Assessing scaling effects of circular economy strategies: A case study on plastic bottle closed-loop recycling in the USA PET market

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Abstract

The Circular Economy (CE) movement is inspiring new governmental policies along with company strategies. This led to the emergence of a plethora of indicators to quantify the "circularity" of individual companies or products. Approaches behind these indicators builds mainly on two implicit assumptions. The first is that closing material loops at product level leads to improvements in material efficiency for the economy as a whole. The second assumption is that maximizing material circularity contributes to mitigate environmental impacts. We test these two assumptions at different scales with a case study on the circularity of PET in the USA market. The Material Circularity Indicator (MCI) reveals that closing the material loops at the product level increases material circularity in one brand and in the USA plastic bottle market but not in the USA PET market as a whole. Life Cycle Assessment (LCA) results reveal that increasing closed loop recycling of PET bottles is environmentally beneficial from product-level assessment scope. When expanding the scope to the whole PET market, recycling PET into film, fiber and sheet industrial sectors results being more material efficient and environmental preferable, unless the postconsumer reclamation rate is significantly improved. Thus, we demonstrate that adopting a systemic approach for CE assessment is essential ; instead of looking at one particular product and seeking the best circular case with respect to a specific material content, we suggest to looking at the whole set of products served by the specific material, and to seek the best material market-wide circular case.

1. Introduction

The idea that we should strive to develop a Circular Economy (CE) – which would notably increase the recycling of materials within the economy to fulfill human needs with only minimal resource extraction – has inspired new governmental strategies and legislations (Zhijun & Nailing, 2007), along with individual action plans by industries (Bocken et al., 2016). For instance, the European commission recently engaged in a campaign promoting CE strategies for plastics. They set an objective to ensure that ten million tons of recycled plastics find their way into new products on the EU market by 2025[1], with 25% going to bottle application (Setboonsarng, 2019). Some companies in textile and other industries stand out by using recycled Polyethylene Terephthalate (rPET) in their product. New applications and sources of rPET are being developed, to find innovative way of reclaiming PET fiber from jackets and introducing bottle-sourced rPET[2]. To support this market development, the Thai chemical company Indorama Ventures, among others, recently massively invested in PET reclamation plants (Setboonsarng, 2019). In general, aiming for a Circular Economy (CE) has a great potential to unite society behind a common goal, calling for a greater coordination between companies, government and civil society, working together towards using less natural resources (or using them more efficiently), while increasing benefits (Lieder & Rashid, 2016) and delivering more useful service (Tukker, 2015) for more people (Meadows et al., 1972).

1.1. CE indicators and assumptions

Often considered as un umbrella concept (Blomsma & Brennan, 2017; Homrich et al., 2017; Korhonen et al., 2018), and sometimes as an offshoot of Industrial Ecology (IE) principles (Erkman, 1997; Ghisellini et al., 2016; Mattila et al., 2012), CE offers a large panel of solutions aiming at decoupling economic growth from resource use (D'Amato et al., 2017). Broadly speaking, CE aims to connect diverse strategies, including production-related and service optimization approaches. Eco-design principles, responsible production and procurement, and reverse logistic are often fostering the creation of material loops, while new business opportunities emerge from service-based approaches, e.g. collaborative economy, maintenance and repair strategies, donating and reselling, performance (functionality) economy, reuse and redistribution or refurbishing.

Recently, a plethora of new tools and methods dedicated to CE assessment have emerged in the literature, as reported in recent reviews (Corona et al., 2019; Elia et al., 2017; Iacovidou et al., 2017; Moraga et al., 2019; Parchomenko et al., 2019; Saidani et al., 2018). New indicators are proposed to quantify the "circularity" of individual products (e.g. (Ellen MacArthur Foundation & Granta Design, 2015; Linder et al., 2017)), companies (e.g. (WBCSD & KPMG, 2019)) and even specific production processes (Wen & Meng, 2015).

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[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1516265440535&uri=COM:2018:28:FIN
[2] See e.g. Norden: https://nordenproject.com/

These indicators mostly combine mass-based quantifications with qualitative attributes, such as longevity (Franklin-Johnson et al., 2016), economic value (Linder et al., 2017) or other physical dimensions such as the exergy (Dewulf et al., 2007; Huysman et al., 2017). The literature often refers to these narrow scopes (product-, company- or process-scopes) as “micro” scopes (Ghisellini et al., 2016). At least two implicit assumptions underly these micro-scopes quantifications of circularity.

Before introducing these assumptions, we must clarify the terms we use throughout the paper. With “material circularity” we refer to strategies favoring the creation of material loops, as commonly defined in the CE discourse, within a given system. The underlying objective of material circularity is to improve material efficiency. A system is material efficient when it uses the least amount of virgin material per unit of service, or offers the maximal amount of service per unit of virgin material (Allwood et al., 2011). Throughout this article, this scope is restricted to describing strategies that reduce the bill of non-renewable and virgin materials directly introduced into the product composition or improve this product’s use and recycling; it does not include the material flows indirectly required for the whole product’s lifecycle. When referring to measuring how well a product is managed in a circular way, we use the term of “product-level circular performance”, and this works also for market- and industry-level.

The first assumption behind micro-scoped circularity strategies is that closing the material loop at the product or company level is expected to lead to improvements in material efficiency for the economy as a whole (see e.g. (Stahel, 2013))**.** In other words, material circular strategies at product level assume implicitly that no negative feedback mechanism outside of their scope may counter their local gains in material efficiency. With this *ceteris paribus* assumption, improving a product’s circularity necessarily contributes to a greater level of circularity overall, and to the transition to a CE.

The second implicit assumption of the CE movement is that increasing the recirculation of materials and avoiding virgin material extraction and production is environmentally beneficial (Ellen MacArthur Foundation, 2019; Ma et al., 2015). CE initiatives are notably put forward as key measures to mitigate climate change (Ellen MacArthur Foundation & Material Economics, 2019). In other words, it is implicitly assumed that any environmental impact caused by the activities needed to increase the recirculation of material flows are negligible compared to the benefits of avoided virgin material production. Although this heuristic is probably justified in most cases, some notable exceptions to the “3R-VE” rule-of-thumb have emerged in the literature (Finnveden et al., 2005; Van Ewijk & Stegemann, 2016; Zink & Geyer, 2018). The objective of this paper is not to prove that this highly useful heuristic is generally false, but rather to document a real-world counterexample that demonstrates how this heuristic may not always be valid, and that product, material or market specificities need to be accounted for in decision making.

1.2. PET and case study

In this article, we test the two aforementioned assumptions through a large-scale case study evaluating the circularity of PET in the USA market by exploring whether increasing the use of recycled PET (rPET) within the bottle industry is preferable for the environment. Water bottle companies increasingly strive to include rPET in their production, making bottles from bottles. While such closed-loop recycling may be good for the bottle industry's image, there is a possibility that open-loop recycling, where rPET is used in other applications – like fiber textile, sheets and films – may constitute an environmentally preferable alternative.

During the last decade, an extensive literature explored the circular potential of the PET lifecycle, often blessing the bottle-to-bottle pathway. Welle (2011) observed an increased used of rPET for bottle application between 1991 and 2011 fostered by an improvement in decontamination efficiencies with the so-called "super clean recycling process". Combining Material Flow Analysis (MFA), Life Cycle Assessment (LCA) and Multiattribute Utility theory, Rochat et al. (2013) recommended bottle-to-bottle recycling for a Columbian municipality due to environmental economic and social benefits. Kuczenski and Geyer (2013) concluded that bottle-to-bottle recycling subject to the Californian refundable plastic bottle system (CA CRV) was environmentally beneficial. However, the competition for rPET extends beyond the bottle sector even though a preferential purchase of rPET for one purpose may force other production (fiber, sheet, film, etc.) to rely on virgin PET (vPET).

This research work aims to investigate whether or not PET bottle producers should increase the recycled content of their bottles to reach a higher material efficiency and environmental performance. In the present case study, we assess whether prioritizing closed-loop recycling within a single brand (subset of all bottles) or within the entire plastic bottle market (bottles of all brands, i.e. bottle industry) leads to both higher material efficiency and to lower environmental impacts, when we take into account (or not) the entire PET market (all industries using PET). Unlike already published studies assessing the benefits of PET recycling, this research work expands the scope of analysis by encompassing all competing uses of the material and constraints within a given market, and proposes an integrated approach combining MFA, LCA and material circularity assessment. Also, unlike the work of Kuczenski and Geyer (2010), this study is applied to a specific case opposing closed- and open-loop recycling scenarios.

2. Material and methods

In this section we describe the selected modeling approaches. We performed MFAs to test material efficiency at different scopes, and we integrated it with LCA to evaluate the environmental performance at different scopes, including the value chain of each of the involved activity in the MFA. Key characteristics and data of the PET system in the USA and modeling assumptions are described. One major improvement in the MFA compared to that of Kuczenski and Geyer (2010) is the data update for the US PET market to 2016, including an extensive data collection on imports & exports, and the technical update with primary data for some specific reclamation processes.

2.1. Selected modeling approach

MFA and LCA provide a good starting point to assessing CE strategies (Moraga et al., 2019). We perform an MFA on the USA PET market based on data collected from different sources, taking the work from Kuczenski and Geyer (2010) as a starting point and refining it with other data such as NAPCOR (2017). We report on these data sources with a detailed process description including all input/output flows in the supporting information (SI). We use the STAN2 software to perform the MFA and OpenLCA software for the LCA using Ecoinvent v3.3 database and IMPACT 2002+[3] for the impact characterization.

We chose the Material Circularity Indicator (MCI) to measure material circularity at the product-level as recommended by Elia et al. (2017) and its many uses in the literature. Its computational structure is flexible enough to capture material flows at the market level. Some recent publications also discussed, tested and compared the MCI to LCA (Lonca et al., 2018; Walker et al., 2018). The methodology for MCI is freely accessible and can be found in Ellen MacArthur Foundation and Granta Design (2015), and a spreadsheet tool is also available online. The SI summarizes the MCI calculation method and data selected for the case study.

In the following sections, we refer to Life Cycle Impact Assessment (LCIA) results as indicators of environmental performance and MCI scores as a material circularity metric. The MFA results serve to scale up LCA scopes.

2.2. Scope and scenarios

We restrict the scope of research, for the MFA and the LCA, to PET material and the products where it is used, i.e. bottle, sheet, film, fiber and strapping. System boundaries encompass material production and vPET distribution within the several industrial applications of the PET market (we further discuss this approach in section 4).

We define three scopes of analysis where two scenarios are compared through two indicators**.** Each scope, i.e. single brand (subset of bottles), plastic bottle market (bottles of all brands) and PET market (all industries using PET), is defined by specific system boundaries as per Figure 1. A scenario maximizing recycled content into bottle production describes a system prioritizing closed-loop PET recycling into bottles over open-loop recycling and therefore addressing the question raised by PET bottle manufacturers; it is

[3] We also test the viability of the chosen method with TRACI v2.1 developed by the USA Environmental Protection Agency, which may constitute a more adequate method given the geographical context, but we observed no difference which could significantly influence conclusions of the study

important to note that this scenario does not increase overall recycling, it only reallocates it. It is compared to a baseline scenario representing the current situation (see section 3.1), with a given share of open-loop and closed-loop recycling provided in the MFA section. The comparison is performed relying on two indicators: the Material circularity indicator (MCI) and climate change impacts from the Life Cycle Assessment (LCA).

Figure 1**Erreur ! Source du renvoi introuvable.** represents the system boundaries according to the three scopes of the analysis: the USA PET market, the bottle market and the brand market. We defined a specific functional unit for each of them.

- The narrow scope (brand) restricts its assessment to the circularity and LCA indicators for the production of a single bottle, omitting any scaling effect, system constraints or competition for rPET. This scope corresponds to the narrow scopes employed in water bottle companies developing a "green" or a "circular" brand in a scenario maximizing recycled content into bottle production, i.e. a single product line to which we associate the following functional unit: *consumption of one PET bottle in the USA.*
- The intermediary scope represents the bottle market, i.e. all bottles of all brands circulating in the USA territory to which we associate the following functional unit: *consumption of 2.78 Mt PET bottle in a year in the USA.* This scope differs from the previous scope by including scale effects and constraints within the bottle market: the percentage of recycled content is limited by the availability of rPET. This scope is still restricted by its exclusion of any other use of PET from its circularity and environmental evaluation.
- The broader scope includes the entire US PET market, encompassing other industries using PET or rPET from post-consumer bottles to which we associate the following functional unit: *Consumption of 2.78 Mt PET bottle, 1.98 Mt PET fiber, 1.13 Mt PET sheet, 500 kt PET film and 69 kt strapping in a year in the USA,* which is representative of the consumption of bottle and non-bottle PET in the USA in 2016. The weights of each product are defined according to the results obtained with the MFA.

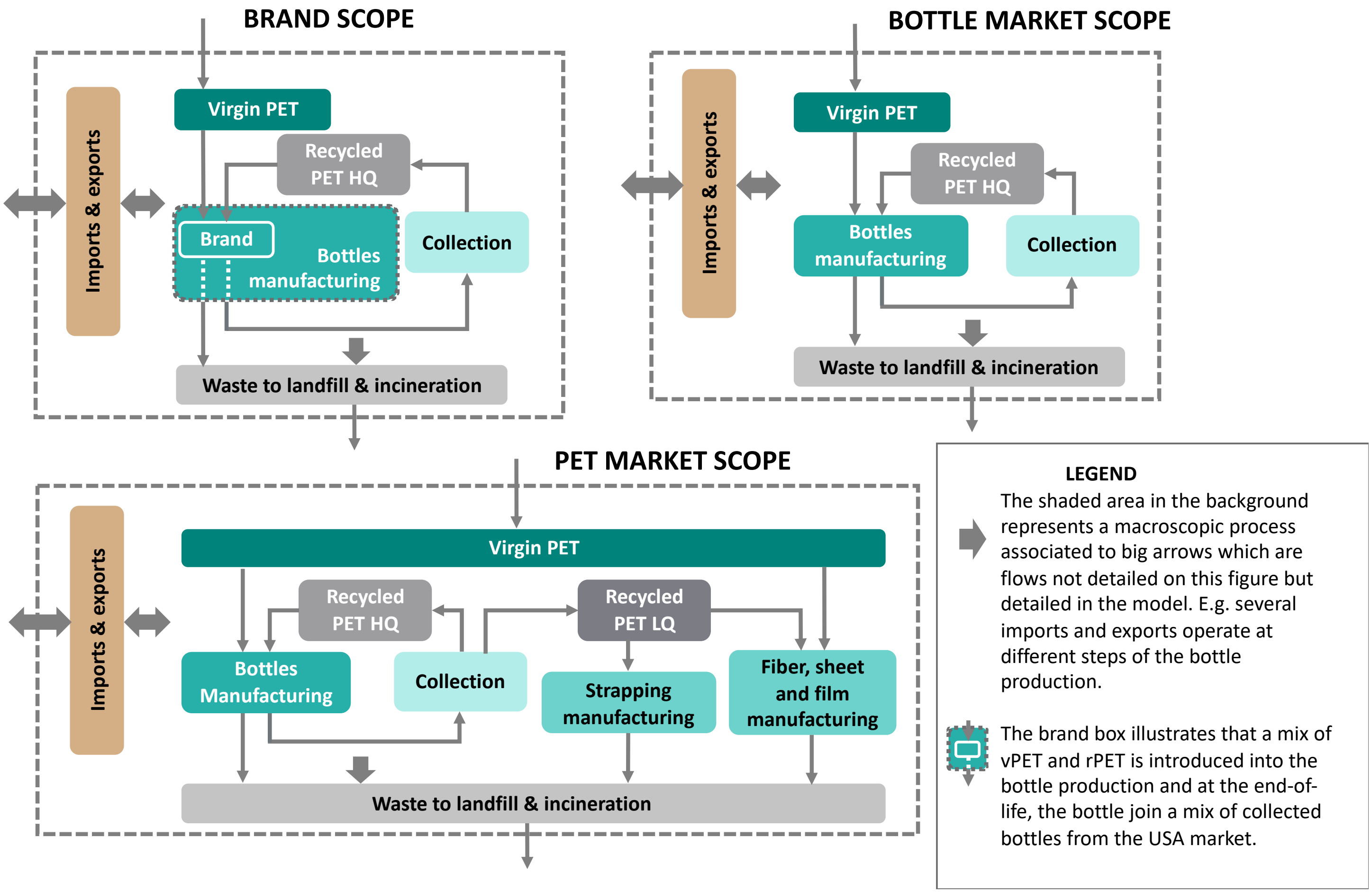

Figure 1 Simplified representation of PET lifecycle activities in the USA market with the definition of system boundaries according to the three scopes of analysis. A more detailed version is available in the supporting information.

For each scope, we test the scenario maximizing recycled content in bottle production, which consists in reallocating all rPET to bottle production. In the narrow brand scope, this leads to a potential of 100% recycled content bottle production, which is rather realistic and even trendy in the industry, as the graphical abstract suggests. The two other scopes, bottle marked and PET market, capture potential scaling issues and maximizing recycled content in the production of all the bottles in the USA market is rather a hypothetical case.

2.3. Processes description and key characteristics of the PET system in the USA

PET bottle production starts with the production of Amorphous PET – often called APET but defined in this paper with a more generic term, i.e. virgin PET – which goes through Solid State of Polymerization (SSP) and other processes further detailed in the SI. The MFA performed by Kuczenski and Geyer (2010) on the USA PET market reveals post-consumer beverage bottles to be the main sources of rPET. In 2016 in the US, 28.4% of post-consumer bottles were collected from 3 different ways: 63.4% were coming from curbside drop-off, 12.4% from deposit program and 24.2% from the California Redemption Value[4] program (CRV). Bottles collected from curbside drop-off were sent to a Material Recovery Facility (MRF) to be separated from glass, metal and paper, sorted by color and cleaned from contaminants. Nearly 20% of PET bottles collected were sent outside the USA (mostly China and India). Among the other 71.6% of non-collected post-consumer bottles, 19.6% were incinerated (Bartolome et al., 2012) – PET has high calorific value ranging between 43.3 and 46.5 MJ/kg (Al-Salem et al., 2009) – and the rest were landfilled. The bottles collected then enter two material streams: back to bottle application (closed-loop recycling) and other applications (open-loop recycling). There is also a share of post-consumer PET exported outside the USA where we assume open- and closed-loop pathways to operate in similar proportions and with similar technologies as in the USA.

Closed-loop recycling is technically more difficult and requires further processing before post-consumer PET can be blended with virgin polymer (Chilton et al., 2010). To use recycled PET in bottle production, a decontamination process is required, yielding a High Quality (HQ) rPET. Contaminations can be of physical or chemical nature. Whereas techniques to tackle physical contaminations are relatively easy to implement (Welle, 2011); chemical contamination is a more complicated problem due to the persistence of some components, e.g. organic substances that have been absorbed into the polymer (Welle, 2011) such as moisture impregnation and flavor food presence. The super cleaning process yields a high-quality material sufficiently decontaminated for food application. The high-quality rPET is transformed into flakes and then pellets before entering the bottle production processes. The material efficiency of the super cleaning process is nearly 67.6% , meaning that 32.4% of the rPET going through that process is sent to waste treatment (NAPCOR, 2017).

Recycled PET can be used for products other than bottles. Such open-loop recycling typically does not require further cleaning process and yields a Low Quality (LQ) rPET. The material efficiency of the LQ recycling process from bottle reclamation is nearly 68.12% (NAPCOR, 2017), which is quite similar to HQ recycling efficiency. Some rPET entering the reclamation market to LQ flake are used to fully replace steel and polypropylene straps for strapping medium and heavy bales. For simplicity, we consider rPET as the only material source for strapping application, which has no significant impact on the final results since the volume of rPET strappings is really small compared to other recycling avenues. LQ rPET also finds applications in sheet, film, fiber production and resin engineering. Film production requires a single extrusion process and finds application for printing and medical imaging. Sheet production requires thermoforming and extrusion processes. Having a greater thickness and stiffness, sheets are used for plastic container for food packaging and shipping (Kuczenski & Geyer, 2010). Recycled PET is also a good

[4] refund after returning the bottle

substitute for vPET used to manufacture fibers, which are widely used in textile industry (Aizenshtein, 2009). Recycled PET is also used in resin engineering for composite materials and polymer blends (Kuczenski & Geyer, 2010).

2.4. Assumptions and modelling choices

We detail in the SI the model choices, input data and assumptions regarding three types of processes: (1) virgin PET and production of PET products, (2) imports and exports and (3) bottle collection and recycling. For import and exports, we found the stream share associated to each country of origin or destination on different databases, such as UN Comtrade database for PET resins or IBIS World dataset for PET bottles. We estimated distances for boat, train and freight lorry transports based on major cities selected on trade activities and geographical location criteria. We adapted the electric mix to each country based on Ecoinvent v3.3 database for production of imported goods. To avoid counting transports twice, we chose to include the environmental impacts of transports only for imports, not for exports, except for post-consumer products that are assumed to displace production elsewhere.

3. Results

3.1. Baseline

Our study yielded an MFA of the flows of vPET and rPET materials in the USA market in 2016, embedded in bottle, fiber, sheet, film and strapping product flows, as they interact with and are transformed by processes of solid state polymerisation, injection, stretch blow moulding in the brand and bottle market scopes, processes such as extrusion, thermoforming in the PET market scope as well as HQ and LQ flakes and pellets reclamation. This detailed MFA is available in full resolution in the SI, notably with estimates of the amount of HQ and LQ rPET pellets going to bottle and other applications.

Figure 2 aggregates and summarizes the key MFA results. One third of rPET available, i.e. after being collected and recycled, entered the closed-loop pathway. Annual production was: 4.2 Mt of vPET, 0.20 Mt of rPET used in bottle application, and 0.48 Mt of rPET used for other applications (0.29 Mt entering the market for fiber application and 0.19 Mt entering the market for sheet and film applications). An additional 7.0 t goes to strapping application. Also, 0.17 Mt of post-consumer PET was exported outside the USA (process called “Bale export”), leading to save 0.1 Mt of vPET production. Thus, 14% of vPET entering the USA PET market during 2016 was recycled into bottles and other applications, when including exported bale PET outside the USA territory it yields a 17%. Within the USA territory, 32% of rPET – which represents 5% of total vPET – entered the closed-loop pathway while 68% of rPET, i.e. 10% of vPET, entered the open-loop pathway. The complete MFA calculated with STAN is detailed in the SI.

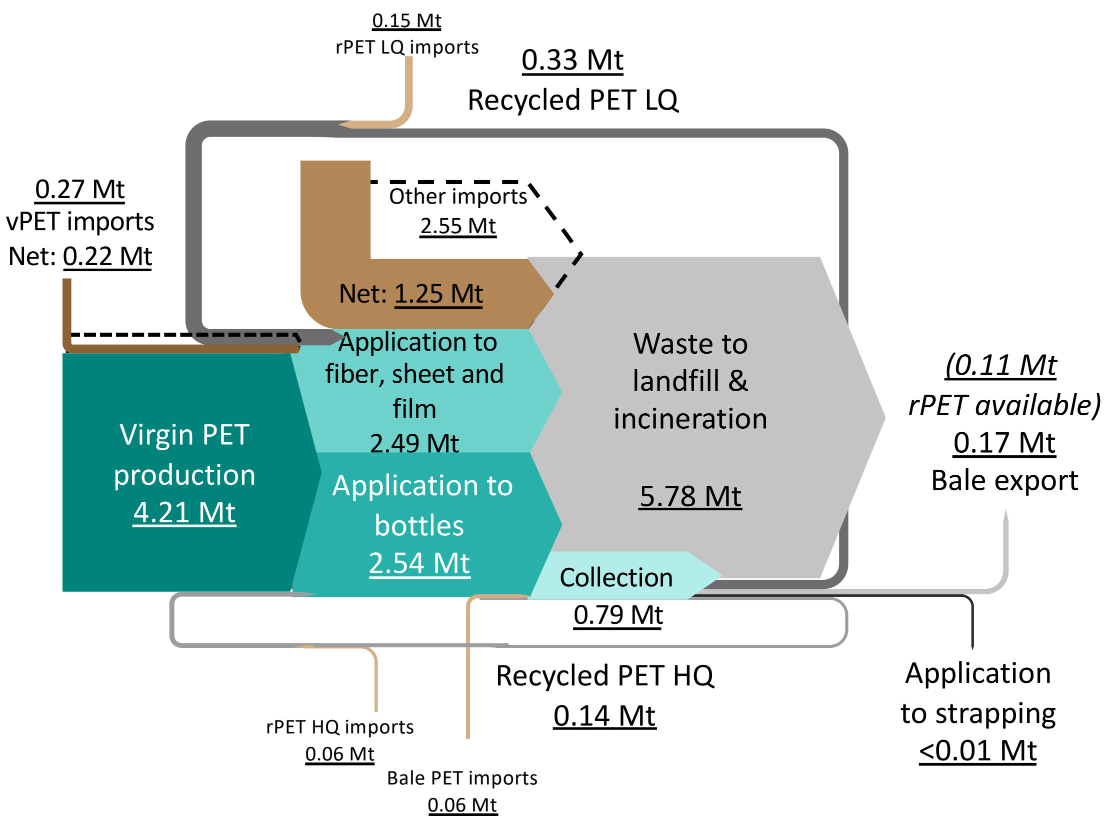

Figure 2 Sankey diagram from the Material Flow Analysis of the USA PET market in 2016 Terminology is consistent with Figure 1 with more details on imports and exports. "Bale export" represents recovered bottles sent outside the USA before reclaimed into flakes and being available as rPET. "vPET imports" and "Other imports" represent the difference between imports and exports (net value). "Other imports" contains resin sheet grade and bottle grade, sheet, film, fiber and bottles as well as post-consumer fiber exports.

3.2. Scenario maximizing recycled content in bottle production

The scenario maximizing recycled content in bottle production assumes all available rPET enters the closed-loop pathway to be used in bottle manufacturing. Two patterns are observed when evaluating the material efficiency of this scenario through the MCI indicator. First, MCI scores are improved compared to the baseline scenario when evaluated within the brand and bottle market scopes, by 171% and 24% respectively (Figure 3). It worsens by a negligible 3.5% when evaluated on the broader PET market scope due to the slightly lower material efficiency of the super cleaning process. Second, the smaller the scope, the higher the MCI that is attainable through maximizing recycled content into bottle production strategy. Within the brand assessment scope, the closed-loop scenario shows the highest MCI score, since the share of recycled content is maximized up to 100%. Although the scenario maximizing rPET in bottle production consists in reallocating all rPET production to bottle manufacturing, the current PET recovery rate is not enough to supply the whole bottle market, leading to no more than 20% recycled content. The MCI is the lowest for the broader PET market assessment scope because other products using PET are not currently recovered, meaning that the diversion of rPET towards the bottle market increases by the same amount the need of vPET for other applications, and shifts recycling from the low-quality to the high-quality process.

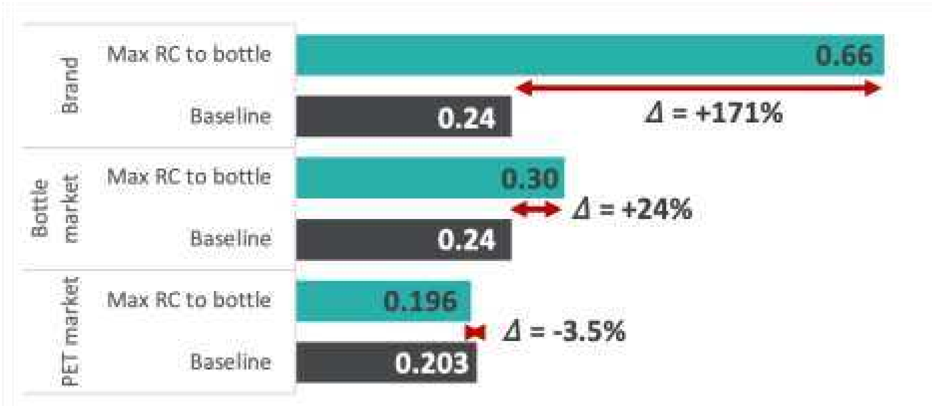

Figure 3 MCI scores variation with the maximizing recycled content into bottle production scenarios corresponding to three assessment scopes. Scores range from 0 to 1. MCI score for baseline scenario in the brand and the bottle market scopes are similar.

The evaluation of environmental performance of the scenario maximizing recycled content into bottle production are presented in Figure 4 for the three scopes of analysis. Results are presented for climate change (CC) indicators. Other indicators are provided in the SI. A brand that would decide to introduce more recycled content into bottles up to 100% would decrease the CC footprints of each bottle by nearly 15%. Environmental gains on CC impacts are due to the substitution of “virgin PET” (responsible for 34% of CC impacts in the baseline scenario) with recycled PET supplied by the aggregated process “Recycling”, which includes the different activities from collection and the reclamation to flakes HQ (including the super cleaning process) and then to HQ pellets production as described in section 2.3. In the baseline scenario, recycling postconsumer PET is responsible for 3% of CC impact which goes up to 21% in the scenario maximizing recycled content in bottle production. This gain is within the range revealed by the literature on the emission reduction by substituting 1 kg of vPET with 1 kg of rPET (Bataineh, 2020; Benavides et al., 2018), i.e. roughly between 25 and 75 % reduction for rPET compared to fossil fuel-derived PET. In both the brand and the bottle market scope, the process called “Product manufacturing” is the biggest contributor to CC impacts. Injection stretch blow molding processes are major contributors to bottle manufacturing as the contribution analysis in the SI reveals.

Bottle manufacturers potentially have access to 0.68 Mt of rPET, i.e. sum of the total rPET available on the USA ground (0.14 + 0.33 Mt) plus the imports (0.15 + 0.06 Mt) (see MFA reported in Figure 2). Scaling the benefits of the scenario "Maximal recycled content into bottle" within the brand scope for 0.68 Mt of rPET would result in 565 Mt CO2eq avoided emission, an improvement of 15% from the baseline.

Expanding the scope of the analysis to the bottle market, introducing more recycled content into bottle production has the potential to decrease vPET supply in the bottle industry by only 15% ("X" in Figure 4), recovered PET in the USA being limited to 0.79 Mtons/year (as per Figure 2). The CC reductions associated with a 15% decrease of vPET production are largely cancelled out by increases in climate impacts of recycling processes, because CC impacts of rPET HQ flake production are very close to those of vPET production. This strategy thus yields a net CC impact reduction of less than 3% across the bottle industry's lifecycle.

Broadening the assessment scope to the whole PET market, the scenario maximizing recycled content into bottle production does not generate improvement in terms CC impacts. It even increases the overall vPET demand by 2% due to a higher loss (about 2%) for the recycling process of HQ rPET relative to LQ rPET. In the next section we analyze the sensitivity of the total emissions regarding these parameters. Hence, using a larger fraction of rPET to produce bottles requires more of HQ rPET, which may be environmentally costly compare to the LQ rPET necessary for other applications. These results show that a circular strategy may seem interesting in a narrow scope, but less interesting when expanding the scope of analysis accounting for further (industrial) synergies and potential burden shift. Additional LCIA results in the SI reveal similar tendencies with impacts on Human Health, Ecosystem Quality and Resources. The Resource impact category exclusively embodies non-renewable energy consumption in the context of the PET market since mineral resources are used only indirectly through the lifecycle to manufacture bottles.

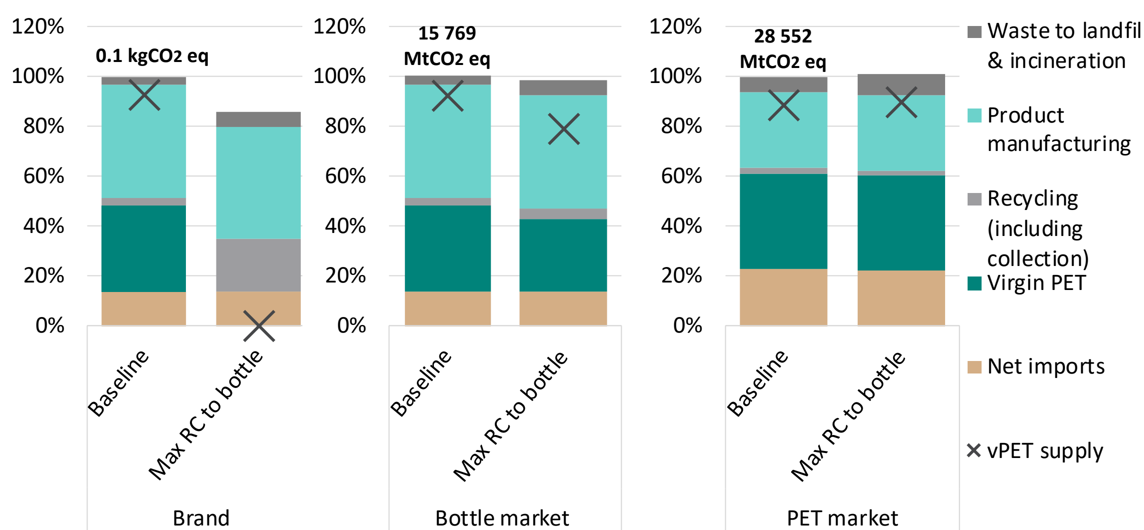

Figure 4 Relative impact scores on climate change and vPET production. Virgin PET supply represents the mass percentage always referring to the baseline scenario. Imports and exports represent all types of flows i.e. vPET, rPET and finished products. Absolute values in kgCO₂eq refer to the baseline scenario. Process called "Virgin PET" refers to the production of Amorphous PET. Process called "Product manufacturing" refers to bottle production-related processes and to fiber, film, sheet and strapping production-related in the PET market scope (further detailed in the SI). Process called "Recycling" refers to

rPET HQ and LQ production-related processes (depending on the scope) and to collection-related processes such as transports.

3.3. Sensitivity analysis on a simplified model

To generalize the analysis and the interpretation of the most influential parameters on system performance in terms of material circularity and environmental impact, we developed a simplified model focusing on the PET feedback loops represented in Figure 5. The model is scaled up to the yearly market size for bottles and other applications using PET in the USA PET market, i.e. fiber, film and sheet. The model is simplified into a restricted number of aggregated unit process: production of virgin PET, bottles, other (products), waste (treatment), HQ and LQ rPET recycling. For each unit process, characterized emissions per unit of output are calculated by aggregating the emissions of more detailed processes, such as injection and stretch blow molding within the bottle production. By doing so, the model assumes no variation of flow size between each detailed process to another due to losses, imports and exports. We analyzed the influence of three key circularity parameters on the total impact score of the system: the fraction of post-consumer bottles collected (μ), the fraction of rPET going to bottle application (θ) and the recycling efficiency of processes leading to HQ and LQ PET pellets (η_{HQ} and η_{LQ})[5]. We add up the characterized emissions per unit of rPET from bottle collection to those of PET reclamation processes (HQ and LQ). Thus, we perform a sensitivity analysis of the key circularity parameters on the simplified model described on Figure 5 using equation 1:

$$I = I_{vPET} + I_{production} + I_{rPET(HQ)} + I_{rPET(LQ)} + I_{waste} \, , \tag{1}$$

where I stands for impact score, climate change in this case. Also, we consider that what flows in each recycling pathway (HQ and LQ) scales the emissions associated to their respective process, not what flows out, which is why η_{HQ} and η_{LQ} do not appear in equations 4 and 5, respectively. Except for "Bottle" and "Other" production processes in equation 2, we can express the impact score of each process as a function of at least one key circularity parameter on each process, as per equations 3 to 6, with variables defined in Table 1.

$$I_{production} = S_{bottle}E_{bottle\,prod} + S_{other}E_{other\,prod} \, , \tag{2}$$

$$I_{rPET(HQ)} = S_{bottle}\mu\theta E_{rPET(HQ)} \, , \tag{3}$$

$$I_{rPET(LQ)} = S_{bottle}\mu(1-\theta)E_{rPET(LQ)} \, , \tag{4}$$

Equation 2 shows that impacts of bottle production are not affected by influential parameters on system performance in terms of material circularity as per the model, contrary to the impacts of HQ and LQ rPET (equations 3 and 4). Equation 5 scales the emissions of vPET production (E_{vPET}) by the net demand of virgin PET (term in bracket),

[5] LCA reveals lower impacts on climate change from importing rPET rather than producing it in USA, because of a lower carbon intensity of the electricity mix where rPET is imported. International trade network is subject to many factors excluded from the scope of this study. To avoid trivial results, we exclude the rPET imports from the tested parameters such that we do not make any differentiation between imported and domestic PET production, i.e. considering that all PET is produced in the USA.

which is estimated based on the total demand for PET ($S_{bottle} + S_{other}$) minus the amount of rPET that can be obtained from bottle recycling (based on μ, θ , η_{HQ} and η_{LQ}). Equation 5 is only valid as long as the production of LQ rPET lower than the demand generated by non-bottle use (S_{other}).

$$I_{vPET} = \left[S_{bottle}\left(1 - \mu\left(\eta_{HQ}\theta + \eta_{LQ}(1-\theta)\right)\right) + S_{other}\right] E_{vPET} \ , \qquad (5)$$

Since we model a system at steady state, the demand for additional virgin materials must equal the non-recycled fraction, i.e. the amount of materials sent to waste management, which explains the similarity between equation 5 and 6.

$$I_{waste} = \left[S_{bottle}\left(1 - \mu\left(\eta_{HQ}\theta + \eta_{LQ}(1-\theta)\right)\right) + S_{other}\right] E_{waste} \ . \qquad (6)$$

Table 1 – Scaling factors, characterized emissions per unit flow and key circularity parameters

S_{bottle}	yearly market size for bottle [Mt]
S_{other}	yearly market size for other applications [Mt]
E_{vPET}	characterized emissions per unit of vPET produced [$kgCO_{2eq}$ /Mt]
$E_{rPET(HQ)}$	characterized emissions per unit of rPET High Quality produced [$kgCO_{2eq}$/Mt]
$E_{rPET(LQ)}$	characterized emissions per unit of rPET Low Quality produced [$kgCO_{2eq}$ /Mt]
$E_{bottle\ prod}$	characterized emissions per unit of bottle manufactured [$kgCO_{2eq}$ /Mt]
$E_{other\ prod}$	characterized emissions per unit of other product manufactured [$kgCO_{2eq}$ /Mt]
E_{waste}	characterized emissions per unit of waste treated [$kgCO_{2eq}$ /Mt]
μ	fraction of post-consumer bottles collected
η_{HQ}	recycling efficiency of processes leading to High Quality (HQ) PET pellets
η_{LQ}	recycling efficiency of processes leading to Low Quality (LQ) PET pellets
θ	fraction of rPET going to bottle application ($1-\theta$ is the share of rPET going to other applications).

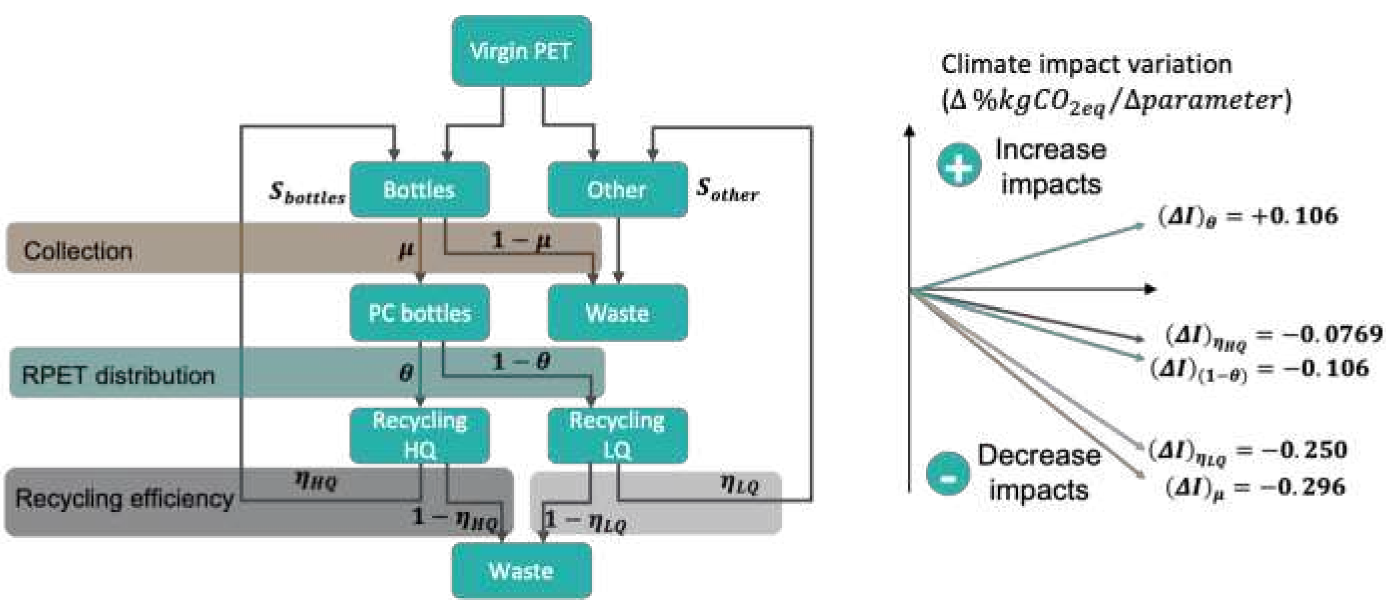

Figure 5 Left: simplified representation of the actual USA PET flows with tested key circularity parameters. Right: slopes representing the influence of key parameters to the total impacts on Climate Change of the USA PET market, such that e.g. $(\Delta I)_{\mu} = \left(I_{\mu_1} - I_{\mu_0}\right) / (\mu_1 - \mu_0)$*. The lower it is, the less overall impacts.*

Sending all rPET to other applications is not the most influential key circularity parameter. Our preceding results revealed that favoring open-loop recycling lowers climate change impacts, unlike bottle-to-bottle recycling. But Figure 5 shows that increasing bottle collection rate is the most sensitive parameter to reducing CC impacts $(\Delta \mathrm{I})_{(\mu)}$, more than sending all rPET to other applications $(\Delta \mathrm{I})_{(1-\theta)}$ or improving recycling efficiencies $(\Delta \mathrm{I})_{(\eta_{HQ})}$. This is aligned with the conclusion drawn from the MFA performed by Kuczenski and Geyer (2010) that increasing both the collection rate and reclamation capacity are the most influential parameters in terms of material circularity improvement in the USA PET market. In fact, reducing impacts on CC is more sensitive to improving recycling efficiency of LQ rPET than acting on the rPET distribution. We further discuss this statement in section 5.1.

4. Discussion

If the CE movement supports material circularity as a means towards both resource preservation and environmental sustainability, we demonstrated with this case study on PET recycling in the USA bottle industry that this heuristic cannot be taken for granted for all materials. Table 2 summarizes case study results. Hereby we discuss the theoretical meaning of the results and their implications for CE assessment.

Scope	Brand	Bottle market	PET market
MCI	+ 175%	+ 25%	- 3.5%
LCA-CC	+ 15%	+ 3%	∽

PET bottle collection constrains the rPET availability to fulfill the demand of the bottle market

PET reclamation process to Low Quality rPET, used in other applications such as fiber textile, is more efficient

Table 2 MCI and climate change impact scores improvements made moving from baseline to maximizing recycled content into bottle production scenario according to each assessment scope. "+" sign means improvements are made moving from baseline to maximizing recycled content into bottle production, whereas "-" means worsening of indicators.

4.1. On material circularity assessment

This case study is an example illustrating that implementing material circular strategies at the product level do not necessarily increase material efficiency for the system as a whole.

By using the MCI, we measured how good we are at implementing circular strategies within a given scope, which is different from measuring the global material efficiency of the strategy. The case study results reveal that implementing circular strategies at the product level does not necessarily lead to higher material efficiency when expanding the scope of the analysis to the bottle market and the whole PET market, as reflected by a worsening MCI score. For instance, maximizing recycled content into bottle production leads to a slight increase of vPET use (+1.9%) for the PET market as a whole, leading to a worsening of the MCI of the whole system by 3.5%, due to the marginally worse material efficiency of the super cleaning process compared to other recycling processes. Thus, the *ceteris paribus* assumption that micro-scale circularity measures will translate into net gains in material efficiency does not hold in this case.

In term of material circularity assessment, this case study also proves that supporting the adoption of circular strategies with a MCI score calculated at the product level can be misleading because of an excessively narrow scope of analysis that overlooks opportunities to improve material efficiency through further symbiosis outside the product system. This also hides potential unintended consequences of competition for the recycled materials with other applications. Thus, promoting product level circular strategies happens to be disconnected from the symbiotic purpose of CE

This example also demonstrates that, contrary to the second implicit assumption of micro-CE analysis (see section 1.1), implementing material circular strategies at product level is not necessarily synonymous with better environmental performance. If we consider CE not as an end in itself but rather as a pathway towards environmental sustainability, it is counter-productive to adopt a circular strategy that leads to increasing environmental impacts. Indeed, resource preservation and environmental impacts reduction are complementary targets (or non-substitutable), i.e. improving one does not compensate for worsening the other. The question of whether CE metrics give robust guidance towards environmental sustainability is not straightforward. As the present case study showed, implementing circular strategies at the product level does not necessarily reduce environmental impacts on a market-wide assessment scope. In fact, focusing on material circular strategies at product level might divert the attention from other opportunities to progress on environmental performance.

Previous works have also provided a similar counterexample such as the case study on used tires in Lonca et al. (2018). However, while that case study explored burden shifting from one lifecycle stage to another, the shift of burden in the present case study comes from a market constraint that can be included only by broadening the scope definition. In terms of CE assessment, this case proves it can be useful to use MFA to complement LCA in monitoring “market leaks”, i.e. displacing the impacts from one PET product to another.

4.2. On the concept of downcycling

The assumption that circularity and environmental impact are improved by closed-loop recycling is at least partly based on the fact that bottles can continue to be recycled, while the open-loop recycling ultimately removes PET from the system. Yet, there is an environmental advantage to open-loop recycling. The definition of closed loop, which is strongly bound to company and product perspectives, overlook circularity opportunities operating at a broader scale such as the material market dynamics. This also supports the point made by Geyer et al. (2015) that distinguishing open loop from closed loop is a blind preference that is environmentally misleading[6].

Geyer et al. (2015) were careful to distinguish between open-loop recycling (where a product is re-used in a different application) and "downcycling" (where the quality of the recovered material is lower). The use of a material in a different process for a different purpose does not necessarily mean that the quality and the utility of the material were reduced. Indeed, Geyer et al. (2015) stress that their defense of open-loop recycling should not be taken as a defense of "downcycling"; " the notion of *impact reduction potential* is a better principle for guiding recycling decisions, given that it disfavors secondary resources of poor technical and economic value while ensuring displacement potential" (Geyer et al., 2015).

Our results seem to constitute a vindication of "downcycling", as prioritizing the production of HQ rPET over LQ rPET brought no benefit. This partial vindication, however, should not be overly generalized. The preference for downcycling is likely to hold true for other systems with similarly (1) low recovery rates of high-quality material and (2) high demand for low-quality material in applications without end-of-life recovery. In such systems, with an important final-use sink for low-quality material, striving for high purity recycling proves futile; the system necessarily relies on high inputs of virgin material regardless of the purity of the recycled flow. In other circumstances, however, where the use of virgin material is driven by the need to dilute impurities in secondary material, the assumption that maintaining high-quality material loops leads to improved resource and environmental efficiency is likely to hold.

5. Limitations and recommendations

5.1. Bottle market forces

As suggested by the sensitivity analysis, PET bottle collection (μ) is the best lever to reduce overall CO_2 emissions, while increasing the share of PET collected going back to bottle production (θ) does not help improving environmental performance of the USA PET market (I). This does not exclude the possibility that improving μ would allow increasing

[6] Geyer and colleagues' demonstration however relies on a dynamic approach of material looping. Considering only one application for a material commodity spontaneously induces to believe that the total amount of secondary material produced during successive years takes the form of a geometric sum. However, Geyer et al. (2015) recall that the geometric sum argument misses the fact that primary input reduces in a closed-loop system.

θ without increasing I. In other words, the environmental benefits from bottle manufacturers to increase the recycled content in their bottles depend on governmental incentives, plastics reclamation plants efficiencies, consumers responsible behavior to improve the PET collection rate and their willingness to pay for potentially more expensive PET bottles.

It is tempting to conclude the best environmental solution at the PET market scale is to increase post-consumer bottle collection and to increase the reclamation rate into other PET applications while improving recycling efficiency of rPET LQ. However, considering circularity parameters as equivalent environmental levers is misleading since they might not imply similar effort, i.e. each percentage improvement in any circularity parameter does not necessarily represent the same effort in terms of e.g. monetary investment. In other words, we did not investigate whether investing one dollar in a PET bottle collection program is more beneficial than investing it in improving LQ rPET recycling facilities. Determining what investment would give the best bang, in terms of material circularity and environmental impacts, for the buck, remains an unexplored but highly promising research area.

5.2. Further targeting resources efficiency

A CE is an economy that fosters resource efficiency (McDowall et al., 2017). Indeed, relying on the idea of productivity (Huppes & Ishikawa, 2005), we can say that decoupling economic growth from resource use is similar to improving resource efficiency of the economy. Thus, a CE fosters resource efficiency by yielding the highest amount of valuable input for society with less resources. In this study, we assumed a fixed demand for PET products, and hence exclude the fact that a change in the vPET market size may have wider impacts on the oil and gas industry and its other applications. By excluding other applications where similar resources are used, we cannot discuss whether increasing recycled content into bottle production is an efficient use of resources or not.

When exploring circular strategies from the PET market perspective, we intend to answer the question: how can we efficiently achieve a given function (or provide a given amount of service) minimizing virgin material (and ultimately resource) use and environmental impacts? Seeking efficiency in an economy driven by the market has empirically demonstrated the ability to generate environmental adverse effects caused by consumption shifting, as per the rebound effect phenomenon (Greening et al., 2000; Makov & Font Vivanco, 2018; Vivanco & van der Voet, 2014; Zink & Geyer, 2017). Instead of looking at one particular product and seeking the best circular case with respect to a specific material content, this article suggests we should be looking at the whole set of products served by the specific material, and to seek the best material market-wide circular case.

6. Conclusion

Plastic products acceptability is declining along civil society, and replacing vPET with rPET in bottle production is increasingly becoming a strong selling argument. The objective of this paper was to assess whether increasing rPET use within plastic bottle production leads to higher material efficiency and better environmental performance. The MFA revealed that 4.6% of the USA PET market in 2016 was circulating in closed loop within a bottle-to-bottle pathway, while a 9.8% was following an open loop pathway towards fiber, sheet and film applications. The integrated MFA-LCA assessment framework revealed that increasing closed-loop recycling within the bottle industry does not reduce virgin PET production, nor reduces GHG emissions, at the whole market perspective. Closed-loop recycling happens to compete with other applications more beneficial from an environmental point of view, even if PET used in these applications cannot be further recycled. Sensitivity analysis reveal that efforts should rather concentrate on increasing the post-consumer bottle collection rate and improving the efficiency of low-quality recycling.

The argument that improving material circularity of one product brand is beneficial for the average product market is not necessarily true. This case study demonstrates that material circular strategies at the product level do not necessarily give significant benefits when there is an important “sink” of the material (final use without recycling options) that is much greater than the recovered quantities, or the recycling process itself is material/energy/emission intensive compared to the supply of virgin material. Combining material circularity assessment and LCA is essential to identify trade-offs between material circularity and environmental performance. Also, the MFA has proven useful to monitor scale effects. Thus, the combined use of MFA and LCA helps the risk of burden shifting due to unintended consequences of market effects occurring outside the scope of a single product. Therefore, we recommend assessing product-level circular strategies considering a broader scope of analysis when there are other competing users in the market of the same material.

From the viewpoint of the practitioner, defining system boundaries larger than the company he works for might be counterintuitive. However, higher benefits from implementing circular strategies on a broader scale can be expected. For instance, a bottle company might not see direct benefits favoring the use of rPET in other products, but favoring PET circularity at the whole market level, e.g. contributing to the effort of increasing the collection and reclamation rather than increasing the competition in the rPET market, may participate in ensuring PET bottle market sustainability.

7. Acknowledgements

The authors are grateful to the students who contributed in this project: Pierre-Olivier Hays, Laurie Douré-Ouillet and Nicolas Mochel. The CIRAIG would like to thank its industrial partners for their financial support: ArcelorMittal, Hydro-Québec, LVMH, Michelin, Nestlé, OPTEL, Solvay, Total and Umicore.

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