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# Factors Shaping the Recycling Systems for Plastic Packaging Waste—A Comparison between Austria, Germany and The Netherlands

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**Abstract:** Setting up strategies for a sound management of plastic packaging waste (PPW) is becoming increasingly crucial at many levels of the value chain in Europe. After the very first implementation of an extended producer responsibility scheme in Germany in 1991, many EU Countries followed. This resulted in a complex network of schemes that differ from one member state to another. This paper brings together the three latest studies describing the current flows of PPW across the waste value chain from Austria (reference year 2013), Germany and the Netherlands (reference year 2017). With this aim, the models of the three single studies have been adapted to fit into a common model, allowing to perform a comparative analysis. Although with a relatively comparable product market, the three countries have different management systems (e.g., separate collection systems, target sorting products and treatment of residual waste), reflecting different national strategies to achieve the circular economy targets. Recycling rates (in terms of washed milled goods at the output of the recycling process) for the three countries resulted in 23%, 43% and 30% of the total mass of PPW generated in, respectively, Austria, Germany and the Netherlands. The fraction of mixed recycled plastics, relevant for Germany and the Netherlands only, was determined to be one of the major determinants of the differences in recycling rates. Furthermore, the discussion revolves around new political targets that have the potential to contribute to addressing the issue of tradeoff between quantity and quality of recycled plastics placed on the market, with measures such as design-for-recycling and eco-modulation of EPR fees playing a critical role, while also pointing out the aspects that inevitably hinder closed-loop recycling.

**Keywords:** plastic packaging waste; recycling targets; packaging recycling; limits to recycling; closed-loop recycling; packaging management systems

## 1. Introduction

The European Union strives toward a circular economy for plastic packages to reduce the use of fossil resources and to limit the generation of waste [1]. This objective is operationalized by the definition of recycling targets for each member state. Up to 2017, member states had to achieve a recycling rate of 22.5% for plastic packaging [2]. Additionally, most member states also defined stricter recycling targets in their national legislation, with varying definition for the calculation of these recycling rates. The latter varied from the collected amounts of plastic packaging waste divided by the amounts of plastic packages placed on the market to the amounts of sorted plastic packaging waste divided by

the amounts placed on the market. For example, the Dutch framework treaty agreed on a recycling target of 47% for plastic packages in 2017, measured with sorted products that have been traded to certified plastic recyclers [3]. With the same measurement rationale as in the Netherlands, Germany set a material recycling target of 36% in 2017, increased by the “Packaging law—VerpackG” to 63% in 2022 [4]. In Austria, the recycling target was set to 22.5% in accordance with the EU target [5].

The discovery of plastic soup in the oceans led to a growing public discontent with the current effluent use of plastic packaging [6]. When Europeans became aware that even their recycling systems contributed to the formation of plastic soup [7], European politicians demanded more ambitious recycling targets [1] as well as stricter export regulations with the latest amendment to the Basel Convention [8]. The former resulted in EU directive 852/2018, according to which member states need to accomplish a recycling rate for plastic packages of 50% in 2025 and of 55% in 2030. Furthermore, a stricter calculation method has been presented in implementation decision EU 665/2019. These recycling rates relate to all types of plastic packaging waste, and hence, both post-consumer and post-industrial.

All member states have implemented various collection and recycling schemes to comply to the European and their national recycling targets. These schemes differ strongly between member states, which relates to multiple differences, such as differences in consumption of plastic packages, national political recycling targets and the collection, sorting and recycling infrastructure and the presence of local plastic converting industries that can use recycled plastics as feedstock. From a research perspective, it is, however, still unclear how these aspects interact with each other and how the involved stakeholders can be aligned under a common umbrella of strategies aiming at a circular economy.

In this framework, the use of tools for an analytical investigation of the current levels of circularity is increasing. Among these, material flow analysis is a well-established method to investigate the flow of wastes through a given system [9]. It has previously been used to describe the flow of plastic packaging waste through various European member states: Austria [10], the Netherlands [11], Germany [12] and Italy [13].

This paper starts with comparing three EU member states, the plastic packaging recycling schemes of which have been described with material flow analysis in detail: Austria, Germany and the Netherlands. This comparison aims at introducing the aspect of how, although these Countries and their collection and recycling infrastructures are comparable and interrelated, remarkable differences in the plastic packaging recycling systems can still be noticed. In this sense, this paper intends to elaborate on the material flow analyses previously published for each country by contextualizing and explaining the abovementioned differences. From there, the paper expands on different policy options (some already in place and some still under discussion), rendering a deeper understanding of those factors that shape plastic packaging waste (PPW) recycling systems and those that hinder the successful implementation of closed-loop recycling.

## 2. Materials and Methods

### 2.1. Case-Study Context

An overview of background data on the country context, in terms of population, gross domestic product (GDP) and waste production, is presented in Table 1. The populations and population densities vary strongly between the countries, but the GDP per capita values are situated in the same range, especially considering that the presented value of Austria is for 2013, and the 2017 value amounts to USD 54,637 purchasing power parity (PPP). With respect to municipal and packaging waste generation (i.e., paper, plastic, metal and composite packaging), Germany reports the highest values, while the lowest values are reported by the Netherlands for municipal waste and Austria for packaging waste production.

In the three countries, every packaging producer is obliged to declare the quantity of material placed on the market, paying a fee to the respective Extended Producer Responsibility (EPR) schemes, thereby transferring the responsibility to manage the end-of-life phase of their packages (from collection to recycling). In Austria, the collection and treatment of packaging waste was managed by one EPR scheme in 2013 (Altstoff Recycling Austria—ARA), although since then, the market was opened, and now, five EPR schemes collect plastic packaging. In Germany, the first EPR scheme was the Dual System Germany (Duales System Deutschland—DSD), established in 1994. Starting from 2003, the market has opened, resulting in nine currently licensed dual system providers. In the Netherlands, producers have to pay fees to one single EPR scheme operator, Afvalfonds [14]. In Austria, mixed municipal solid waste (MSW) is mainly collected using curbside collection. Around 80% is incinerated directly, whereas the rest is sent to mechanical–biological treatment for stabilization, yet not for the recovery of plastic packaging [15]. Across the country, different, separate collection systems for plastic packaging exist, ranging from the collection of rigid plastics only to the collection of all plastic packaging, in some cases together with other packaging waste fractions such as metals, beverage cartons and wood. Both drop-off containers and curbside collection systems are operated simultaneously. The separately collected PPW is then sorted into 20 different sorting fractions intended for recycling, ranging from PET bottles separated by color to mixed PE films. Additionally, mixed fractions are produced as a refuse-derived fuel (RDF) as well.

In Germany, the MSW is collected through curbside collection and transported to municipal waste-to-energy facilities for energy recovery. Separate collection of plastic packaging items takes place nationwide, usually through a commingled collection of plastic-, paper-, metal- and composite-based packaging and non-packaging material (exceptions still exist in some regions). As in Austria, both drop-off and curb collection systems exist. Furthermore, a dedicated deposit refund system (DRS) exists for PET bottles for carbonated beverages. After separate collection, the PPW is transported to sorting facilities, where it is typically sorted into twelve sorted products, with the recyclable ones carrying a purity level defined by the DKR specifications [16]. Among these, there are four pure polymeric sorted products (PET, PE, PP and PS), one film fraction and one mixed plastics sorted product. In the Netherlands, mixed MSW is predominantly curbside collected, and high-rise buildings are facilitated with drop-off containers. In 2017, 17% of MSW was sent to mechanical recovery facilities (MRF) to recover plastics, beverage cartons and metals. The rest of the MSW, and the residues of the MRFs, were incinerated. As a relative new development, MSW collection in rural areas is increasingly changed to “reversed collection schemes” in which recyclables are collected curbside, and mixed MSW has to be brought to drop-off containers [17].

In the Netherlands, lightweight packaging (LWP) waste is largely managed similarly to Germany. Afvalfonds remunerates municipalities for collecting LWP, organizes the sorting of LWP with sorting facilities and pays for processing fees at recycling facilities when required. The most common collection portfolio of LWP is plastic packages, metal packages and beverage cartons, locally abbreviated as PMD or PBD. Municipalities can choose their own collection systems. The most common approach is curbside collection of LWP in wheelie bins and bags for neighborhoods with low-rise buildings and drop-off collection for neighborhoods with high-rise buildings. Both the recovered and the separately collected LWP is sorted in the same fractions, in accordance with the DKR sorting specifications: PET bottles (DKR 328-1), PE rigids (DKR 329), PP rigids (DKR 324), flexible packages (DKR 310), mixed plastics (DKR 350) and a PET-tray-sorted product (DKR 328-5). Furthermore, three DRS are in place for large (>0.5 L) PET water and soda bottles [18].

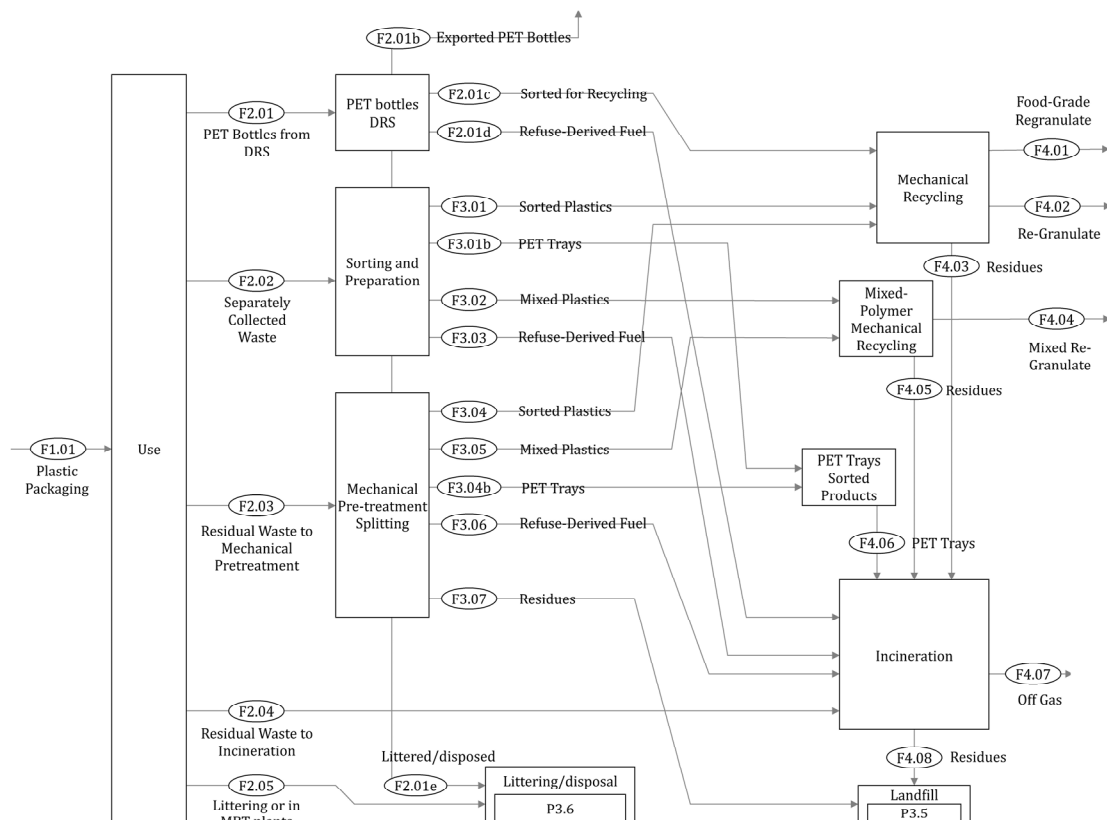
**Table 1.** Data on the country context of each of the case studies.

Parameter	AT (2013)	DE (2017)	NL (2017)
Population [19]	8,451,860	82,521,653	17,081,507
Population density (/km <sup>2</sup> ) [20]	103	234	501
GDP per capita (USD PPP) [21]	47,922	53,012	55,348
Total MSW production * (kg/cap) [22]	578	627	513
Packaging waste production (kg/cap) [23]	150	227	183
National plastic packaging recycling target, 2017 [%]	22.5% <sup>a</sup>	36% <sup>b</sup>	47% <sup>c</sup>

<sup>a</sup> BMLFUW [5]; <sup>b</sup> BMU [24]; <sup>c</sup> Dutch Ministry of Infrastructure and the Environment. [3]. GDP: gross domestic product. PPP: purchasing power parity. MSW: municipal solid waste. \* MSW includes waste from private households and comparable establishments, e.g., from administrative buildings, schools and small commercial businesses. Additionally, it includes waste resulting from cleaning activities, e.g., from parks, market waste and street sweepings [25].

## 2.2. MFA's System Boundaries

Material flow analysis (MFA) is used to comprehensively assess the flows of plastic packaging wastes through the respective waste management systems, following Brunner and Rechberger [9]. As packaging products generally have shorter lifespans than one-year [26], no stocks are considered. The general MFA framework used in the comparison is displayed in Figure 1. The system boundaries encompass the collection and treatment of PPW from households until the final recycling, incineration or landfilling step. Where data are available, the flows are subdivided into four waste categories: PET bottles, rigids, flexibles and others (which includes EPS-based packaging, i.e., blocks and trays). The temporal context of the three models differs slightly, with the data for Austria referring to 2013, while for Germany and the Netherlands, 2017 is the reference year.



**Figure 1.** System boundaries and overview of plastic packaging waste flows. DRS: deposit refund system. MBT: mechanical biological treatment plant.

Four different types of destinations were considered for the packaging waste: separate collection through DRS (only relevant for PET bottles in Germany and the Netherlands, F2.01) or in a conventional separate collection system (F2.02), as well as collection with the residual waste sent to mechanical pre-treatment (F2.03) or incineration (2.04). In all three countries, a landfill ban is in place; hence, direct landfilling after collection is not possible. A fifth path was considered, describing the flows of PPW going to littering or to mechanical biological treatment (MBT) plants. This flow was only relevant for Germany and is different from F2.03 because it carries aggregated data for both littering and MBT.

With respect to the sorting outputs, a distinction is made between sorted plastics that are recycled as single polymers (F3.01) and the intentional production of a mixed polymer stream sent for recycling (F3.02). The residues of the sorting process are sent to incineration or to cement kilns as an RDF (F3.03). An additional sorting output is added solely for the Dutch model, describing the flows of PET-tray-sorted products that are sorted but sent to incineration (F3.01b).

In Austria and the Netherlands, a part of residual waste is sent to a mechanical treatment process (F2.03). This is performed with different objectives in the two countries. In Austria, this is part of the general pre-treatment of residual waste, ensuring the stabilization of the residual waste before landfill while producing a waste stream that can be used as an RDF, and no plastics are recovered for recycling. In the Netherlands, however, residual waste is processed for the recovery of plastics as well, thus increasing the amount of waste sent to recycling in addition to the separately collected fractions. As in the case of F2.02, residual waste entering mechanical pre-treatment is sent to either further mechanical reprocessing (F3.04 and F3.04b), mixed plastics recycling (F3.05) or incineration (F3.06, where flows of PET trays sorted from residual waste—F3.04b—eventually converge). Landfilling of residues from mechanical pre-treatment is only performed in Austria (F3.07), and as this stream can include small fractions of plastic packaging, this flow is included in the model as well. In the Netherlands, this flow stream cannot be directly landfilled and has to be incinerated with the RDF fraction. Following the flows of food-grade regranulate (F4.01)—originating exclusively from recycling PET bottles—pure polymer and mixed plastics regranulates (respectively, F4.02 and F4.04) define the net material recycling potential. Finally, the residues from sorting and recycling processes, as well as untreated residual wastes, are sent to waste-to-energy facilities.

### 2.3. Data Sources

The comparison in this paper is based on the data reported in the studies describing the respective countries: Van Eygen et al. [10] for Austria, Brouwer et al. [11] for the Netherlands and Picuno et al. [12] for Germany. In this sense, the data of the three studies were adapted to fit in a comparative framework, as explained in further detail in this section. The mentioned adaptations made justify the minor differences in the outcomes compared to the original studies. Nevertheless, in all instances, these differences fall within the uncertainty levels identified in the same studies. Particularly in the case of Germany and the Netherlands, for which the original data had a more extensive categorization, a higher level of data aggregation was needed, in order to end up with the four target flows of PET bottles, rigids, flexibles and others. Some variations exist in how each of the studies quantified plastic packaging waste flows. These variations as well as, where relevant, the adaptations made in the single models are briefly described below.

For Austria, detailed data on the outputs of the sorting process were available from the EPR scheme. Additionally, the contents of plastic packaging in residual waste were investigated for the EPR scheme using waste characterization, market research on the sales of relevant product types, as well as trade statistics. Therefore, for the data on waste generation and composition and for the sorting process, the study mainly relied on secondary information provided by the EPR scheme, and no additional waste characterization efforts were carried out by the authors. Treatment efficiencies for mechanical treatment and recycling were estimated using primary data for some processes, complemented

by literature data. Furthermore, the original study quantified PPW from all sources, whereas in this study, only PPW from private households is considered (i.e., collected in drop-off containers and through curbside collection). PPW from commercial wastes was therefore subtracted from the original model. Although the results of the original study refer to 2013, they remain relevant for the comparison. Since then, no major new waste legislation for packaging has been introduced, as the transposition of the new EU packaging directive [2] into national legislation is only expected for late 2021 or 2022. Therefore, the system of packaging collection and recovery has remained largely the same. This is illustrated by data from Eurostat, which show that the total plastic packaging waste generation per capita remained at 34 kg/cap until 2018, while the recycling rate decreased slightly from 34% in 2013 to 32% in 2018 [27].

For the Dutch model, all relevant material flows were sampled, sorted into 37 packaging categories, 7 non-packaging categories and 6 different material categories and statistically averaged per flow and mathematically processed to deliver the material flow analysis, as described in Brouwer et al. [28]. These data were aggregated on a higher level to be comparable to the categorization used in the Austrian study, namely PET bottles, other rigid packages, flexible packages and other packages. This also implies that all the amounts used in this study only relate to plastic packages, and contributions from non-packaging plastics were subtracted. Thus, the numbers for the amounts of washed milled goods are slightly lower in this study in comparison to the previous reported numbers [11].

For the German model, primary compositional data were gathered on the sorting stage. This was achieved by performing manual sorting analyses on the separately collected waste fraction as well as on the sorted products after the industrial sorting process. Manual sorting was performed based on 32 product types, of which 17 were plastic packaging types and the rest were either non-packaging plastics or non-plastic packaging and non-packaging, as described in detail in Picuno et al. [12]. The data were fed into a model having a similar structure as that in Brouwer et al. [11], which allowed us to model flows of each waste category from the sorting stage to the production of washed milled goods. Data on the DRS flow as well as on the packaging collected in the residual waste and sent to energy recovery were elaborated from literature sources, as in Picuno et al. [12].

### 3. Results

In the following sections, the plastic packaging waste flows for each of the countries are shortly described on a per capita and net weight (without contaminants) basis, after which the three systems are compared in depth.

#### 3.1. Household PPW Flows in Austria

The results of the MFA for waste packaging plastic flows in Austria for 2013 are displayed in Figure 2. The total waste production was 25.44 kg/cap (215,000 Mg), composed of 21% PET bottles, 29% rigids, 37% flexibles and 13% others. Around 60% is collected separately, with the highest values for flexibles (77%) and PET bottles (61%). In the sorting process, around half of the waste input is recovered and sent to recycling. The sorting process mainly focuses on the production of fractions destined for single-polymer recycling (99% of outputs going to recycling), and mixed-polymer fractions are mainly recovered thermally. PET bottles especially display a high sorting efficiency (83%), whereas rigids (44%), flexibles (40%) and others (10%) are recovered to a lesser extent. The input into recycling thus amounts to 29%, while the losses in this process reduce this value at the output to 23%.

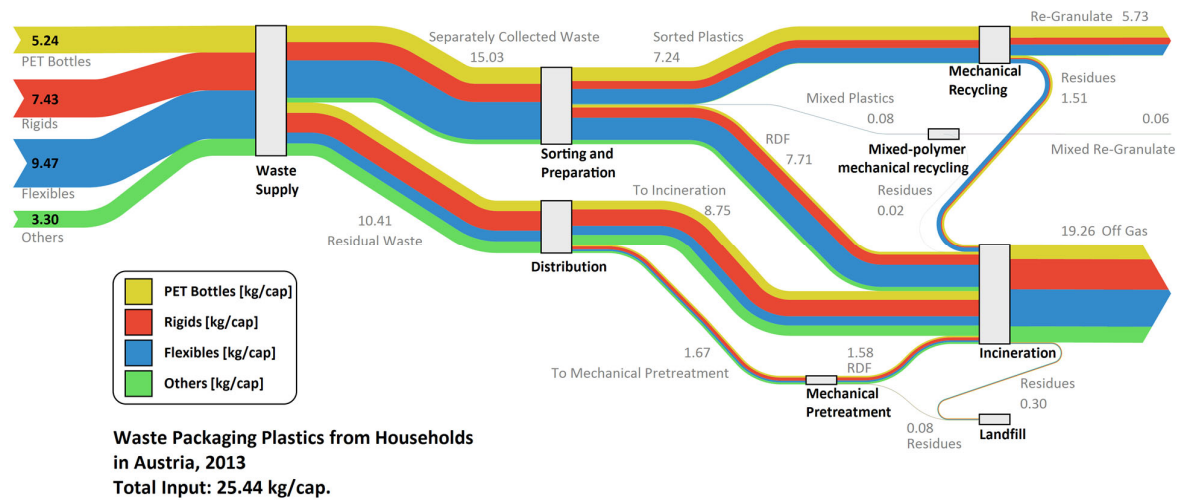


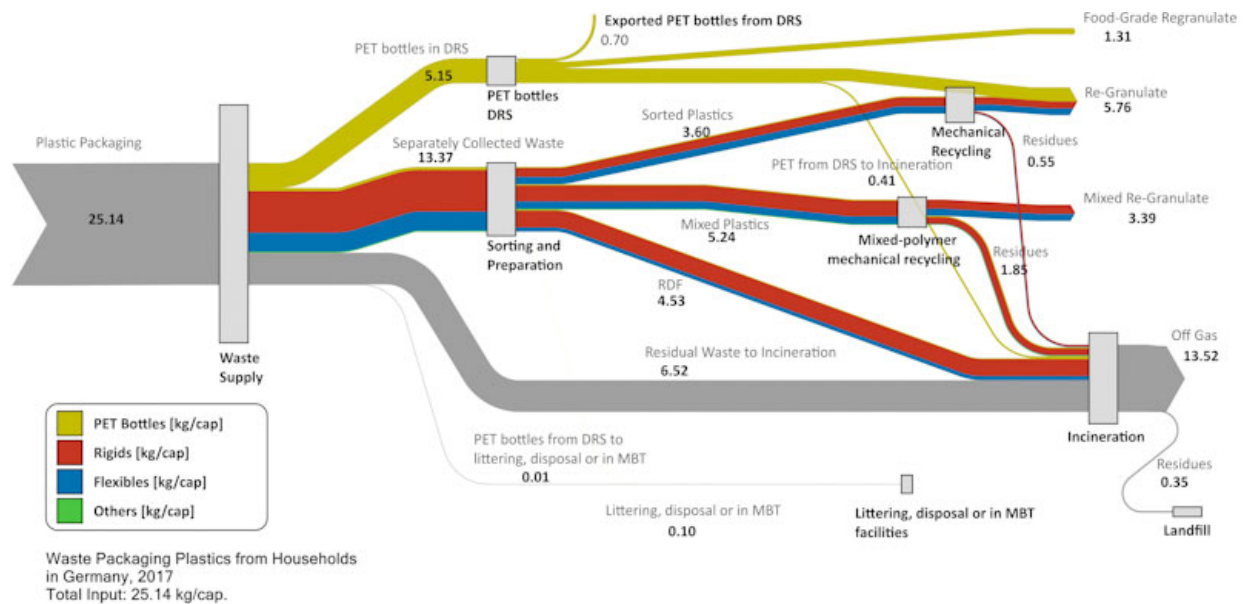
Figure 2. Waste packaging plastic flows from households in Austria in 2013 (kg/cap).

Plastic packaging in residual waste is mainly incinerated directly, while only a small fraction is first sent to mechanical pre-treatment, during which the plastics end up in RDF fractions, which are subsequently incinerated as well. Only minor waste flows, namely, losses from mechanical pre-treatment and residues from incineration, are landfilled.

### 3.2. Household PPW Flows in Germany

In 2017, 25.14 kg/cap of plastic packaging waste was generated by German households, as pictured in Figure 3. Differently from the models of the other two countries, no compositional data were gathered for PPW in residual waste. For this reason, the distribution of PPW according to the four packaging categories is operated only on the separate collection systems. In all, 88% of waste PET bottles (smaller and bigger than 500 mL) were collected through the DRS, with 424,938 Mg channeled into this system. Of these, 14% was exported for recycling, whereas 334,490 Mg was transformed either into food-grade regranulates (32%) or into films, fibers or other non-food contact applications [29]. As for the separate collection stream, 13.37 kg/ca PPW was separately collected, with this fraction mostly composed of rigid plastics (64%), followed by films (29%), PET bottles (5%) and EPS-based packaging (2%). At the sorting stage, the efficiency of correctly sorting into the respective sorted product (e.g., PET-based packaging in the PET sorted product) calculated on the basis of the material entering the sorting process was 35% for PET bottles, 21% for rigid plastics, 39% for films and 9% for the “others” category. For all categories, the highest fraction was sorted into the mixed plastics sorted product (respectively 37%, 38%, 39% and 84%). The rest was either sorted into the residues or wrongly sorted into the non-polymeric sorted products (e.g., aluminum, beverage cartons, tin plate). Overall, accounting for both Dual System and DRS collections, 108,484 Mg of food-grade regranulate, 475,510 Mg of regranulate and 279,363 Mg of mixed plastics regranulate were produced.

Residues from sorting and mechanical recycling processes, as well as the fraction of PPW collected in the residual waste, were sent to incineration, resulting in 1,115,502 Mg of off-gasses and only a minor fraction of incineration bottom ashes to be landfilled.



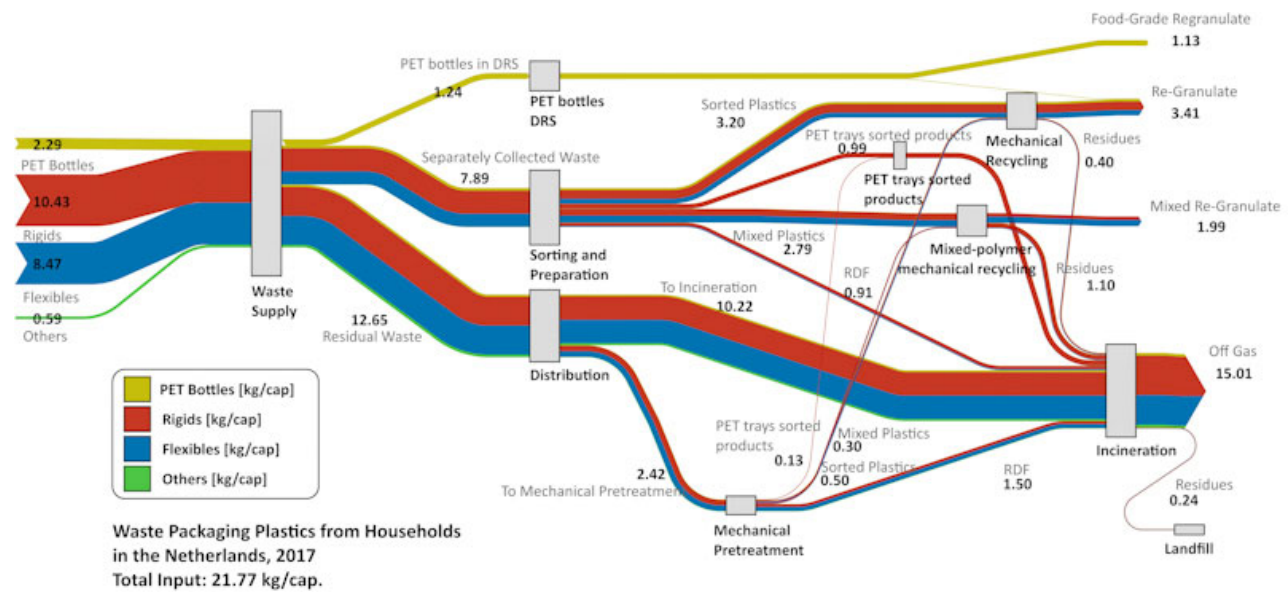
**Figure 3.** Waste packaging plastic flows from households in Germany in 2017 (kg/cap).

### 3.3. Household PPW Flows in the Netherlands

The per capita production of PPW from Dutch households was of 21.77 kg in 2017 (refer to Figure 4). Circa 87% of these are represented by two of the four packaging categories considered, namely, rigids (48%) and flexibles (39%). The DRS also performed fairly well in the Netherlands, capturing 95% of the bottles. The overall collection rate of all PET bottles amounted to 54% through this system (typically bottles with a >500 mL volume). Of the total amount of PPW collected with residual waste, circa 11% were further recovered and sorted for recycling, while the rest was sent to incineration. As mentioned in Section 2.1, sorting is performed according to three pure polymeric fractions (i.e., PET bottles, PE and PP), two product types (i.e., PET trays and films) and one mixed plastics fraction. Except for circa 1.12 kg/cap of PET trays that, after sorting, are sent to incineration, a total of circa 3.70 kg/cap and 3.08 kg/cap are sent to pure polymer and mixed polymer mechanical recycling, respectively. Specifically, for the separately collected waste, the following sorting efficiencies were found: 79% for PET bottles, 37% for rigids, 39% for films and 9% for the “others” category. These are calculated on the total amount of each category entering the sorting process. For the same waste flow, 10% of PET bottles, 29% rigids, 51% films and 46% of “other” entering the sorting facility were sorted in the mixed plastics fraction.

Finally, 19,248 Mg of food-grade regranulate was produced from mechanical recycling of PET bottles from the DRS, 58,291 Mg was the net amount of re-granulate produced and 33,945 Mg the amount of MPO.





**Figure 4.** Waste packaging plastic flows from households in the Netherlands in 2017 (kg/cap).

### 3.4. Collection Rates, Sorting Efficiencies, Recycling Rates

The comparison of the three countries is made based on the following indicators: separate collection rate (CR), sorting efficiency (SE), recycling input rate (RRi), and recycling output rate (RRo), as defined below:

$$CR = \frac{\text{mass of collected waste destined for sorting}}{\text{mass total waste}}$$

$$SE = \frac{\text{mass of sorted waste destined for mechanical recycling}}{\text{mass of collected waste destined for sorting}}$$

$$RRi = \frac{\text{mass of sorted waste destined for mechanical recycling}}{\text{mass total waste}}$$

$$RRo = \frac{\text{mass of recycling output (washed milled goods or regranulate) used for material applications}}{\text{mass total waste}}$$

The results of these indicators are presented in Table 2.

**Table 2.** Separate collection rates, sorting efficiencies and recycling rates. The corresponding values for PET bottles, rigid, flexible and others are provided in the SM.

Indicator	AT	DE	NL
CR (including PET DRS)	-	74%	42%
CR (excluding PET DRS)	59%	67%	38%
SE from separate collection to single-polymer recycling	48%	27%	53%
SE from separate collection to mixed-polymer recycling	1%	39%	35%
SE from separate collection total	49%	66%	88%
SE from residual waste to single-polymer recycling	-	-	26%
SE from residual waste to mixed-polymer recycling	-	-	12%
SE from residual waste total	-	-	38%
RRi single-polymer recycling	28%	36%	28%
RRi mixed-polymer recycling	0%	21%	14%
RRi total	29%	57%	42%
RRo single-polymer recycling	23%	29%	21%
RRo mixed-polymer recycling	0%	14%	9%
RRo total	23%	43%	30%

## 4. Discussion

### 4.1. Deposit Refund System for PET Bottles

The DRS for PET bottles represents the best example of a highly efficient collection strategy. The Dutch operator SRN estimates the capture rate to be roughly 95%, and the German data prove that almost 92% of the bottles put on the market are successfully captured and channeled into mechanical recycling routes (either inland or abroad). On the other hand, without a DRS system in Austria, a separate collection rate of only 64% is achieved for PET bottles. Therefore, the DRS system has extraordinarily high potential for the achievement of material circularity. This is particularly relevant in view of the requirement contained in Directive 2019/904, according to which, in all EU member states by 2029, at least 90% of the single-use plastic products placed on the market should be separately collected [30]. Consequently, the Netherlands will expand its DRS system in July 2021 to include small PET bottles for water and soda drinks. Moreover, since there are only a few incumbents, design-for-recycling issues are quickly addressed and corrected, so that the polymeric purity of the rPET is maintained.

Nevertheless, the concept of closed-loop recycling is still far from an actual scaled-up implementation. Two perspectives exist in this context: one focusing on the quantity of material available for the same application and the second one looking at the quality of the material. The presence of high amounts of recycled material provides no assurance as regards reaching closed-loop recycling. Specifically, 32% of the PET bottles collected through the DRS in Germany are recycled for food contact applications. This is certainly a high figure, especially if compared to that of other material streams, yet a substantial level of uncertainty exists on whether it can further increase in the next future or, in other words, if closed-loop recycling is at all a realistic goal for any product type. In this context, the most limiting issue is related to intentionally added substances (IAS) and, above all, to non-intentionally added substances (NIAS) [31,32]. The latter are substances that occur in practically all materials used for packaging (whether virgin or recycled) as a consequence of use, manufacturing processes or reaction between a polymer's constituting material and external factors [33–35]. On the other hand, there are substances that are intentionally added during manufacturing—calcium stearate as a release agent and carbon black as a pigment, to name a few. The element of concern is represented by the fact that the number and, most importantly, the nature of such constituents is still not completely known [36]. Additionally, some chemicals are proven to potentially migrate into packaged products [37], thereby constituting a food safety hazard [38]. Some chemicals have a known structure which allows for a clear determination of their potential risk as carcinogenic, mutagenic or reprotoxic (CMR) substances. Other chemicals' structures and associated health hazard are still unknown, and their detection may be unfeasible with the currently applied analytical methods [36]. This is by far one of the most relevant issues that needs to be fully investigated when considering whether to implement technical and marketing strategies for closed-loop recycling.

### 4.2. Mechanical Recovery of PPW from Mixed MSW

The mechanical recovery of plastic packaging waste from mixed municipal solid waste started in 2009 in the Netherlands at two material recovery facilities (MRF). In 2011, a third facility followed, and mid-2017 a fourth facility became operational. In 2021, a total of six recovery facilities are operational. In 2017, the capacity was 527,000 Mg input MSW, and this has risen to 1,445,000 Mg input MSW in 2021. The initial three MRFs were existing MRFs that were retrofitted to also recover plastics and beverage cartons from MSW. The three later MRFs were constructed as a response to the disappointing results of separate collection of PPW in the urban centers of the western parts of the Netherlands. Only small amounts of PPW were collected with elevated levels of non-targeted contributions. The low collection rates were attributed to low participation rates [39]. The quality of this separately collected PPW was so poor that substantial amounts had to be rejected and incinerated.

The six MRFs produce two types of plastic concentrates: one rigid plastic concentrate, mainly composed of bottles, pots, tubs and trays, and a flexible plastic concentrate, mainly composed of carrier bags, flow packs, pillow packs and stand-up pouches. Both are separately sorted in sorting facilities to produce the same type of sorted products as those produced from the separate collection of LWP. Although sorted products that originate from separate collection and mechanical recovery both comply to the named DKR specifications [16], they still differ slightly. As expected, the level of attached moisture and dirt is slightly higher for mechanically recovered and sorted plastics than for separately collected and sorted plastics [11]. Conversely, recovered and sorted plastic products contain slightly less non-targeted plastics (PS, PVC, etc.) in comparison to separately collected and sorted plastics, presumably because the former have been sorted twice with NIR sorting machines and the latter once [11]. These sorted products are traded with certified recycling facilities [40]. At first (2009–2010), most recycling facilities were hesitant to accept and process mechanically recovered and sorted plastic products, since these contain more attached dirt to be removed, and not all recycling facilities were equipped to deal with this. In 2017, several dedicated recycling facilities for recovered sorted plastic products were operational, along with the bulk that simultaneously process sorted products from both origins and a few recycling facilities that only process separately collected and sorted products. The quality of the recycled plastic products of both origins is comparable to a large extent for most quality aspects: color, optical and mechanical properties. The polymeric purity of recovered plastics tends to be slightly higher compared to separately collected plastics, but these small differences are unlikely to affect the mechanical properties [11]. The particle contamination of recycled PET (the only polymer for which this parameter can be measured fairly easily) tends to be higher for recovered plastics [41]. The odor of cold-water-washed recovered film material tends to be pungent phenolic ink-like, whereas the odor of cold-water-washed separately collected film material tends to be rancid-fruity. In cases where both film products are washed with hot water, the recovered material smells soap-like, and the separately collected material still smells rancid-fruity [42]. Similar experiments with Spanish film material yielded slightly different results, showing that Spanish separately collected film material smells earthy and moldy, whereas Spanish recovered film material smells cheesy and fecal [43]. These differences in odor between Dutch and Spanish film samples are not completely understood yet and for the moment are attributed to differences in temperatures that result in differences in decomposition of the organic part of MSW.

As the quality of recycled plastics originating from MSW is relatively comparable to the quality of recycled plastics originating from separate collection, both amounts of recycled plastics are combined to calculate the formal recycling rate in the Netherlands. In other European countries, recycled plastic from MSW is not formally accepted as a form of recycling and hence not accounted for in the recycling rates. This issue is also relevant for the calculation of the separate collection target for PET bottles as mandated by the single-use plastics directive [30]. These legal differences might stem from differences in qualities of recycled plastics from MSW in the various countries and different levels of necessity to account for these numbers to achieve the recycling target.

#### *4.3. The Necessity to Create Added Value for Mixed Plastics*

Both in Germany and in the Netherlands, substantial amounts of plastic packages are sorted to the sorted product named “mixed plastics” according to the specification DKR 350. This is traded to dedicated recycling facilities that produce recycled mixed plastics under the condition that a service fee is paid. These mixed plastics are mostly composed of polyolefins [44] and are used in relative large applications—pallets, garden pots, garden palisades, etc. [45–50]. The capacity of mixed plastic recyclers is limited, and most of them are not planning to expand this capacity, since the market for their products is limited. In the last five years, the supply of sorted mixed plastics has increased as a consequence of governmental policies to target higher recycling rates, but the demand for mix

recyclers has remained nearly constant. In Austria, on the other hand, the focus on mixed plastics lies mainly in its use as an alternative fuel in the cement industry. This leads, among other factors, to a very high thermal substitution rate of 81% in 2018, compared to 69% for Germany and averages for the EU28 of 48% and the world of 18% [51].

Although the production of mixed plastics can be limited with stricter sorting policies, its production can currently not be avoided [28]. Any sorting operation with plastic waste will create a “mixed plastic sorted product” of objects that cannot be sorted positively into one of the valuable sorted products (PET bottles, PE rigids, PP rigids and PE film) for three main reasons. Firstly, some targeted plastic objects have complex designs (often featuring a combination of different polymers and/or materials for the different packaging components), or they have a black color, or they are too contaminated and/or deformed to be positively sorted. Secondly, there are also non-targeted plastic objects present (PS, PP films, laminated flexibles, etc.). Thirdly, the current sorting technologies have limited efficiencies, implying that some targeted objects will not end up in the desired sorted products.

Redesigning non-recyclable plastic packages to recyclable plastic packages or packages of alternative materials is partially possible. Adaptation of these alternative packages can, however, result in dilemmas; non-transparent packages with reduced consumer appeal can result in lower sales and reduced keepability which can, in turn, cause increased food waste [52–54]. Consequently, the level of non-recyclable plastic packages is currently only reducing gradually [55], even though multiple producers have pledged that their packages will be recyclable in 2025 or 2030 [1], and therefore, the need for a mixed recycled plastic fraction will remain in the coming decades [28].

Recycling schemes with high collection rates and relative low recycling targets can focus on the sorting of valuable sorted products, after which they can sell the mixed plastics as RDF for waste-to-energy operations or export them (this was the situation in Germany up to 2020 and of Austria). Recycling schemes with more moderate collection rates and relatively high recycling targets do also need to recycle sorted mixed plastics (the Netherlands, Germany from 2020 on). However, with an oversupply of sorted mixed plastics and under-demand at the recycling facilities, this introduces friction to the market, as well as rising service fees, stricter acceptance criteria, etc. To alleviate this mismatch in supply and demand, several European petrochemical companies are establishing pyrolysis facilities to process sorted mixed plastics into a pyrolysis oil that can be converted into a cracking feedstock [56–59]. Some of these new facilities have just commenced operation (OMV, Renasci), while others are filing permits and plan to be operational in 2022–2025.

The pyrolysis of mixed plastics produces pyrolysis oils with too high concentrations of heteroatoms (O, N, Br, Cl, S, etc.) [60]. Therefore, this material needs to be sorted to remove objects with high concentrations of these elements, such as specific types of PET packages and specific types of multi-layered flexibles [61]. The pyrolysis process itself is claimed to have yields of up to 80% [62] (from mixed plastics to pyrolysis oil). However, representatives of operational facilities state that these are volumetric yields (% v/m) and that the mass yields are closer to 50–60% (m/m). This pyrolysis oil needs an additional processing step to make it suitable as cracking feedstock, lowering the mass yield. Thus, although the new pyrolysis route can alleviate the supply and demand mismatch for mixed plastics as well as contribute to the production of food grade recycled plastics, it will marginally help EPR scheme operators to attain the recycling targets. Moreover, it is unclear if this activity can count toward reaching recycling targets, especially if pyrolysis oil is introduced into conventional refinery and is therefore mainly used energetically. EPR scheme operators that are forced to attain recycling targets might therefore still prefer the mechanical recycling of mixed plastics (open-loop) over the chemical recycling route (closed-loop).

#### 4.4. Contextualizing Recycling Targets and Ensuing Policies

DRS on well-defined packages such as PET bottles achieve high capture rates, proving that the system could well support member states in the successful implementation of

EU directive 2019/904. Unfortunately, its success depends on its limited scope, and it cannot easily be expanded to packages other than bottles and cans.

A separate collection system is required to collect all types of PPW. The national recycling targets of Austria and Germany up to 2020 were moderate, and with the relative high collection rates, EPR scheme operators could comply easily by recycling the relatively valuable rigid packaging plastics and sending most of the flexible and non-recyclable packaging waste to incineration. In 2019, German recycling targets were raised, and the EPR scheme operators will now have to recycle more flexible and non-recyclable packages to produce mixed polyolefins and recycled mixed plastics. The Netherlands started much later than the other two countries (in 2009) with a separate collection system, originally only for PPW and, from 2015, expanded to LWP.

In the rural areas of all three countries, separate collection systems for LWP were easily implemented and proved to be effective. In most cases, the houses in these regions have sufficient space to keep the LWP separate, and the population was easily motivated to participate in these separate collection schemes. In Germany, bins in rural areas were able to capture almost 70% of the potential LWP generated per capita [63]. In the Netherlands, separate collection systems failed to deliver in the larger urban centers. In these cities, only drop-off facilities could be accomplished, which resulted in too-low participation rates. Due to the ambitious high recycling targets set by the Dutch national government, in combination with the large share of the population living in urban centers in which the separate collection system caused low collection rates, the Dutch EPR scheme operator was forced to recycle all collected plastic packages and hence to maximize the amount of sorted mixed plastics that was sent to recycling. Additionally, they were forced to establish MRFs for the urban centers to mechanically remove PPW from mixed MSW.

This implies that national governments of countries with predominantly rural areas can demand relatively high recycling targets, which can be achieved with separate collection systems. In cases where the recycling target remains below approximately 35%, only the relatively valuable rigid plastic packages need to be recycled, and the rest can be incinerated. In cases where the recycling target is set higher, then flexible packages and mixed plastics also have to be recycled. With the current portfolio of plastic packages and the high level of poorly or even non-recyclable packages, a larger share of plastics is recycled into non-circularly recyclable objects. Governments of countries with a relative high level of urbanization can either set a low recycling target and then operate mediocrely performing separate collection systems, or they can set higher recycling targets but then will have to rely on a combination of DRS and mechanical recovery to attain these targets.

As it turns out, not harmonized and, sometimes, conflicting management strategies—within and among EU Countries—have engendered instability in the plastic packaging recycling sector, which has been required to find solutions to problems that are currently barely understood by scientists and policymakers. In fact, with the best intentions to accelerate toward the circular economy, EU countries have put in place ambitious recycling targets [64], without first making sure that a strong and self-sustaining communication system exists between all involved stakeholders [65]. This inevitably created a rush to achieve the recycling targets by each member state—addressing exclusively the quantity of recycled material placed on the market—to the disadvantage of the quality of the produced recycled material [66]. Therefore, it should not surprise that, for the time being, 40% of converters in Europe consider the quality of the post-consumer recycled (PCR) material currently available on the market to be insufficient [67]. Further raising recycling rates will only result in the production of increasingly lower-quality recycled plastics, for which there is hardly any market. Instead, new regulations should address the issue of quantity and quality of the produced recycled plastics in a harmonized manner. For instance, this could be achieved by regulating the packaging market and favoring the implementation of design-for-recycling strategies. The current challenge for policymakers is to develop policy interventions that can most effectively facilitate the mass adaptation of design-for-

recycling measures by the FMCG industry and simultaneously align all other actors (collection agencies, sorting and recycling facilities) to produce more high-quality recycled plastics. This would facilitate the development of a more circular economy. In this sense, an eco-modulation of EPR fees, whose structure can be disaggregated per packaging category, might represent a good driver for implementing design-for-recycling guidelines. For instance, EPR fees for mono-material packaging (as far as the main packaging as well as secondary components, such as labels and closures, are concerned) would result in a direct incentive for the producer to favor placing this material on the market. Some member states, such as Italy, have these systems in place, with the fee categories defined on the basis of the recycling and sorting capacities installed in the country [68]. Nevertheless, the implementation phase is still hampered by potential practical implications, e.g., choosing the right incentives for the right actor and finding effective control mechanisms, possibly in a harmonized manner through the European market [69]. In this respect, these future policies could potentially meet strong backlash from the marketing branches of the FMCG industry, which will experience restrained freedom in their packaging design.

## 5. Conclusions

The road toward the achievement of an ideal (or better idealized) circular economy is proving to be long ahead. The network of actors involved is complex. This, combined with the lack of scientific knowledge that one faces when addressing the issue of how their deeds influence the quantity and quality of recycled plastics, continues to feed the mismatch between supply and demand of recycled plastics from plastic packaging. In the present paper, it was shown that all three studied countries have developed recycling economies for their PPW, differing slightly with regard to the recycling rates and qualities of recycled plastics made. These differences stem from differences in recycling targets and collection options. The substantial contribution of mixed recycled plastics in calculation of the recycling targets was a relevant discussion point, stemming from the comparison of the RRo of Austria and that of the other two countries. In this context, the relevance of a discussion around closed-loop recycling is minimized when compared to the potential that needs to be found in new policy interventions.

None of these recycling economies represents a circular economy, since they all fail to actualize policy interventions that enforce design-for-recycling while simultaneously keeping stakeholders aligned. The future challenge is to improve the scientific understanding of the recycling system for PPW; to determine the breakeven point between quantity and quality of produced PCR material and quantify the extent to which design-for-recycling guidelines will resolve this tradeoff; and to develop effective policy interventions that support design-for-recycling.

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