PET bottles into PET bottles; (2) chemical recycling of PET bottles into PET bottles; (3) mechanical recycling of PET bottles into PET fibers; (4) mechanical recycling of PET trays into nonfood PET trays; (5) chemical recycling of PET trays into PET bottles; (6) mechanical recycling of PET fibers into PET fibers; and (7) chemical recycling of PET fibers into PET bottles. The distance-to-target from each of the seven recycling pathways is calculated by applying the developed framework. The results indicate that for the recycling of PET bottles, mechanical recycling has the lowest distance-to-target (0.96) and, thus, the highest quality of recycling compared with chemical recycling (1.10). For PET trays, mechanical recycling from trays into nonfood trays results in a distance-to-target of 1.34, whereas chemical recycling results in a distance-to-target of 1.35. Thus, both recycling pathways score very similar in terms of quality. For PET fibers, the distance-to-target was slightly higher with chemical recycling (1.38) than with mechanical recycling (1.33). However, in anticipating a reduction in carbon footprint from electricity production, the gap in the distance-to-target of both recycling pathways might narrow in the future, as demonstrated in this study through a sensitivity analysis.

For the glass recycling case, five recycling pathways were compared: (1) re-melting bottle and container glass into bottle and container glass; (2) washing of bottle and container glass collected through a deposit−refund system and reusing it as bottle and container glass; (3) re-melting domestic glass into domestic glass; (4) re-melting flat glass into flat glass; and (5) re-melting flat glass into mineral wool. Applying the framework on these pathways demonstrates that for bottle and container glass, the highest distance-to-target (1.24) and, thus, the lowest quality of recycling are achieved by re-melting, while the lowest distance-to-target (1.05) and, thus, the highest quality of recycling are achieved through the material collected via a deposit−refund system. For flat glass, the lowest distance-to-target (1.11) is measured for recycling the glass into mineral wool.

In future research, the presented framework could be applied in more detail to single materials. One example could be the recycling of metals, such as aluminum. Depending on factors such as origin, collection method, and contamination level, lower or higher value markets can be entered (i.e., selling wrought rather than casting alloys), which would in turn affect the quality of recycling.[54]

4.4. Limitations and Future Work. This study should be viewed as a stepping stone for advancing the understanding of quality of recycling, with the goal of supporting recycling that maximizes material recovery rates while minimizing primary resource consumption and emissions. The framework can be operated across different sectors and can strengthen conclusions in a decision-making context. However, applying the framework for a certain waste material does not imply that other substitution options, which are not secondary materials (e.g., fuel and base chemicals[55]), cannot be used to substitute virgin materials. Furthermore, the framework also requires more elaboration with respect to (1) estimation of TSS based on industrial experience, (2) developing IUSL scenarios, (3) application to industrial case studies, and (4) setting boundary conditions further on how to apply the framework in a proper way. With respect to (1), one may want to launch studies in which the recycling industry and manufacturers are involved to improve knowledge about TSS factors based on the properties listed in Table S1 (or those that industry views as the "relevant ones" for each material-application combination). With respect to (2), a similar study may be launched in which other types of expertise or tools may be used to estimate lifetimes for a range of products. With respect to (3), the application to a set of real case studies should be done together with stakeholders, e.g., the recycling industry and EPR organizations, to test the framework on a variety of recycling pathways. These points will deliver experience to define boundary conditions further on how to apply this framework with respect to (4). Furthermore, more work is envisaged for the environmental impact dimension, notably how to aggregate the multiple environmental indicators obtained in an LCA.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c03023.

Illustrative calculation of the IUSL (Figure S1), technical properties that should be evaluated (Section S1), main requirements for the technical properties (Table S1), determination of the TSS for the PET example (Section S2), TSS determination used in the PET example (Table S2), market weights used in the PET example (Table S3), EOL-RR used in the PET example (Table S4), life span used in the PET example (Table S5), environmental impact used in the PET example (Table S6), values used to standardize the three dimensions in the PET example (Table S7), glass recycling example (Section S3), market weights used in the glass example (Table S8), TSS calculations used in the glass example (Table S9), EOL-RR used in the glass example (Table S10), calculations of the VDP of different glass recycling pathways (Table S11), life span used in the glass example (Table S12), environmental impact used in the glass example (Table S13), and values used to standardize the three dimensions in the glass recycling example (Table S14) (PDF)

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Notes

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■ REFERENCES

(1) EPA. Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks, 2023. https://nepis.epa.gov/Exe/ZyPDF.cgi/60000AVO.PDF?Dockey=60000AVO.PDF (accessed June 04, 2023).
(2) Gaeta, G. L.; Ghinoi, S.; Silvestri, F.; Tassinari, M. Innovation in the Solid Waste Management Industry: Integrating Neoclassical and Complexity Theory Perspectives. *Waste Manage.* **2021**, *120*, 50−58.
(3) Ragaert, K.; Delva, L.; Van Geem, K. Mechanical and Chemical Recycling of Solid Plastic Waste. *Waste Manage.* **2017**, *69*, 24−58.
(4) Das, S.; Lee, S.-H.; Kumar, P.; Kim, K.-H.; Lee, S. S.; Bhattacharya, S. S. Solid Waste Management: Scope and the Challenge of Sustainability. *J. Cleaner Prod.* **2019**, *228*, 658−678.
(5) Zeng, X.; Ogunseitan, O. A.; Nakamura, S.; Suh, S.; Kral, U.; Li, J.; Geng, Y. Reshaping Global Policies for Circular Economy. *Circ. Econ.* **2022**, *1*, No. 100003.
(6) Pinyol Alberich, J.; Pansera, M.; Hartley, S. Understanding the EU's Circular Economy Policies Through Futures of Circularity. *J. Cleaner Prod.* **2023**, *385*, No. 135723.
(7) Tonini, D.; Albizzati, P. F.; Caro, D.; De Meester, S.; Garbarino, E.; Blengini, G. A. Quality of Recycling: Urgent and Undefined. *Waste Manage.* **2022**, *146*, 11−19.
(8) Ciacci, L.; Reck, B. K.; Nassar, N. T.; Graedel, T. E. Lost by Design. *Environ. Sci. Technol.* **2015**, *49*, 9443−9451.
(9) Helbig, C.; Thorenz, A.; Tuma, A. Quantitative Assessment of Dissipative Losses of 18 Metals. *Resour., Conserv. Recycl.* **2020**, *153*, No. 104537.
(10) Beylot, A.; Ardente, F.; Sala, S.; Zampori, L. Mineral Resource Dissipation in Life Cycle Inventories. *Int. J. Life Cycle Assess.* **2021**, *26*, 497−510.
(11) Zeng, X.; Li, J. Emerging Anthropogenic Circularity Science: Principles, Practices, and Challenges. *iScience* **2021**, *24*, No. 102237.
(12) Nakamura, S.; Kondo, Y.; Kagawa, S.; Matsubae, K.; Nakajima, K.; Nagasaka, T. MaTrace: Tracing the Fate of Materials Over Time and Across Products in Open-Loop Recycling. *Environ. Sci. Technol.* **2014**, *48*, 7207−7214.
(13) Nakamura, S.; Kondo, Y.; Matsubae, K.; Nakajima, K.; Tasaki, T.; Nagasaka, T. Quality- and Dilution Losses in the Recycling of Ferrous Materials from End-of-Life Passenger Cars: Input-Output Analysis under Explicit Consideration of Scrap Quality. *Environ. Sci. Technol.* **2012**, *46*, 9266−9273.
(14) Grant, A.; Cordle, M.; Bridgwater, E. In *Quality of Recycling: Towards an Operational Definition*; Canfora, P.; Dri, M.; Antonopoulos, I.; Gaudillat, P., Eds.; Publications Office of the European Union, 2020.
(15) Vadenbo, C.; Hellweg, S.; Astrup, T. F. Let's Be Clear(Er) about Substitution: A Reporting Framework to Account for Product Displacement in Life Cycle Assessment. *J. Ind. Ecol.* **2017**, *21*, 1078−1089.
(16) Rigamonti, L.; Taelman, S. E.; Huysveld, S.; Sfez, S.; Ragaert, K.; Dewulf, J. A Step Forward in Quantifying the Substitutability of Secondary Materials in Waste Management Life Cycle Assessment Studies. *Waste Manage.* **2020**, *114*, 331−340.
(17) Zeng, X.; Li, J. Measuring the Recyclability of E-Waste: An Innovative Method and Its Implications. *J. Cleaner Prod.* **2016**, *131*, 156−162.
(18) Uekert, T.; Singh, A.; DesVeaux, J. S.; Ghosh, T.; Bhatt, A.; Yadav, G.; Afzal, S.; Walzberg, J.; Knauer, K. M.; Nicholson, S. R.; Beckham, G. T.; Carpenter, A. C. Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics. *ACS Sustainable Chem. Eng.* **2023**, *11*, 965−978.
(19) Ghosh, T.; Avery, G.; Bhatt, A.; Uekert, T.; Walzberg, J.; Carpenter, A. Towards a Circular Economy for PET Bottle Resin Using a System Dynamics Inspired Material Flow Model. *J. Cleaner Prod.* **2023**, *383*, No. 135208.
(20) Roosen, M.; Mys, N.; Kleinhans, K.; Lase, I. S.; Huysveld, S.; Brouwer, M.; Thoden van Velzen, E. U.; Van Geem, K. M.; Dewulf, J.; Ragaert, K.; Dumoulin, A.; de Meester, S. Expanding the Collection Portfolio of Plastic Packaging: Impact on Quantity and Quality of Sorted Plastic Waste Fractions. *Resour., Conserv. Recycl.* **2022**, *178*, No. 106025.
(21) Haupt, M.; Vadenbo, C.; Hellweg, S. Do We Have the Right Performance Indicators for the Circular Economy?: Insight into the Swiss Waste Management System. *J. Ind. Ecol.* **2017**, *21*, 615−627.
(22) Roithner, C.; Rechberger, H. Implementing the Dimension of Quality Into the Conventional Quantitative Definition of Recycling Rates. *Waste Manage.* **2020**, *105*, 586−593.
(23) Eriksen, M. K.; Damgaard, A.; Boldrin, A.; Astrup, T. F. Quality Assessment and Circularity Potential of Recovery Systems for Household Plastic Waste. *J. Ind. Ecol.* **2019**, *23*, 156−168.
(24) Fellner, J.; Lederer, J. Recycling Rate - The Only Practical Metric for a Circular Economy? *Waste Manage.* **2020**, *113*, 319−320.
(25) Jehanno, C.; Alty, J. W.; Roosen, M.; De Meester, S.; Dove, A. P.; Chen, E. Y.-X.; Leibfarth, F. A.; Sardon, H. Critical Advances and Future Opportunities in Upcycling Commodity Polymers. *Nature* **2022**, *603*, 803−814.
(26) Moraga, G.; Huysveld, S.; De Meester, S.; Dewulf, J. Development of Circularity Indicators Based on the In-Use Occupation of Materials. *J. Cleaner Prod.* **2021**, *279*, No. 123889.
(27) Demets, R.; Van Kets, K.; Huysveld, S.; Dewulf, J.; De Meester, S.; Ragaert, K. Addressing the Complex Challenge of Understanding and Quantifying Substitutability for Recycled Plastics. *Resour., Conserv. Recycl.* **2021**, *174*, No. 105826.
(28) Andreasi Bassi, S.; Tonini, D.; Ekvall, T.; Astrup, T. F. A Life Cycle Assessment Framework for Large-Scale Changes in Material Circularity. *Waste Manage.* **2021**, *135*, 360−371.
(29) Talens Peiró, L.; Nuss, P.; Mathieux, F.; Blengini, G. *Towards Recycling Indicators Based on EU Flows and Raw Materials System Analysis Data*; Publications Office of the European Union: Luxembourg, 2018.
(30) EC—European Commission. *Towards Recycling Indicators Based on EU Flows and Raw Materials System Analysis Data: Supporting the EU-28 Raw Materials and Circular Economy Policies through RMIS*; Publications Office of the European Union, 2018.
(31) Graedel, T. E.; Allwood, J.; Birat, J.-P.; Reck, B. K.; Sibley, S. F.; Sonnemann, G.; Buchert, M.; Hagelüken, C. *UNEP Recycling Rates of Metals—A Status Report, A Report of the Working Group on the Global Metal Flows to UNEP's International Resource Panel* UNEP DTIE, Sustainable Consumption and Production Branch: Paris, 2011.
(32) Brouwer, M.; Picuno, C.; Thoden van Velzen, E. U.; Kuchta, K.; De Meester, S.; Ragaert, K. The Impact of Collection Portfolio Expansion on Key Performance Indicators of the Dutch Recycling System for Post-Consumer Plastic Packaging Waste: A Comparison between Between 2014 and 2017. *Waste Manage.* **2019**, *100*, 112−121.
(33) Hahladakis, J. N.; Iacovidou, E. An Overview of the Challenges and Trade-Offs in Closing the Loop of Post-Consumer Plastic Waste (PCPW): Focus on Recycling. *J. Hazard. Mater.* **2019**, *380*, No. 120887.
(34) Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the Circular Economy: An Analysis of 114 Definitions. *Resour., Conserv. Recycl.* **2017**, *127*, 221−232.
(35) Moraga, G.; Huysveld, S.; de Meester, S.; Dewulf, J. Towards a Circularity Indicator to Assess Products' Materials and Lifetime: In-Use Occupation. *Procedia CIRP* **2020**, *90*, 10−13.
(36) European Commission Joint Research Centre. *EC-JRC Product Environmental Footprint (PEF) Guide*; European Commission Joint Research Centre, 2012; p 154.

(37) Huysveld, S.; Ragaert, K.; Demets, R.; Nhu, T. T.; Civancik-Uslu, D.; Kusenberg, M.; Van Geem, K. M.; De Meester, S.; Dewulf, J. Technical and Market Substitutability of Recycled Materials: Calculating the Environmental Benefits of Mechanical and Chemical Recycling of Plastic Packaging Waste. *Waste Manage.* **2022**, *152*, 69−79.
(38) Christensen, T. H.; Damgaard, A.; Levis, J.; Zhao, Y.; Björklund, A.; Arena, U.; Barlaz, M. A.; Starostina, V.; Boldrin, A.; Astrup, T. F.; Bisinella, V. Application of LCA Modelling in Integrated Waste Management. *Waste Manage.* **2020**, *118*, 313−322.
(39) Khoo, H. H. LCA of Plastic Waste Recovery Into Recycled Materials, Energy, and Fuels in Singapore. *Resour., Conserv. Recycl.* **2019**, *145*, 67−77.
(40) Graedel, T. E.; Barr, R.; Chandler, C.; Chase, T.; Choi, J.; Christoffersen, L.; Friedlander, E.; Henly, C.; Jun, C.; Nassar, N. T.; Schechner, D.; Warren, S.; Yang, M.; Zhu, C. Methodology of Metal Criticality Determination. *Environ. Sci. Technol.* **2012**, *46*, 1063−1070.
(41) Graedel, T. E.; Harper, E.; Nassar, N.; Nuss, P.; Reck, B. Criticality of Metals and Metalloids. *Proc. Natl. Acad. Sci. U.S.A.* **2015**, *112*, 4257.
(42) Ügdüler, S.; Van Geem, K. M.; Denolf, R.; Roosen, M.; Mys, N.; Ragaert, K.; De Meester, S. Towards Closed-Loop Recycling of Multilayer and Coloured PET Plastic Waste by Alkaline Hydrolysis. *Green Chem.* **2020**, *22*, 5376−5394.
(43) Kawecki, D.; Scheeder, P. R. W.; Nowack, B. Probabilistic Material Flow Analysis of Seven Commodity Plastics in Europe. *Environ. Sci. Technol.* **2018**, *52*, 9874−9888.
(44) Eunomia. *PET Market in Europe: State of Play 2022*; Eunomia, 2022.
(45) Eriksen, M. K.; Astrup, T. F. Characterisation of Source-Separated, Rigid Plastic Waste and Evaluation of Recycling Initiatives: Effects of Product Design and Source-Separation System. *Waste Manage.* **2019**, *87*, 161−172.
(46) Delva, L.; Ragaert, K.; Kuzmanovic, M.; Demets, R.; Hubo, S.; Mys, N.; De Meester, N. *Mechanical Recycling for Dummies*; Capture (Belgium), 2017.
(47) Eriksen, M. K.; Pivnenko, K.; Faraca, G.; Boldrin, A.; Astrup, T. F. Dynamic Material Flow Analysis of PET, PE, and PP Flows in Europe: Evaluation of the Potential for Circular Economy. *Environ. Sci. Technol.* **2020**, *54*, 16166−16175.
(48) Antonopoulos, I.; Faraca, G.; Tonini, D. Recycling of Post-Consumer Plastic Packaging Waste in the EU: Recovery Rates, Material Flows, and Barriers. *Waste Manage.* **2021**, *126*, 694−705.
(49) Geyer, R.; Jambeck, J. R.; Law, K. L. Production, Use, and Fate of All Plastics Ever Made. *Sci. Adv.* **2017**, *3*, No. e1700782.
(50) Henry, B. K.; Russell, S. J.; Ledgard, S. F.; Gollnow, S.; Wiedemann, S. G.; Nebel, B.; Maslen, D.; Swan, P. 10—LCA of Wool Textiles and Clothing. In Woodhead Publishing Series in Textiles. In *Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing*; Woodhead Publishing, 2015; pp 217−254.
(51) Gileno, L. A.; Turci, L. F. R. Life Cycle Assessment for PET-Bottle Recycling in Brazil: B2B and B2F Routes. *Cleaner Environ. Syst.* **2021**, *3*, No. 100057.
(52) Tua, C.; Grosso, M.; Rigamonti, L. Reusing Glass Bottles in Italy: A Life Cycle Assessment Evaluation. *Procedia CIRP* **2020**, *90*, 192−197.
(53) European Commission. A European Green Deal, 2023. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed June 06, 2023).
(54) Zhu, Y.; Chappuis, L. B.; De Kleine, R.; Kim, H. C.; Wallington, T. J.; Luckey, G.; Cooper, D. R. The Coming Wave of Aluminum Sheet Scrap from Vehicle Recycling in the United States. *Resour., Conserv. Recycl.* **2021**, *164*, No. 105208.
(55) Lase, I. S.; Tonini, D.; Caro, D.; Albizzati, P. F.; Cristóbal, J.; Roosen, M.; Kusenberg, M.; Ragaert, K.; Van Geem, K. M.; Dewulf, J.; De Meester, S. How Much Can Chemical Recycling Contribute to Plastic Waste Recycling in Europe? An Assessment Using Material Flow Analysis Modeling. *Resour., Conserv. Recycl.* **2023**, *192*, No. 106916.

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