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Eligibility of Post- Consumer Plastic Waste Recycling

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Abstract

Concept of recycling implies converting waste materials into new products, thereby reducing consumption of primary raw materials and saving landfill space. The well known pyramid of waste hierarchy favoring recycling over all kinds of waste disposal methods appears to be constructed during the time when European development strategy was still focusing on fast economic growth rather than on principles of sustainable development, preserving natural resources. However, when prioritizing recycling we have also to consider the fact that recyclability of a material depends on its technological adequacy to reacquire the properties it had in its original state as well as the fact that waste-to-energy is a recovery method, although it works as a final sink. Whatever the strategy, it does not seem to be legitimate to favor recycling when some other method, whichever it is, provides better solutions for the environment and the economy. Comparative analises scrutinizing environmental and economic performance of different systems of integrative waste management for selected materials can provide valid answers to such dilemmas. In this article, the focus is put on the alleged potential of plastic waste recycling methods regarding their ability to reduce consumption of virgin materials. By comparing mass and energy balances of two antagonistic, judiciously simplified systems of waste management, one with- and other without practising plastic waste recycling, we concluded the result is ultimately the same in both of these cases. Preserving natural resources, which is the main objective of waste recycling by definition, is therefore not fulfilled, while costs, environmental risks and emissions running such a technologically complicated system can be only larger than without recycling.

Key words: Post- Consumer Plastic Waste; Recycling; Integral System Of Waste Management; Waste To Energy; Comparative Analysis

List of abbreviations: EU (European Union); HDPE (high density polyethylene); IWM (integrated waste management); LDPE (low density polyethylene); MSW (municipal solid waste); PCPW (post- consumer plastic waste); PE (polyethylene); PET (polyethylene terephtalate); PP (polypropilene); PS (polystyrene); PVC (polivinyl chloride); RDF (refuse derived fuel); SRF (solid recovered fuel); WM (Waste management); WtE (waste to energy)

Introduction

In Slovenia, most of landfills were closed during the transitional time between 2000 and 2015, while the systems of IWM took over their role progresivelly. Similar processes were occuring in other EU countries during that period and earlier, too. Legislators promulgated new order as one which is based on the paradigm of circular economy and sustainable development. However, when contemplating reasonibility of managing some of the most important waste material flows today, such as those related to dry, combustible MSW fractions and those related to sewage sludges, the established IWM systems do not seem to be sustainable neither from the environmental nor from the economical aspect. Excessive environmental pollution with macro- and micro plastic blaming corporations and environmentally unconsiouss people for it rather than the system within which they are living and operating is one of such manifestations. Obiquitous presence of storage yards fully- filled with PCPW instigating casual fires releasing toxic pollutants into the air and soil is also indicative. Some critically oriented technologists and environmentalists working on the local level in WM sector in Slovenia already predicted such-an-outcome decades ago. The proposed suggestions to quantitatively compare performance of contrastingly conceived IWM systems in order to be able to select the best one based on criteria of the smallest environmental impact and smallest costs before implementing new regulations were not heard. Today, we are faced with the suspition that theoretical WM- related conceptions, such as

- Extended producer responsibility
- Hierarchy of (five) waste management methods
- "zero" tolerance for pollution and environmental risks
- Circular economy and sustainable development
- Obligatory public- domain- managed environmental protection services, etc.,

were not implemented into practice rationally. They seem to be largelly in collision with one– another, resulting in antagonistic rather than synergistic environmental and soc-economic effects.

According to the EU Directive [1], waste can contribute to reducing the Union’s dependence on the import of raw materials and facilitate the transition to more sustainable material management and to a circular economy model, which includes PCPW as an important resource. Consequently, member states have to provide an environment for businesses to recycle this waste efficiently, which is *via* establishing efficient collection schemes and effective sorting systems supported by an elaborate financing system, etc. As expected by a commonsense reasoning, the result is quite the opposite: this segment of circular economy appears to be uncompetitive and the resources managed unrationally. Smaller, short lasting success stories are exalted while the obvious technical fact that PCPW tipically contains high amounts of impurities to which plastic recycling methods are extremely sensitive is ignored. Indeed, it is possible to organize large scale production of thick- walled (heavy) plastic products even by using some selected polymer mixtures containing high contents of inert impurities as well, however, demand for such products is limited due to their inherently high cost, while the possibility for their repetitive recycling is miniscule. Legislators nevertheless persist pushing the narrative hoping for some kind of technological breakthrough to happen, although it is obvious the problem is conceptual rather than technological in nature. Failings of businesses operating in this segment of economy are perceived as a standard capitalism- related phenomenon: only the most innovative are expected to survive on the developmental path towards the sustainable society.

In European statistics, the entire mass of PCPW submitted to recycling companies is generally considered as being recycled [1]. This way of gathering data allows compliance schemes (i.e., third parties that help organisations meet the extended producer responsibility for packaging waste requirements) to formally comply with EU plastics circular economy action plan goals [2] much more easily. Secondary waste generated in recycling companies is classifed as industrial, obscuring statistical connection to PCPW's source of origin, which is municipal. However, when comparing environmental and economic performance of contrastingly conceived systems of IWM, the fact that large part of PCPW mass received in recycling companies is not transformed into the mass of new products can not be ignored. Much of this mass rather ends up in WtE plants against payment. Another "hidden" multifaceted phenomenon favoring reycling over energy recovery manifests itself as worsened quality of plastic products when they are made from recycled- rather than primary raw materials [3-5], triggering downstream effects like generation of larger quantities of new waste.

The comparative method and the related analises comparing effectiveness of differently designed systems of IWM is intended to be presented in the companion article. The focus of this article is put on analysing rationality of recycling PCPW and other low-value MSW-derived combustible fractions.

Estimating Content of Impurities Accumulating within the Recycling System

Let us suppose we want to evaluate the percentage of impurities which would accumulate within the products in the long run when performing recycling by continually remixing recycled- and virgin raw materials in the same proportion. The model additionally simplifies the reality by supposing that

- The same original batch of material is recycled over and over again
- The same percentage of new impurities (or any unwanted substances, typically absent in virgin materials) enters the circular system during each of the recycling steps
- Differences between many kinds of impurities are not considered as relevant

Such-a-model may not be of much value for waste recyclers, however, it can be one of the tools for researchers in the field of waste management for assessing general trends in raw material quality deterioration when performing repetitive recycling.

E.g., if the material for producing new goods was composed of 50% virgin- and 50% material which is going to be recycled for the first time harboring 5% impurities, mixed material would contain 2.5% impurities. The second batch for producing new goods would therefore contain 7.5/2 = 3.75 % impurities (because the part which is going to be recycled for the second time already contains 7.5% impurities, i.e., 5% brought-in anew plus 2.5% coming from the previously recycled batch). With continuing repetitions the percentage slowly rises to get the following result in the infinity:

$$2.5+2.5/2+2.5/4+2.5/8+2.5/16+2.5/25+2.5/26+....+2.5/2n+ ...... = 5\% \quad (1)$$

On average and in the long run, the mass of waste leaving the circular system should equal the mass of virgin material entering the circular system (i.e., 50% in the case presented above):

$$m_{virgin-materials-inputs} = m_{sinks} = m_{system-losses} + m_{ultimate-waste-disposal} \quad (2)$$

Relative amount of waste bound for ultimate disposal can be reduced if the recycled amount increased accordingly, however, we are potentially limited with some maximally tolerable percentage of unwanted substances entering the process of production of new goods. Alternately, we could try to reduce the amount of impurities contained within the recyclables by sorting and cleaning them thoroughly, however, such approach can be restricted, too, due to unacceptably high costs and/ or excessive environmental burden.

As shown in equation (1), when assuming constant ratio between virgin and recycled materials used in the process of repetitive recycling, the percentage of impurities usually approaches a certain limit level when the number of repetitions goes to infinity. The general formula for the related sum of series is:

$$D_{n-impurities} = \sum_{n=1}^{n} d_{impurities} * d_{Rc}^{n} \quad (3)$$

$D_{n-\ impurities}$ …. relative amount of unwanted ingredients present within the raw material prepared for the production of new goods after executing "n-th" recycling step

$d_{impurities}$ …… relative amount of unwanted ingredients contained within the processed recycled raw material (input of unwanted ingredients at each recycling step, considered to be a constant)

d_{Rc} …….. relative amount of recycled part of raw material, considered as a constant, set for the preparation of ultimate blend of raw material used for the production of new goods)

Using the formula (3), it would be interesting to evaluate general tendencies when the recycled amount is smaller or bigger than half. E.g., if the material to be recycled for the first time contains 10% of impurities and we mix 25% of such material with 75% of virgin material in order to prepare raw material for making new products, ultimate raw material contains 2.5 % impurities (virgin material + first time to be recycled material in the proportion of 3:1). By repetitive recycling ($n \to \infty$) we get the end result, which is 3.33% of impurities (3- times less when compared to the initial material, which had to be recycled for the first time). If the material to be recycled for the first time contains 10% of impurities, and we mix 75% of such material with 25% of virgin material in order to prepare raw material for making new products, the mix contains 7.5 % impurities (virgin material + first time to be recycled material in a proportion of 1:3). The second time prepared material contains 13.125% impurities (virgin material and 1- time already recycled material in a proportion of 1:3), while in the limit the material contains 30% impurities, that is, three times more than first- time to be recycled material.

We have also to consider impurities deriving from parallelly occuring processes of material degradation which are taking place during the recycling production events as well as during the products life-times and waste- stage periods [4]. The all- including formula could be written as:

$$D_{n-impurities} = \sum_{n=1}^{n} d_{impurities} * (d_{Rc} * f_d)^n \quad (4)$$

f_d ……….. recycling material degradation- rate factor ($f_d \geq 1$, usually $1 \leq f_d < 2$)

E.g., if 5% of impurities entered the recycled material during each recycling step (this can be expected when considering PCP-W) and the amount of recyclables intended for the preparation of granulate to produce new goods was 50% (other 50% being virgin material) and the estimated rate of degradation was f_d = 1.5 (characterising moderate degradation processeses, such as when recycling mixed post- consumer PET material), the relative amount of impurities when performing third recycling step would equal 8.672%. At high repetition numbers, the ultimate value would approach 15%. If the relative amount of recyclables was 100% (i.e., without any virgin material input), the level of impurities would rise to 35.6% already during the third recycling step. By inserting even worse data values into the formula, the end result (i.e., the percentage of impurities) would rise above the theoretically possible 100 %. As independent observers, it is therefore reasonable to be suspitious about the rationality to exercise PCPW recycling. The approach inherently implies ample insertion of virgin materials into the circular system in order to dilute the percentage of impurities and other unwanted ingredients, knowing the products will be of lesser quality anyway when compared to the ones which derive exclusively from virgin raw materials.

Estimating Recyclability of PCPW and the Related Repercussions

A lot of definitions of the recyclability concept can be found on the web [11, 12, 13], contemplating the issue from diverse technological-, economic- and environmental aspects. Regulatory, ideological and financial- stimulation- aspects can also be included into contemplation, prioritizing recycling over energy recovery methods as meritorious. However, a meaningful quasi-quantitative method of research to characterize recyclability of clean, industrial mono-waste streams already exists, i.e., by counting the number of technologically and economically successfully executed successive recycles which can be acquired within the closed recycling system, utilising one and the same batch of material. E.g., we already know that different plastic polymers have very different recycling potentials: PET can be thermo-mechanically recycled up to 8- times, HDPE up to 5- times (PE on average maybe 2- times, since LDPE does not appear to be recyclable at all, at least not in an economical way), while PP and PVC less than once on average. Some polymers can also be recycled as a mix, however, usually only once. Other polymer types appear to be mostly unrecyclable. Also, presence of certain additives can seriously impact the recyclability of otherwise recyclable polymers [3, 8, 9, 10, 14, 15, 28]. Composite materials are in general non-recyclable in an economical way, too [3]. Chemical methods of recycling plastic do also exist. They can be applied to all types of plastic and their mixtures, however, such approach has in general demonstrated to be technologically demanding, environmentally questionable and inherently uneconomical [10, 14, 15, 18, 19, 20]. We can conclude that the IWM system for managing PCPW favoring the method of recycling is logistically extremely complicated, technologically heterogenous and economically and environmentally vulnerable when compared to IWM systems designed to recycle paper, base metals or glass.

It would be desirable to logistically interconnect in such-an-unequivocal way defined notion of recyclability (i.e., by counting the number of successfully executed recycles) with general notions of recycled raw-material quality, lifespan of recycled goods and the related repercussions on waste generation rates comparing linear and circular economies performing recycling of low--grade recyclables. We can do this by introducing theoretical conceptions of relative producibility/ recyclability and relative quality of recycled raw materials. Quantities defined in relative terms are dimensionless, while the value of "one" (or 100%) can be reserved to characterize average properties of virgin raw materials for purposes of comparing them to the properties of the companion recycled raw materials, whose values therefore lie within the interval between zero and one generally. For researchers working in the field of WM, the most representative average properties of raw materials quality can be considered to be those which are acquired on multi- annual- and multi- national- level scales. E.g., when designating average relative quality of raw materials for producing PET with the value of 100%, we are referring to average technological properties of virgin raw materials characteristic for the present day developed countries. In this way characterised relative recyclability of 100% can be therefore backed not just with the loosely defined average value counting the number of successfully executed recycles performing recyclability tests (e.g., $n \approx 6$ for PET), but also with data sets derived by well established methods characterising reference technological properties of these virgin raw materials. However, we do not necessarily need to be acquainted with all the available information in detail to be able to compare performance of companion linear and circular economies. Here applied approach designating multifacetted recyclability parameters with unequivocal relative values can be perceived as an effort to simplify complex relations between the entangled quantities in order to become palpable for purposes of performing quantitative comparative analises. Parameters can be quantified with probability density functions rather than with discrette values. E.g., we can characterize the property of recyclability much more reliably by quantifying the acquirable number of successively executed recycles with an appropriate normal distribution (e.g., μ=6, σ=1 for PET).

The overall line of reasoning to assess the value of relative recyclability of recycled raw materials as a function of the applied number of executed recycles is quite straightforward. E.g., the information that PET can be recycled up to 8 times means that the quality of material of 8- times recycled PET deteriorates to the point it can not be successfully recycled for the ninth time, at least not in most of the real- life cases. It also means that raw material derived from 8-times recycled PET is of worse quality for making new PET products when compared to 7-times recycled PET. Therefore, in order to define producibility/ recyclability of a certain material, the personnel performing recyclability tests had arbitrarily (subjectively) to decide which recycling step to consider the last-one during which the quality has not deteriorated too much yet in order to still be deemed as successful. If we consider producibility and quality of average virgin raw material to equal 100% in the relative sense (in figure 1 depicted as a point with ordinate value of one when the abscissa is zero), relative producibility/ recyclability and quality of recycled raw materials can be valued as 100% only in the case of infinitely recyclable materials, such as Al cans (in figure 1 depicted as a dotted horizontal line with the ordinate- value of one). Relative recyclability and quality of recycled plastic raw materials is however much smaller than 1, declining towards the value of zero fast when rising the number of performed recycles (e.g., in figure 1 depicted with curves VIII, VII, IV, etc.).

We can suppose 25% deterioration in recycled raw material quality performing recyclability tests as an approximately acceptable margin the experts subjectively used when counting the number of successfully executed recycles for clean mono-waste streams (we will define this number as nacquirable). The slowest fall is characteristic for PET (nacquirable ≈ 6) and HDPE (nacquirable ≈ 4), respectively (curves II and III in figure 1).

However, the fall can also be immediate, as in the case of almost non-recyclable PS, which is not depicted in figure1. In this way, the impacts of repetitive recycling on recyclability and quality of raw material can be expressed in relative terms. These constatations are of course valid only vagualy and on average. Obviously, such type of information may not be practical for actual plastic recyclers or chemical engineers working in the sector, however, it can be useful for waste management researchers and decision makers to assess general long- term trends.

The proposed predisposition therefore is: "$n = n_{acquirable}$" → "Rec_r" (relative recyclability of the recycled raw material when compared to the virgin one) = "$q_{relative}$" (relative quality of the recycled raw material when compared to the virgin one) = 75% .

The same margin of 25% deterioration in quality properties can also be deemed as still tolerable or hardly detectable from the perspective of an average consumer buying such products. We have to be aware that substance ingrained within new products is usually only partly composed from recycled materials. Relative recyclability of raw materials prepared by mixing virgin and recycled ingredients is of course superior to raw materials composed from recyclables only. The higher the input of virgin ingredients, the slower the long-term fall of relative quality of raw materials for producing new goods, approaching some limit value lying between zero and one (in figure 1 presented by the curves V and VI).

The formula for assessing relative recyclability and quality of mixed (virgin + recycled) raw materials could be written as follows:

$$Rec_r = q_{\text{relative}} = 1 - d_{Rc} + d_{Rc} * f_{Rc}^{-n} \quad (5)$$

Rec_r …………….	relative producibility/ recyclability of mixed raw material
$q_{relative}$ …………….	relative quality of mixed raw material
d_{Rc} …………….	relative amount of recycled raw material contained within the mixed raw material used for the production- of new goods
f_{Rc} …………….	rate of raw material quality- decline- factor for repeatedly recycled materials
$f_{Rc} \approx 1 \rightarrow$	highly- recyclable material (e.g., Al and Fe cans)
$f_{Rc} \approx 1.5 \rightarrow$	poorly- recyclable material (e.g., loosely presorted post-consumer HDPE)
$f_{Rc} > 2 \rightarrow$	almost non- recyclable material (e.g., mixed post-consumer plastic waste)
n ……………….	number of executed repetitive recyclings

Supposing that recyclability of clean recycled material is known (given by the number of acquirable repetitions performing recycling tests within a closed system) and considering the fact that relative amount of recycled material executing such tests is 100% (dRc = 1, which means, no addition of virgin raw material is meant to enter into the circular system), the factor "fRc" can be calculated backwards using the equation (5), e.g.:

$$if\ (n_{acquirable} = 4) \longrightarrow f_{Rc}^{\ -4} = 0.75 \longrightarrow f_{Rc}^{\ 4} = 1.33 \longrightarrow f_{Rc} = 1.074 \qquad (6)$$

After calculating factors "f_{Rc}" for desired waste materials, relative- recyclability curves based on formula (5) can be drawn. Curves labeled II and III in figure 1 are sketched utilizing already mentioned information regarding recyclability of pure polymer materials (PET and HDPE, respectively). However, recycling companies often deal with materials, which are not so pure. They should perform recyclability tests utilizing their own raw materials or to provide some reasonable estimations for its relative properties. E.g., $n_{acquirable}$- value for some medium- quality, partly recycled HDPE- derived granulate can be estimated to be just "2" instead of "4" (~two times smaller recyclability rate when compared to virgin HDPE granulate). After calculating the related f_{Rc} - value, relative recyclability curve can be drawn as well (curve No. IV, figure 1).

Curve No. V in figure 1 characterizes raw material composed from 75% virgin HDPE and 25% medium-quality recycled HDPE (d_{Rc} = 25%, $n_{acquirable}$ = 2), while curve No. VI characterizes material composed from 25% virgin HDPE and 75% medium- quality recycled HDPE (d_{Rc} = 75%, $n_{acquirable}$ = 2).

The most recyclable PCPW item, i.e. PET bottles, is largelly not recycled back into PET bottles, which is due to rigorous requirements to produce food- contact- grade raw material and generally due to food safety- concerns [22]. PET- bottles are rather recycled into other PET products, like into PET (polyester) fibers. However, items like PET carpets are in practice drastically less recyclable compared to PET bottles. The curve numbered VII in figure 1 attempts to represent long-term recyclability of PET plastic in a more realistic way, supposing PET bottles to be largelly produced from 100% virgin raw materials and then, after becoming waste, i.e., during the first recycling step, largelly down-cycled into less recyclable or non-recyclable products. Therefore, the related curve is composed from two parts: gently inclined, high-recyclability-segment (considering $n_{acquirable}$ = 6) on the left side of the vertical line with the abscissa $n=1$, and more steeply inclined, low-recyclability-segment (in this case considering $n_{acquirable}$ = 1.2) on the right side of vertical line $n=1$.

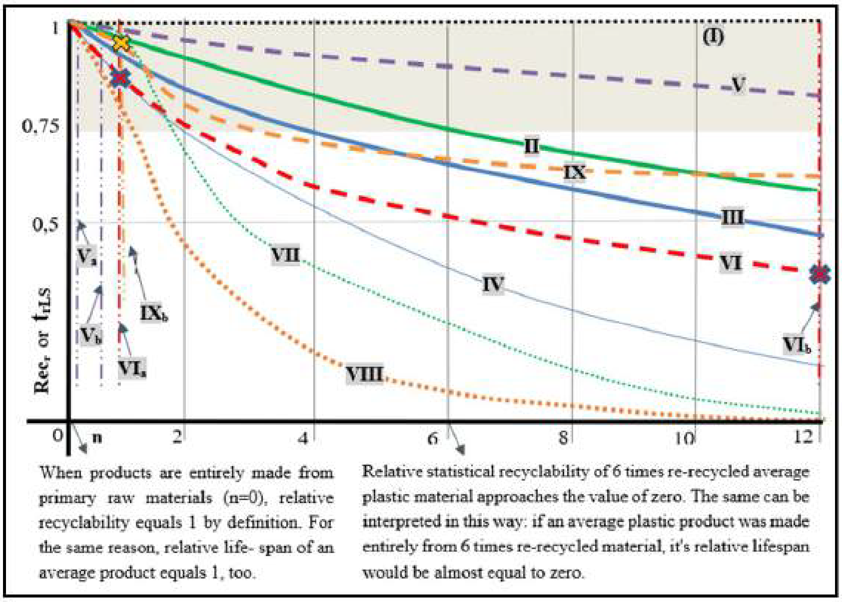

Figure 1: Relative recyclability (Rec_r) of plastic- waste recyclables. Also, relative lifespan (t_{rLS}) of plastic- waste- derived raw materials ingrained within the mono-material- composed products. Roman numbering related to the text in section 3

From the statistical standpoint, the notion of recyclability can be applied to plastic waste as a whole, too. This can be done by multiplying relative amounts of annually generated plastic waste by polymer type (as given by the official data, e.g., Official Journal of the European Union, 2018 [1]), with their recyclabilities (given by their $n_{acquirable}$ values) and summing the terms up in order to get information about the average $n_{acquirable}$ value for plastic waste as a whole. We have also to consider the fact that recyclability of PCPW is drastically smaller when compared to pre-consumer plastic waste, which is due to (1) technological and economical inability to satisfactorily separate mixed waste streams on all those fractions, which are theoretically recyclable, (2) the fact that external impurities and foreign additives can enter the circular system much more easily and (3) the need to consider realistic rates of polymers degradation (e.g., taking into account degradation effects occuring during the lifespan of products before becoming waste, too) [4, 6, 9, 11, 15, 16, 17]. Curve No. VIII sketched in figure 1 attempts to represent approximate relative statistical recyclability of an average PCPW assuming partial polymer inputs as follows: $n_{acquirable} = 1.5$ for HDPE, $n_{acquirable} = 4$ and $n_{acquirable} = 1.2$ for PET (i.e., considering the effect of down-cycling PET bottles into other PET products to a certain degree) and $n_{acquirable} = 0.4$ as a lumped-in value characterizing all the other post- consumer- grade- polymers combined.

Real- life recycling companies don't recycle one and the same batch of material. This can happen only when performing recyclability tests within a closed recycling system. They have to deal with mixed recycled material instead, typically composed from parts which were either once, twice or n- times applied in the process of making new products in the past. It is therefore necessary to estimate the average number of recycles characteristic for a considered raw material in order to be able to quantitatively estimate its relative properties. Portions of multiple- times recycled fractions of plastic waste tend to be much smaller when compared to the portion of once recycled fraction, because they were multiple times exposed to the probability of being droped out of the circular system, as opposed to the only once recycled fraction. This is due to the fact that recyclability of plastic-waste- materials is inherently low, which means, it is indispensable for plastic waste to abundantly sink out of the circular system, virgin materials replenishing the vacant mass accordingly.

Let us suppose we are dealing with an old, matured circular system, where raw material for producing new goods was/is constantly prepared by mixing virgin- and recycled materials in the proportion of 1:1 (i.e., $d_{Rc} = ½$). In this case, 50% of the recycled material consists from the substance which happened to be exactly once incorporated into the mass of recycled products in the past (i.e., as a virgin material) and is now going to be recycled for the first time. Then, 25% consists from the substance, which was twice incorporated into the mass of recycled products up to now and dedicated to be recycled for the second time, etc. In general, the sum of series looks like this:

$$\bar{n} = \frac{1}{2^1} + \frac{2}{2^2} + \frac{3}{2^3} + \ldots + \frac{n}{2^n} = 2 \;\; or \;\; \bar{n} = \sum_{n=1}^{\infty} \frac{n}{2^n} = 2 \quad (7)$$

From the formula above it follows that when the number of already performed recycling steps *"n"* within a circular system is high enough, the average number of executed recycles $n_{average}$ approaches the value of "2" (which means, the material appears to be recycled just two- times on average, even if the number of mathematically executed recycles was infinite). However, nowadays plastic recycling systems appear to be relatively young and the number of already performed recycles happens to be rather low. Younger circular systems exhibit lower $n_{average}$- values than the older ones, which means, the average quality of recyclates deteriorates as circular systems grow older. If the oldest substance present within the recyclate appears to be recycled two times up to now and is now expected to be recycled for the third time (i.e., the parameter "n" in formula (7) runs from 1 to 3 instead of from 1 to ∞), the considered batch of material is going to be recycled for the 1.375th time on average ($n_{average}$ = 1.375). If we additionally considered virgin material itself into the calculation for some reason, too, which forms one half of the ultimate raw material for producing new goods, $n_{average}$- value for the mixture as a whole would therefore be just 0.6875.

For any value of d_{Rc}, the formula (7) can be written as

$$\bar{n} = \sum_{n=1}^{n} = n * d_{Rc}^{n} \quad (8)$$

Once $n_{average}$- value is known, relative recyclability can be assessed. This can be done directly, by using formulae 5 and 6, inserting $n_{average}$ – value for the parameter *n*, or graphically, determining ordinate- value for the intersection between the given recyclability-rate curve and the related $n_{average}$ vertical line. For example, if raw material for preparing new goods is made by mixing 25% recycled- and 75% virgin material (d_{Rc}=1/4, as is the case with the curve No. V in figure 1), $n_{average}$- value will approach 0.44, if the number of recycles already performed in the past was high, and will of course be just 0.25, if the already performed number of recycles was nil. These two values are presented with two vertical lines (V_a and V_b in figure 1).

However, if the portion of d_{Rc} was 3/4, the $n_{average}$- value would be 0.75 in the case no recyclings were performed before and would approach the outstanding value of 12, if the number of recycles performed in the past was high. These two vertical lines are depicted as VI_a and VI_b in figure 1. Intersections with the correlated curve No. VI are marked as well. If the portion of d_{Rc} was even bigger, e.g., 9/10 (raw material for producing new goods consists primarily from the recycled material), the following relations can be calculated: if n = 1→ $n_{average}$ = 0.9 ; if n = 10 → $n_{average}$ = 10.92 ; if n = 15→ $n_{average}$ = 43.67. Therefore, when d_{Rc}>1/2 (i.e., when the recycled material amounts to more than half of raw material mass for producing new goods) the value of $n_{average}$ can easily rise above the acquirable recyclability values $n_{acquirable}$, characteristic for ideally clean polymers (n ≈ 6 for PET, n ≈ 4 for HDPE), which is of course impossible. Therefore, plastic-waste- circular economy is able to operate in a continual way only in the case the portion of recycled part of raw material (dRc-value) was small enough, much smaller than ½ in most of realistic cases.

We can broaden the already defined concepts of relative recyclability and relative quality of recycled raw materials with the interconnected concepts of relative lifespan of recycled products and relative rate of waste generation due to performing recycling of low-grade recyclables. If certain products are made entirely from virgin raw materials (their relative qualities are already characterised with the value of 100% on average), the lifespan of such products can also be characterised with the value of 100% in relative terms in order to be able to make comparisons with equivalent products made (partly) from recycled materials. Certain products are entirely made from just one type of recycled material (such as PET bottles), therefore, their average relative lifespan should correspond to the relative quality of the actual raw material they are produced from. Therefore, parameter- values of relative recyclability Rec_r and relative lifespan of simple monomer plastic products (like PET bottles) t_{Rc} appear to be equal (figure 1).

However, products are usually composed from different components, some of which may partly derive from recycled ingredients and some don't, etc. Lifespan of weaker components often decide the lifespan of aggregate/ composite- made products as a whole. Even in the case the weared or failed components were repairable or replacable, people tend to toss low-valued aggregate products entirely. Therefore, if we supposed relative lifespan of recycled aggregate products to be mathematically dependent only on relative amounts of ingrained recycled materals they contain and their relative recyclabilities, we would considerably overestimate the average relative lifespan- value of such products. Some proportionality factor value F_{wci} should be proposed in order to consider the impact of shorter lifespan of weaker components on the lifespan of an averagely compounded product as a whole. $F_{wci} = 2/3$ seems to be an acceptable, conservative- enough value used for the purpose. Of course, to be more reliable, we can use some reasonable probability density function for the factor F_{wci} rather than a discrette value.

Formula for assessing relative lifespan of recycled products is therefore similar to formula (5), assessing relative recyclability values:

$$t_{Rc} = t_{prim} * \left[(1 - d_{Rc}) + d_{Rc} * f_{Rc}^{-n}\right] * F_{wci} \quad (9)$$

t_{Rc} .... average relative lifespan of raw materials incorporated into the related products before becoming waste

$t_{prim} = 1$ .... relative lifespan of products made exclusively from primary- or infinitely recyclable raw materials

d_{Rc}, f_{Rc}, n .... as explained in the formula 5

F_{wci} .... weak- component- impact- factor (to consider shortened lifespan of an average product)

The phenomenon of shortened lifespan of recycled products comparing them to ordinary products retrospectivelly manifests itself as an increase of annual quantity of generated waste associated with them, as written below:

$$q_{r-Rc} = q_{r-withoutRc}/t_{Rc},\ or\ q_{r-withoutRc} = q_{r-Rc} * t_{Rc},\ or\ q_{IWM-2} = q_{IWM-1} * t_{Rc}\ (10)$$

$q_{r-Rc} = q_{IWM-1}$........................ relative quantity of waste generated when performing PCPW recycling

$q_{r\text{-}without\ Rc} = q_{IWM-2} = 1$ .... relative quantity of waste generated without performing PCPW recycling

Relations between all of the four introduced parameters (i.e., relative producibilty/ recyclability of the recycled raw material, relative quality of the recycled raw material, relative lifespan of the recycled materials while being ingrained within the related products and relative rate of waste generation) are presented in table 1.

Table 1: Proportionality connections between parameter values associated with the notion of recyclability

Relative producibility/ recyclability of raw materials	Relative quality of raw materials	Relative lifespan of newly produced goods	Relative rate of waste generation
Virgin Rec_r = 100%	*Virgin* $q_{relative}$ = 100%	*related to the portion of ingrained virgin raw materials* $t_{Rc} = t_{prim}$ = 100%	*related to the portion of ingrained virgin raw materials* W_r = 100%
Recycled Rec_r = (0 – 100)%	*Recycled* $q_{relative}$ = (0 – 100)%	*related to the portion of ingrained recycled raw materials* $^*t_{Rc} = Rec_r \cdot F_{wci}$ [%]	*related to the portion of ingrained recycled raw materials* $W_r \geq 100\%$
$Rec_r = q_{relative} \propto t_{Rc}$			$W_r = t_{Rc}^{-1}$

** for monomaterial products, the relation is $t_{Rc} = Rec_r = q_{relative}$.*

E.g., if HDPE products contained 10% of recycled material of 80% average relative quality, the concept implies relative lifespan of HDPE- only made products would diminuish according to the factor of (0.1·0.8) + 0.9·1 = 0.98 (i.e., for 2%) when compared to equivalent products made fully from virgin materials. However, when we want to consider relative lifespan of the total mass of HDPE ending up being ingrained within the sum of all goods produced in one year in some country, the issue of shortened lifespan of an average product should be considered, too, taking the factor F_{wci} into account. E.g., if HDPE raw material on average consisted from 10% recycled material of 80% relative quality and 90% from the virgin HDPE, the concept implies relative average lifespan of HDPE ingrained within the average product to diminuish according to the factor of (0.1·0.8)·2/3 + 0.9·1 = 0.9533 (i.e., for 4.5%) on average when compared to the situation, if raw materials originated from primary sources only. Although HDPE- related waste appears to be heavily mixed with other kinds of materials and dispersed among plethora of different waste sub-streams, relative increase in HDPE- related waste generation can be therefore roughly assessed. In this case, yearly amount of generated HDPE waste would increase according to the factor 1/0.9533 = 1.049 (i.e., for 4.9%) when related to the situation HDPE- containing products were fully made from virgin raw materials.

If we display Germany as a model technologically highly developed, environmentally- conscious- country, where recycling is systematically favorized and a lot of the related research is going on for a long time, we can still constatate that only 1/3 of generated plastic waste was recycled (part of which outside Germany) in 2018 (32% mechanically, 1% chemically). The rest almost entirely ended in incineration- and co-combustion plants and kilns [3]. The related relative recyclability- rate curve for an average plastic waste mix which consists from 66% virgin- and 34% recycled raw material ($d_{Rc} = 0.34$) is marked as No. IX in figure 1. We can calculate the related value of $n_{average}$ to be 0.8. Relative recyclability can be then calculated, too: $Rec_r = \sim 0.93$. Grafically, this is presented by the ordinate value for the intersection IX_b, figure 1. Estimated relative lifespan of an average product containing recycled plastics is somewhat smaller, due to the weak-component-effect: $t_{Rc} = 0.93 \cdot 2/3 = 0.62$.

According to the above assumptions, 1.61– times more waste is generated when practising PCPW recycling ($W_r = 1/0.62 = 1.61$) than without performing PCPW recycling. We can broaden this estimate to include all low-grade combustible recyclables deriving from light, dry MSW fractions, such as composite beverage packaging. Namely, PCPW represents the vast majority of light weight MSW fractions diverged into recycling (paper waste is not included, because it is always collected separately). This portion of MSW- stream, when considered together, can be designated as light- weight, low- grade recyclables ($_{lg}Rc$). The symbol of $_{lg}Rc$ should be reserved only to characterise sub-portion of light- weight miscellaneous MSW which really ends up as a substance ingrained into the new products. In contrast, high- grade recyclables ($_{hg}Rc$), like metal cans outsorted from mixed packaging waste almost entirely end up their life as a substance ingrained into the new products.

IWM systems operating in the developed world today generally favor recycling over energy- recovery methods for treating light weight fractions of MSW; such system can be vaguely labeled as IWM_1 in formula (10). By employing the recommended system IWM_2, which does not support recycling of combustible materials of low value and recyclability, the quantity of newly generated waste would therefore decrease by some factor around the value of $t_{Rc} \approx 0.62$, that is, the quantity would be reduced by some 38%. This reduction applies only to that part of total MSW mass flux, which ends up being ingrained within the structure of new plastic and other low- grade recyclables derived products. If we need to present relative decrease of annual waste generation in terms of generated mass of MSW as a whole, the expression would be

$$q_{MSW,IWM-2} = q_{MSW,IWM-1} * (1 - t_{Rc} * {}_{lg}Rc) \quad (11)$$

The portion of low- grade recyclables incorporated into new products amounts to some 6% of MSW mass ($_{lg}Rc = 6\%$ can be considered as an optimistic estimation characteristic for actually operating IWM_1 systems in the developed world today), therefore, the quantity of newly generated MSW as a whole would decrease for some 3.7% by employing the recommended IWM_2 system (since $t_{Rc} \cdot {}_{lg}Rc \approx 3.7\ \%$).

Taking measures intended to reduce the amount of generated waste is deemed to be the most preferable approach considering 5-step hierarchy of WM methods. Namely, decrease in generated waste automatically results in proportional decrease of all kinds of emissions which would be caused by treating this waste on its path from the cradle to the grave:

$$\text{All-kinds-of-spec.-emiss.}_{(IWM-2)} = \text{All-kinds-of-spec.-emiss.}_{(IWM-1)} * (1 - t_{Rc} * {}_{lg}Rc) \quad (12)$$

Contemplating Differences in Paper- and Plastic- Waste Recyclability

In some cases, circular economy appears to be essentially more effective than the linear- one. E.g., some base metals can be recycled infinite number of times in an economically effective way, which is also environmentally an fundamentally better approach than mining and smelting metal ores. However, many recycling- industry- branches are faced with the reality that quality of recycled material deteriorates progressively when performing repetitive recycling. E.g., when paper waste passes through a series of recycle, cellulose fibers become shorter and stiffer [26, 27]. Similarly, when plastic waste passes repeatedly through a series of recycle, photochemical, radiological, mechanical, chemical, thermal and hydrolitic processes of polymer degradation are taking place (not just during the production events, but during the lifespan of produced goods and waste- storage periods, too) [3, 4, 10, 14, 15]. Relative amount of hardly removable, damaging foreign matter rises progressively within the circular system in the form of external impurities and foreign polymers as well as in the form of additives or their residues already ingrained within the recyclables (such as UV and thermal stabilizers, pigments, fillers, crosslinkers, plasticizers, hardeners, flame retardants, antioxidants, antimicrobial additives, antistatic and foaming agents, etc. [3, 4, 10, 22]).

Virgin material has to be added continuosly to retain satisfying quality of the mixed raw material in the long run. Paper as a material sinks abundantly within the circular system, consequently, virgin material needs to be added anyway in order to satisfy mass balance requirements. Some items, like newspapers and paper packaging can be produced from 90% recycled material, while some sorts of specialty paper only from virgin fibers. The overall proportion between virgin and recycled fibers ingrained within new products reached maturity and stabilized at around 50/50 ratio on average in EU [26]. Waste- paper recycling potential is therefore more or less consumed, paper industry can work properly as a holistic system only with a provision that primary raw material content amounts to roughly 50%. All things considered, paper waste recycling demonstrated to be a beneficial process, decreasing environmental impact on forests and reducing costs significantly. Simplified mass balance is shown below:

Paper- industry linear economy:

$$1\ W \rightarrow 1\ P_{product}$$
$$1\ P_{product} \rightarrow 1\ P_{waste} \rightarrow 1\ P_{\Sigma sinks}$$

Paper- industry circular economy (EU):

$$\tfrac{1}{2}\ W + \tfrac{1}{2}\ P_{wasteRc} \rightarrow 1\ P_{product}$$
$$1\ P_{product} \rightarrow \tfrac{1}{2}\ P_{wasteRc} + \tfrac{1}{2}\ P_{\Sigma sinks}$$

Explanation:

W, $\mathbf{P_{xyz}}$ …… one unit- equivalents of paper fiber occurring in different forms; **W**… raw material (mostly processed wood); $\mathbf{P_{product}}$ … produced paper tissue; $\mathbf{P_{waste}}$ … wasted paper tissue ; $\mathbf{P_{wasteRc}}$ … recycled paper tissue; $\mathbf{P_{\Sigma sinks}}$ …. paper lost out of the circular system. Examples of possible sinks: (1) sanitary paper; (2) paper-waste intermixed within MSW, biodegradable waste, miscellaneous packaging waste and other kinds of communal waste streams, ultimately ending into combustion plants, landfills and compost plants; (3) rejects from paper- recycling industry; (4) paper lost in building construction industry; (5) littering, etc.

As opposed to paper waste recycling, energy utilization represents the only reliable sink in order to diverge surplus plastic waste out of the circular system in the long run [25]. Namely, landfilling of any calorific waste is an environmentally unacceptable practice, prohibited in EU, except in special cases. However, there are many other aspects which suggest post- consumer paper waste as a fundamentally better material for purposes of recycling when compared to PCPW. In Table 2, general differences in recyclability between the two materials are pointed out.

Table 2: Comparison of post- consumer paper and plastic waste- recyclability- characteristics

Waste → Characteristic ⍗	Paper	Plastic	Layered drink-box composites
Number of acquirable recycles of the same batch of material	4 - 7	0 - 3	(-)
Sinking rate out of the circular system (not considering landfilling and WtE conversion)	Considerable	Weak	(-)
Possibility of selecting waste fractions in regard to the number of executed recycles in the past	Considerable	Weak	(-)
Possibility of producing goods, which do not require high quality of ingrained material	Considerable	Weak	(-)
Possibility of excessive raw material contamination with undesirable ingredients	Small	Considerable	Considerable
Technological possibilities of removing impurities preparing raw material for producing new goods	Considerable	Very complex problem	Small
Technological possibilities to recycle mixed materials derived from different sources	Considerable	Small	Small
Amount of waste material, which can not be recycled in a technologically and economically reliable way	Small	Very high	Very high
Economic value of recyclables	Slightly positive	Negative to very negative	Very negative
Characteristic (average) period of time to effectuate one step of recycle	Relatively short (1 year)	Relatively long (more years)	(-)

(-) ……… difficult to comtemplate reasonably

All these differences manifest- themselves in the economic field, too. Recycling companies are willing to accept post- consumer paper waste for free or to pay some small price for it, in contrast to PCPW and other low grade recyclables, which are generally accepted only against some heavy payment from the side of their owners. Therefore, in general, the value of PCPW is negative, which is a clear indication that circular economy does not perceive these kinds of waste as useful raw materials. Nevertheless, some recycling companies strive to ingrain some of the received PCPW mass back into the mass of new products in spite of the associated risks involved, which is partly due to the income gained for accepting PCPW in their storage yards and partly as a reaction to sociopolitical incentives favoring recycling methods as inherently benefitial for the environment. Green marketing approaches can be helpful in this regard, however, no recycling company can afford the quality of their products to decrease to the point the costumers would start to avoid.

We can conclude that reliable technological approaches intended for purposes of large- scale, long-term PCPW recycling do not seem to exist, at least not when taking environmental and economical issues both into account simultaneously [29, 30]. In contrast, this is not the case when practising properly designed, integrative WtE approach to treat PCPW [31, 32]. However, a really detrimental deficiency of the PCPW recycing system lies in the fact that the repeatedly recycled plastic has to finish its way in combustion plants sooner or later anyway, which is due to its limited recyclability properties and unavailability of alternate sinks. This phenomenon was already recognised by the researchers in the past, too [25]. Therefore, IWM systems performing PCPW recycling have to be equipped with infrastructure to treat the very same batches of waste by means of energy recovery, too. One may ask himself why then even to bother with PCPW recycling, if the end result manifests itself merely as a temporal storage of recycling material in the form of low- grade recyclables and less valuable products. We can add to this the unnecessary exposure to risks stemming from excessive amounts of environmentally undesirable and leakable substances ingrained within the overly recycled plastic [4, 5, 8, 23, 24, 25]. Such approach can be even seen as non- compliant with EU Directive narrative [1] which advocates member states to take measures to reduce the content of hazardous substances in materials and products, including recycled materials.

We tried to proove the thesis that no virgin material is saved when practising PCPW recycling by comparing the related IWM system to the alternate system which does not practice PCPW recycling. We took both-, fossil hydrocarbons and alternate PCPW materials into consideration as reliable resources for producing both, thermal energy and new plastic products. The comparative scheme is illustrated in figure 2. From the attached explanation it can be concluded that the economy as a whole really consumes the same amount of virgin materials if performing PCPW recycling or not. Consequently, the environmental burden for extracting virgin resources has nothing but to be equal for the two systems, too.

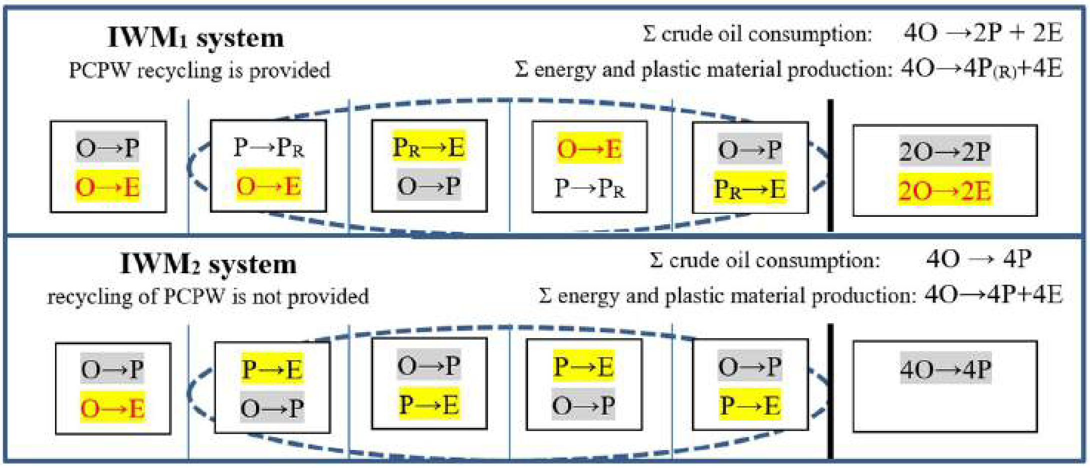

Figure 2: Relative amounts of crude oil consumption comparing two systems of IWM

Explanation related to figure 2:

Preserving natural resources (crude oil to simplify things) is considered to be the main objective of performing PCPW recycling. We want to verify reliability of this constatation by comparing mass- and energy balances of two antagonistic IWM systems: one practising- and other refusing practicing PCPW recycling (IWM_1 and IWM_2, respectively). The two economies can be labeled as circular- (the one which sees recycling of PCPW as an advantegous treatment method, while combustion with energy recovery as a secondary, looked-down- upon- method) and linear- (which acknowledges energy recovery of PCPW in the form of SRF as a preferred treatment method).

Comparative scheme inherently presumes both economic systems should be capable of providing the society with fuels for energy consumption (E) and raw materials for producing new plastic goods (P) in the required quantities at any time. Real-life mass ratio between the two uses appears to be around 10 : 1, however, for purposes of greater clarity when comparing the systems, we will suppose the more illustrative ratio of 1 : 1 to be the case at first. We acknowledge the fact that PCPW can be either recycled ($P \rightarrow P_R$) or energetically valorized (P→E). PCPW potential for repetitive recycling is around one cycle on average (figure 1, curve VIII, $n_{average} \approx 1$). Our comparative system therefore constatates that on average PCPW mass is completely recycled once. It can not be recycled for the second time, but only thermally valorized ($P_R \rightarrow E$).

Symbols "O", "P", "P_R" and "E" signify one unit of crude oil "O" or its equivalents in the form of virgin plastic "P", recycled plastic "P_R" or utilizable thermal energy "E" it contains as a primary or alternative form of fuel. Each successive conversion stage for each of the two IWM systems is presented in a separate column. During each consecutive stage and considering the ratio 1:1, one unit of energy "E" and one unit of plastic "P" or "P_R" should be provided. At the beginning (the first column), energy "E" and plastic material "P" could be produced only from the primary source "O". Therefore, the initial conversion step (in contrary to the successive conversion steps) is equal for both IWM systems, consuming two units of primary resource: one for the production of plastic (O→P) and one for the production of energy as a fuel (O→E).

The number of succeeding conversion steps which form a set which begins to repeat itself appears to be 4 (four) for circular economy and 2 (two) for linear economy (figure2). Therefore, if we ignore the first initial phase, which does not repeat, we can realize that from 4 units of crude oil "O" 4 units of energy "E" and 4 units of plastic material ("P" or "$P+P_R$") are ultimately produced in both of the cases. Therefore, the ultimate consumption of crude oil is equal, regardless if we perform PCPW recycling or not. When performing recycling, crude oil is diverged for energy and plastics production equally (4O→2P+2E), but exclusivelly diverged into the production of plastics when not performing recycling (4O→4P). However, because primary source consumption for energy needs is in fact ~10 times greater then for production of plastics, a realistic mass balance should be written as 44O →2P+42E for IWM_1 system and 44O →4P+40E for IWM_2 system. Therefore, within the PCPW circular economy, 95.5% of primary source is diverged for energy consumption and 4.5% for plastic materials production, while within the linear-one, the ratio is 90.9% : 9.1%.

There are some other differences between the two IWM systems, though. IWM_2 system assumes plastic products are never produced from PCPW- derived recycled materials, consequently, average quality of plastic products appears to be superior and their lifespan a little bit longer when compared to performance of the actually operating system IWM_1 (section 3). Also, IWM_2 system inherently assumes SRF to be produced from PCPW and other low- grade combustible fractions, which represents an environmentally cleaner version of fuel when compared to alternate fuels formed from random mixtures of residual PCPW and other left- over materials, mostly in the form of RDF, which is characteristic for the actual system IWM_1.

Discussion

In 2020, European Commission renewed its original action plan from 2015 intended to accelerate circular economy setting up a target that 10 million tonnes of recycled plastics should be utilized to make products in the EU by 2025 (i.e., some 30% of PCPW generated in EU in one year) [2]. The plan seems to be counter- intuitive when contemplated from waste management and environmental standpoints, but not when taking into account cultural factors, like the existance of dedicated segments of (chiefly) younger European population, who like such kind of plans, knowing that active engagement of citizens is encouraged by the EU in the field of recycling. Such plans offer them excuse and opportunity to fight for apparently higher-, even if unattainable ideals. Since other segments of society do not seem to be bothered about these things, such ideas can be recycled repeatedly for decades without any need to show reliable results by their proponents.

Notwithstanding such kind of trends, researchers in central and northern European countries nevertheless mastered to develop efficacious IWM approaches for energy valorization of combustible MSW fractions. They handled the issue of environmental protection in a preventive way, considering production of environmentally advantageous, customized types of SRF for purposes of large- scale applications in industrial kilns and combustion plants [31, 32]. Costs tend to be much smaller and energy conversion efficiencies bigger when compared to treating combustible MSW fractions in incinerators. Only fractions exhibiting high pollutant contents (e.g., chlorine containing plastic waste, which can be efficiently outsorted from the mixed PCPW or simmilar MSW-derived, separately collected streams) are still required to be treated in the incinerators.

According to our findings, consumption of alternate fuels in industrial kilns and combustion plants may eventually decline a little bit as a consequence of the above- mentioned EU plan to increase the rate of plastic waste recycling, however, this can only happen as a short lived episode. Namely, any amount of plastic waste additionally stored within the system of circular economy is destined to be burnt in the end anyway, only with some time delay. In fact, generation of waste diverged into combustion will even increase a little bit in the longer run, due to a shortened lifespan effect of an average plastic product put on the market.

One of the major misconceptions environmentalists favoring recycling methods are prone to believe in sounds something like this: "It is obvious that the amount of plastic waste which was recycled was also spared from being incinerated at the same time, therefore, such approach can be nothing but benefitial for the environment". However, this constatation is valid only for concrette batches of waste recycled during that concrette limited amount of time. Namely, these same batches of material are destined to end up their path in WtE plants ultimately. Undesired combustion was avoided only temporarily. As soon as the circular economy begins to function as a quasy- steady- state system, receiving equal amounts of recycled material on the input side as droping it out on the output side, the whole IWM system, too, begins to function in the quasy steady state mode: the same amount of PCPW which is generated by the society on an annual basis also ends up in combustion plants during the very same years, too, as if recycling is not happening in parallel at all. Therefore, equal capacity of WtE infrastructure should be ultimately provided by the society whether performing recycling or not. In contrast, IWM systems which perform energy recovery of PCPW as a chosen treatment method do not recycle low-grade combustible recyclables by definition. Therefore, pollutant emissions, environmental risks and costs related to the recycling method represent nothing but an additional burden for the environment and the society when comparing performance of circular economy to the linear- one in this segment of WM.

Some societies don't like to deal with WtE plants operating in their backyards, Slovenia being a typical country. However, environmental conceptions like "zero tolerance for pollution and environmental risks" are in fact harmful for the society and the environment, when they are perceived literarily. PCPW and other low grade combustible MSW fractions have to be combusted in the end in spite of eventual efforts made to accelerate their recycling rates. Therefore, export appears to be the only way out left in order to alleviate the problem of storage yards overly filled with PCPW and and other low grade combustible MSW fractions in such countries. Fortunately for Slovenia, there are countries in its vicinity, like Austria, where co-incineration is generally accepted as being an important part of IWM [31, 32]. Trust of people living in the vicinity of cement kilns and power plants there utilizing SRF as a main energy source was built slowly. Air in their surroundings continues to be reasonably clean year after year, decade after decade. People realized that health indicators do not deviate from average values typical for the country as a whole. However, at the same time, the notion of adequacy of using step-wise (cascade) principle to treat recyclable fractions of plastic waste (like PET bottles) is still well and alive in Austria. In a way, energy recovery is perceived only as being the last, although a very significant step to treat PCPW.

In general, we do believe that PCPW recycling methods are already perceived as being innefficient by many people and professionals today. At the same time, nobody likes to be exposed writing articles which are not consistent with mainstream doctrinal views. Therefore, societal implications of continuing to indiscriminately favorize PCPW recycling over energy recovery could be counter- productive in the longer run. However, it is not easy to change IWM strategy direction which was so intricately planned in EU decades ago as being ethically noble. It is reasonable to expect the process of transition would be slow.

Conclusion

A new approach was designed for purposes of quantitatively estimating the effects of repetitive PCPW recycling on raw material quality, lifespan of recycled goods and waste generation rates. Reasons for general differences in performance between post-consumer paper waste and PCPW recycling systems were specified as well. Mass- and energy balances comparing performance of two IWM systems, one practicing and another omitting practicing PCPW recycling were theoretically examined.

General conclusions are pointed out below. Many of them are cause-and-effect related.

IWM system for managing PCPW favoring the method of recycling is found to be logistically extremely complicated, technologically heterogenous and economically and environmentally vulnerable when compared to IWM systems designed to recycle paper, base metals or glass. As opposed to paper waste recycling, energy utilization represents the only reliable sink in order to diverge surplus plastic waste out of the circular system (landfilling of calorific fractions of MSW is, rightfully so, prohibited in EU).

Recyclability of plastic- waste- materials is inherently low, which means, the related circular economy is able to operate in a continual way only in the case the portion of recycled part of raw material for producing new goods was small enough, much smaller than ½ in most of realistic scenarios. The approach inherently implies ample insertion of virgin materials into the circular system in order to dilute the percentage of impurities and other unwanted ingredients, knowing the products will be of lesser quality anyway when compared to the ones which derive exclusively from virgin raw materials.

The notion that recycling methods possess the ability to divert PCPW away from combustion is misleading. Indeed, disposal happens to be avoided when referring to concrette batches of waste incorporated into the mass of new products, at least temporarily. Also, disposal appears to be partly avoided when referring to annual mass flows of PCPW during the time the established circular system is still relatively young. During this particular amount of time, flow rate of PCPW- derived raw materials annually ingrained into the mass of new products appears to be greater when related to the yearly flow of at least once already recycled substance finnishing its way into WtE plants. However, as the circular system grows older, differences between the input and output mass flows decrease progressively, until fading away. The system begins to function in a steady state mode.

The first paradox: Mature PCPW- related circular economy inherently functions in a (quasy) steady state mode, which means, the same amount of PCPW- derived material ending up into the mass of new products is also leaving the circular system in order to be energetically valorized. Consequently, the whole PCPW- related IWM system is functioning in a steady state mode, which means, the same amount of PCPW annually generated by the society is also ending up its path in combustion plants, as if recycling is not occuring at all. Therefore, no amount of PCPW is really diverted away from disposal due to practicing methods of PCPW recycling in the long run. The end result of performing PCPW recycling manifests itself merely as a long-term dynamic storage of certain amount of PCPW in the form of recyclates and less valuable products. If utilization of PCPW recycling methods ceased to be favorized by the society for some reason, the remaining IWM system would begin to function in an unsteady- state mode once again. During this particular period of time, greater amount of PCPW- derived material would be annually combusted than annually generated anew. This would last until all of PCPW- derived mass stored within a circular system during the recycling era was consumed.

The second paradox: Consumption of virgin materials is the same whether performing PCPW recycling or not, as opposed to paper waste recycling, where the facts show the consumption of virgin material is truly reduced by one half in EU today. Even if the recyclability of PCPW increased to some degree due to the effect of subsidies encouraging growth in the sector of plastic waste recycling today, the consumption of virgin material would not decline in the longer run at all, only the ratio between the amounts intended for production of fuels versus production of plastic granulates would change a little bit, almost invisibly

The third paradox: IWM system, which practices PCPW recycling, has also to be equipped with WtE infrastructure, including for purposes of incinerating the very same batches of waste which were already recycled. WtE infrastructure of the same capacity should be ultimately provided by the society in order to dispose of the generated mass of PCPW, whether performing recycling or not. This is especially true during the time the related circular economy grows a little bit older.

The fourth paradox: IWM system utilizing PCPW recycling method is ultimately obligated to treat the very same waste by means of energy recovery, too. Therefore, IWM system favoring PCPW recycling generates additional environmental risks, additional costs and emits additional pollutants into the environment, unknown to IWM system favoring energy recovery method, where recycling of PCPW is not practiced by definition.

By employing the recommended system which does not support recycling of combustible materials of low value and recyclability, the quantity of newly generated waste would decline for several percents related to the mass of MSW as a whole. Such decrease would result in proportional reduction of all kinds of emissions treating this waste on its path from the cradle to the grave.

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