Received: 17 January 2019 | Revised: 2 October 2019 | Accepted: 17 October 2019
DOI: 10.1002/amp2.10034

RESEARCH ARTICLE

JOURNAL OF ADVANCED MANUFACTURING AND PROCESSING WILEY

Life cycle energy comparison of different polymer recycling processes

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Abstract

This article is to demonstrate a consistent, transparent approach to comparing plastic recycling technologies. The uniform comparison is based on each recycling technology having the same input (waste PET), mass basis for processing, output as new product (new PET product or fuels), and the concept of the same multiple (two) closed loops of recycling. We seek to demonstrate, at the fundamental technology level, how energy use differentiates plastic recycling technologies. Five polymer-recycling processes are examined using a uniform, quantitative comparison of 1 kg PET bottles (about 100 single-serve 0.5 L water bottles): direct reuse, 100% mechanical recycled content, depolymerization, and re-polymerization of new resin and 100% to bottles, reclaiming energy value, and landfill. The life cycle energy benefit for recycle technologies with varying product recycled content can be determined by a single equation. All these recycling processes resulted in total energy reduction per kg PET bottles compared to landfilling. The base case of three cycles per 1 kg PET bottles is used to explore the influence of recycling loops. Direct reuse gave a 290% energy improvement with three cycles. Other processes, all at 100% recycle content, gave improvements: mechanical (250%), depolymerization/repolymerization (150%), and energy recovery (120%). More information would improve the analysis of the depolymerization process assessment. These preliminary data describe the analyses that are needed to quantify the benefit of recycling any polymer using these recycling methods. The Environmental Genome ("EGI") provides valuable information for these calculations as it contains the polymers and supply chains for such evaluations.

KEYWORDS

depolymerization, mechanical recovery, polymer recycling, recycle content, recycle loops

1 | INTRODUCTION

The field of chemical recycling for polymers has a number of existing commercial and developing technologies. These have been reviewed qualitatively as separate technologies for process descriptions and importance for a circular economy with plastics.[1,2] Reviews cover polypropylene,[3] nylon,[4] polyethylene,[5] and PET.[1] However, a quantitative, energy-based comparison of the major approaches to reuse/recycle would be essential to establishing the measurable benefits of such technologies. In these polymer-recycling reviews, the mechanical recycling (grinding, sorting) is covered for thermoplastics, which can be re-melted and injection molded or extruded. Thermosets are sorted and ground into a fine material that is used as filler with virgin resin. Reviews also describe depolymerization to monomers and co-monomers, followed by purification to obtain monomers to repolymerize into new resin with exactly the same quality as virgin resin. The article by Geyer, et al[6] provides a comprehensive evaluation of some of the central concepts that emerge from evaluating plastic recycling technologies, but without quantitative data.

2 | APPROACH AND OBJECTIVES

Recycling environmental benefits are linked to knowledge of chemical manufacturing of virgin inputs. The molecular building processes beginning with natural resources in the earth produce virtually all the 100 000 chemicals used in-commerce.[7] These processes require energy inputs (steam, Dowtherm heating, furnaces, transport fuels, and potential energy recovery) and operate at less than 100% mass efficiency (losses as wastes or emissions to the environment). Manufacturing process energies are made available by consumption of fuels, Table 1. For each mega Joule (MJ) of energy put into the chemical manufacturing process, there are direct fuels needed to create that MJ of energy and fuel is also needed to deliver these fuels to the point of use, as described in Table 1. In this article, the energy values in Table 1 are used and referred to as natural resource energy (nre).

Molecular building often occurs in separate chemical plants, over geographic and temporal domains. Value chains are assemblages of these chemical processes and were discovered to have a repeatable pyramidal structure.[7] There are various points into which a recovered chemical can be substituted for the same virgin chemical (in the same or a different product). If recycling is not involved, these supply chains are referred to as virgin chemicals.

The objective of this article is to demonstrate a consistent, transparent approach to comparing plastic recycling technologies. The uniform comparison is based on each of the recycling technologies having the same input (waste PET), mass basis for processing, output as a new product (new PET product or fuels), and the concept of the same multiple loops of recycling [two]. We seek to show transparently, at the fundamental technology level, how energy use differentiates plastic recycling technologies. The Environmental Genome database is essential for the kind of polymer supply chain and recycling information needed for such comparisons. This article is to quantitatively examine the hypothesis: The alternatives in polymer recycling demonstrate degrees of circularity in reuse, recycle, or recovery of chemicals or fuel value which then show a quantitative difference in a continuum from low to high energy improvement. This continuum is also influenced by the number of recycle loops (eg, depolymerization may give very large numbers of loops, while mechanical recycling might suffer from polymer degradation and have fewer loops). For this preliminary study, the yield and reusability of the recycled products are assumed to be 100%. The complexity of collection and segregation are recognized as a common challenge for all the technologies herein and hence is a common factor that is not addressed further. Refinement of less than 100% yield is very company-specific and not within the scope of this initial comparison. The high transparency herein permits a direct assessment of actual recycling technology results and serves to support the collection of more in-depth data for updating this preliminary comparison.

3 | RESULTS

In order to calculate an energy benefit for chemical recycling we keep track of two energy categories:

TABLE 1 Relationship of MJ energy used in chemical manufacturing processes to MJ total natural resource energy (nre) consumed to produce that energy[8]

Scale-up factors	Electricity[a]	Dowtherm	Steam	Non-transport direct use of fuel	Transport fuel	Heat potential recovery
Precombustion factors, MJ fuel extracted and used per MJ delivered (This excess is consumed in delivery)	1.1	1.15	1.15	1.15	1.20	1.15
Generation/combustion factors, MJ HHV fuel delivered per MJ energy to process	3.13	1.25	1.25	1.00	1.00	1.25
Total scale up factor (precombustion times generation/combustion), MJ total fuel consumed for this use per MJ into process, nre	3.44	1.44	1.44	1.15	1.20	1.44

[a]Based on United State energy grid.

	Level 9	Level 8	Level 7	Level 6	Level 5	Level 4	Level 3	Level 2	Level 1	Level 0
	bottle, PET from TPA 1,000	PET pellet, from TPA 1,000	PET melt, from TPA 1,000	**ethylene glycol 336**	ethylene oxide 243	**ethylene 183**	naphtha 186	oil (in ground) 188		
						oxygen 178	air (untreated) 179			
					water for rxn 94.3	water (untreated) 94.3				
				terephthalic acid 858	terephthalic acid, crude 870	acetic acid 57.5	**carbon monoxide 30.2**	**carbon dioxide 15.1**	**natural gas 3.11**	natural gas (unprocessed) 3.17
									nitrogen from air 5.81	air (untreated) 5.81
									oxygen from air 2.58	air (untreated) 2.58
									water for rxn 4.03	water (untreated) 4.03
								natural gas 10.2	natural gas (unprocessed) 10.4	
								water for rxn 6.17	water (untreated) 6.17	
							methanol 31.6	**natural gas 16.2**	natural gas (unprocessed) 16.6	
								oxygen from air 16.2	air (untreated) 16.2	
								water for rxn 29.0	water (untreated) 29.0	
						oxygen from air 703	air (untreated) 703			
						p-xylene 582	hydrogen 0.936	naphtha 3.28	oil (in ground) 3.33	
								oxygen 3.28	air (untreated) 3.28	
								oxygen from air 2.15	air (untreated) 2.15	
								water for rxn 1.43	water (untreated) 1.43	
							xylenes 580	**pyrolysis gas 168**	naphtha 172	oil (in ground) 174
								reformate, from naphtha 413	naphtha 420	oil (in ground) 425
Supply chain energy by stage, MJ nre/1,000 kg PET bottle	**10,064**	**180**	**3,009**	**10,305**	**6,768**	**11,959**	**2,854**	**5,162**	**1,935**	**0**

FIGURE 1 Supply chain from natural resources in the earth (salmon-colored cells), 1866 kg to make 1000 kg of PET bottles, numeric values are mass flows in kg (bottom row shows the energy of each level of supply chain, which total to 52.2 MJ nre/kg PET). PET, polyethylene terephthalate[8,9]

1. Category 1: The energy of fossil resources used to form a polymer structure (feedstock—salmon colored cells, Figure 1). These are typically crude oil (45 MJ/kg) and natural gas (53.5 MJ/kg) in various proportions (inorganic feedstocks are not tabulated as category 1 energy). These go into the polymer structure, and are thus fossil materials not available for other uses and thus are expressed as consumption of fuel resources.
2. Category 2: The energy needed for the entire set of unit processes (distillation, reactors, etc.) in each chemical plant that occurs in the supply chain (natural resources in the earth to the final product). When evaluating the energy benefits of using recycled content by a particular process, we subdivide this category into two concepts
   a. Energy required to make 1 kg of polymer product from virgin inputs (solid lines in Figures below).
   b. Energy to process waste polymer products at end-of-life into usable chemicals, materials, or fuels (dotted lines in Figures below).

It is categories 1 and 2a that can be accessed easily and transparently with the methods in the Environmental Genome (www.environmentalgenome.org), but category 2b can use more specific technology data.

These recycling scenarios would warrant an article on each to explain the complexities of the process, process flow diagrams, the calculation of the energies and mass losses, and application to multiple polymers. This article provides just a summary description with energy values that can be explained and followed directly in the calculations. Issues not directly related to a uniform comparison of recycling technologies are not included herein, such as mismanagement at end-of-life, public issues of trash or marine pollution, ongoing recycling rates at the State or national level, detailed differences in equipment, social benefits of jobs, and so forth. This comparison, begins with cleaned plastics, therefore, all the energy associated with the collection, sorting, or cleaning prior to recycling are not included.

Figure 1 shows the supply chain of each chemical needed to produce 1000 kg of PET bottles, as found in the environmental genome database, while in this article 1 kg of PET bottles is used to reflect a more consumer-based perspective. Each stage represents the addition of new chemical inputs with the associated mass shown starting with extraction of raw materials to finished PET bottles.

At the bottom of Figure 1 the sum of the energy per 1000 kg of PET required for each stage is provided, which are the values on each of the following Figures to create product A (1 kg of PET). For PET there are nine stages from the raw materials in the earth to the virgin product. The zero stage is natural resources from the earth (salmon-colored cells). For PET bottles the total natural resources are about 1.88 kg to make 1 kg of PET bottles (~100 single-serve 0.5 L water bottles). This is in the range of other chemical supply chain ratios (typical range 1.5-4.5).[9] For PET, all products that do not use recycled material must include fossil resources for new products and thus include the category 1 energies, 37.2 MJ/kg PET bottles (9) (calculated from Figure 1 as the mass of crude oil and natural gas as natural resources that go into the final PET structure. The energy for crude oil (45 MJ/kg) and natural gas (53.5 MJ/kg) are in Appendix 1 and used to arrive at the 37.2 MJ nre/kg PET bottle.

The scenarios that follow are examples from the four main categories of plastics recycling.

3.1 | Scenario 1: Virgin inputs with bottle to landfill

The first, second, and third PET bottles are made identically from fossil resources in the earth. This base case is PET bottles going to landfill or becoming land or ocean litter. The replacement bottle from the virgin supply chain begins with the 37.2 MJ category 1 energy reflecting the fossil resources in the actual PET, Figure 2. The supply chain processes then convert the fossil resources into the monomers (terephthalic acid and ethylene glycol) and polymerize these into 1 kg of polyethylene terephthalate (PET) resin, which is pelletized and injection molded into 1 kg PET bottles. The category 2a energy for the PET bottles is 52.2 MJ nre/kg PET bottles. The first, second, and the third PET bottles are each 89 MJ nre/kg PET bottle (3.4 kg CO_{2eq}/kg PET bottles). The shape of the cumulative energy supply chain curve, Figure 2, points to potential

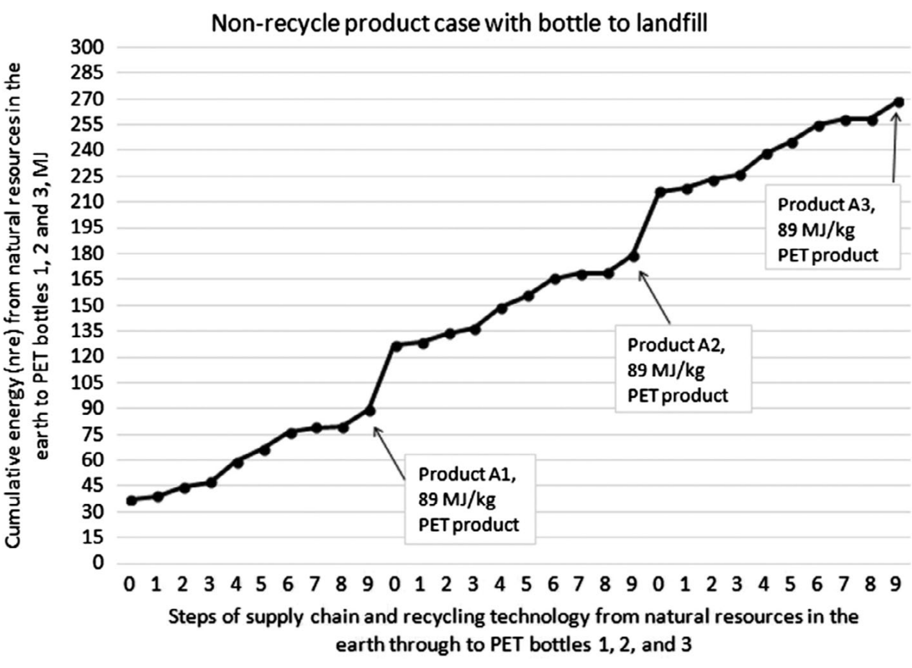

FIGURE 2 Virgin inputs—Bottle to landfill. Note: the small energy for landfilling is not included for simplicity

energy benefits of replacing all or a portion of the second and third bottle cycles with recycled content.

3.2 | Scenario 2: Direct PET bottle reuse with only transport or simple process to next user

An example of direct product reuse would be a PET windshield washing fluid reservoir container from a damaged automobile removed and installed directly into another automobile. Manufacture of one polymer product (89 MJ nre/kg PET bottles), then leads to essentially direct reuse of the product in the same form. Transport of about 300 km is estimated at 0.9 MJ/kg PET bottles, using 0.003 MJ nre/kg km (Appendix 1). So two products are $89 + 0.9 =$ 90 MJ nre/2 kg PET bottles, Figure 3 and each bottle is now about 45 MJ/kg PET bottles (1.8 kg CO_{2eq}/kg PET bottles). Progressing to the third bottle gives us a third bottle for a cumulative energy of 91 MJ nre for three bottles or 30 MJ nre/bottle (1.3 kg CO_{2eq}/kg PET bottles). This is probably the lowest energy scenario because we are eliminating both the category 1 and essentially all category 2a energy inputs with recycling. At some point, usage or successive recycling damages the PET polymer and the sequence of direct reuse must stop, but it is unclear when that might be and so just at two bottle cycles, the energy (and carbon footprint) are a 290% energy-related improvement. That is, landfilling is a 290% greater impact on the environment based on energy use alone. In the limit of very high numbers of recycling loops (such as 2000 cycles), a PET bottle could approach 0.9 MJ nre/kg PET, an astronomical 9800% improvement, an interesting theoretical limit.

3.3 | Scenario 3: Mechanical recycling: Reuse by grinding, extrusion, pelletizing, and injection molding to bottle

Manufacture of one polymer product is 89 MJ nre/kg product, then mechanically grinding PET into flake (2.5 MJ nre/kg PET), extruding and pelletizing (2.2 MJ nre/kg PET and 0.18 MJ nre/kg, respectively), and injection molding (10 MJ nre/kg PET) into the second bottle, Figure 4 (data in Appendix 1). Based on two bottle cycles (104 MJ nre/2 kg PET bottles), this is 52 MJ nre/kg PET bottle cycle (2.3 kg CO_{2eq}/kg PET bottles). The category 1 energy is eliminated and replaced by the grinding, extrusion, pelletizing, and injection molding. For the third bottle cycle, we get 119 MJ nre/3 kg PET bottle, or 36 MJ nre/kg PET bottle (1.9 kg CO_{2eq}/kg PET bottles). At the third cycle, mechanical recycling offers a 250% improvement over all virgin energy inputs.

3.4 | Scenario 4: Reuse by grinding, depolymerizing to terephthalic acid and ethylene glycol, repolymerizing, and injection molding to bottle

While there are different methods for depolymerizing PET, there is scant data about the energy use associated

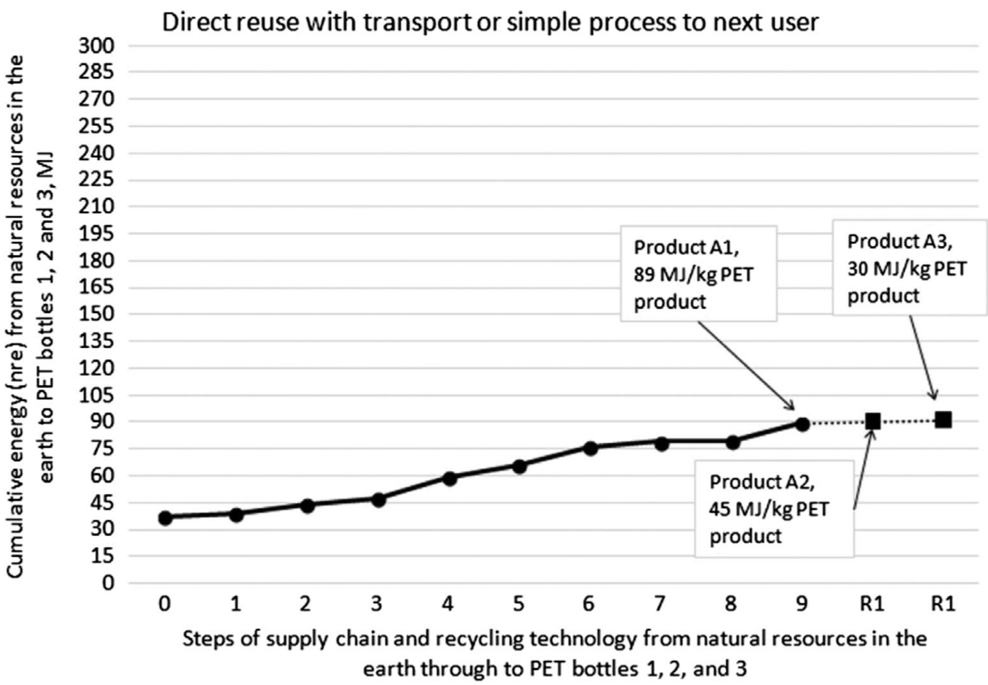

FIGURE 3 Scenario 2 direct reuse

with these processes. This assessment is based on the reduced global warming potential of the process published on the website of loop industries[10] reporting a 63% reduction. This would mean the production of PET pellets from the depolymerized/purified/repolymerized terephthalic acid (TPA) plus ethylene glycol is 37% of virgin PET. Manufacture of the first polymer product is again 89 MJ nre/kg PET bottles. The recycle process begins with grinding (2.5 MJ nre/kg) and depolymerizing the flake in a process that reacts the PET to the co-monomers, terephthalic acid, and ethylene glycol. These co-monomers are then purified and repolymerized at some location back to PET as a pellet product. From the energy reduction as reported on the website, the Loop process is (89*0.37 = 33 MJ nre/kg PET bottles). Their PET product is then injection molded (10 MJ nre/kg PET bottles) to give the second cycle of PET bottles, Figure 5. This gives 135 MJ nre/2 kg PET bottles or 67 MJ nre/kg PET bottles

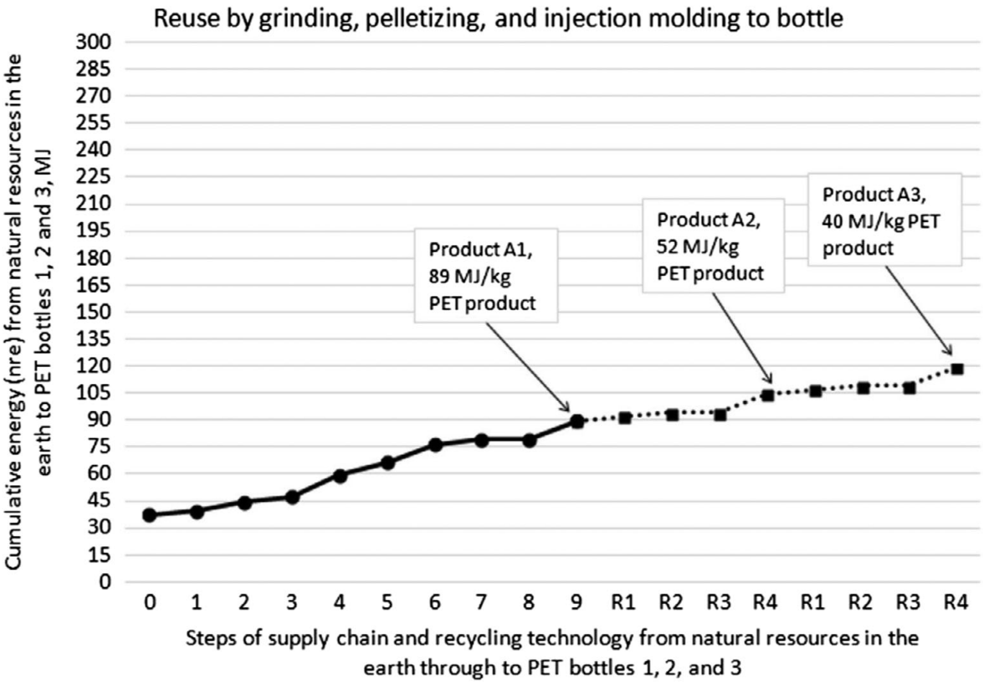

FIGURE 4 Mechanical recycling

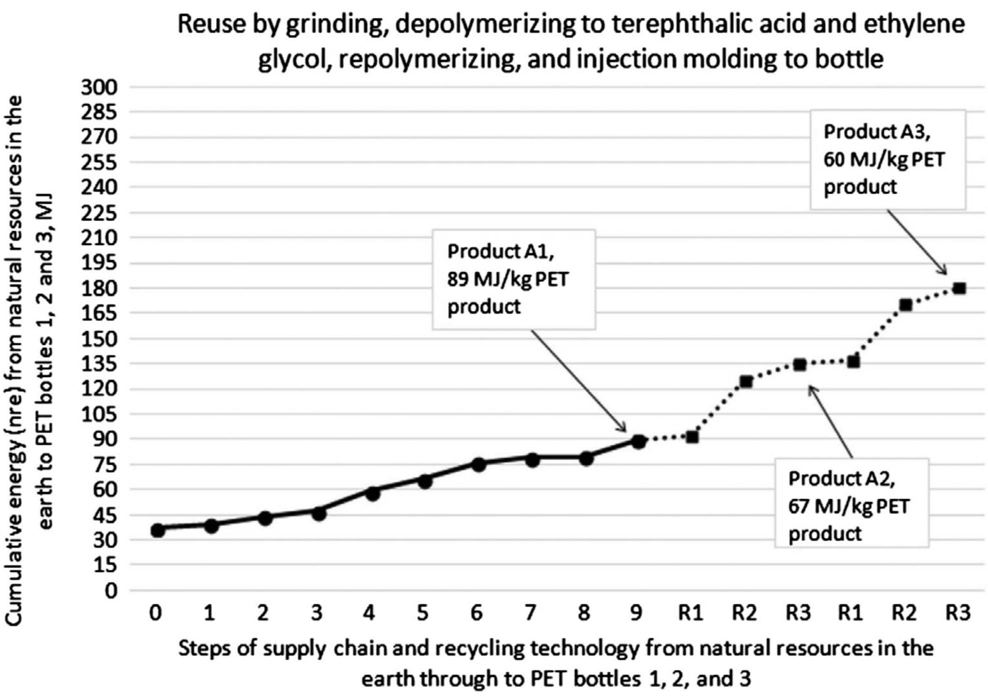

FIGURE 5 Reuse through depolymerization and reforming PET for bottle. PET, polyethylene terephthalate

(3.2 kg CO_{2eq}/kg PET bottles). Continuing this circularity, to the third bottle, we have a cumulative energy of 180 MJ nre/3 kg PET bottles or 60 MJ nre/kg PET bottle (3.1 kg CO_{2eq}/kg PET bottles). This technology in the chemical recycling continuum is an improvement of 150%.

3.5 | Scenario 5: Energy Recovery: Reuse by grinding and burning as a solid fuel, with new PET bottles from virgin inputs

As before, manufacture of the first polymer product is 89 MJ nre/kg PET bottles. This bottle is ground (2.5 MJ nre/kg PET) as waste polymer and used as a solid fuel to provide heat, electricity or combined heat and power (CHP). The fuel value of PET is only about 22 MJ nre/kg PET bottle.[11] In this case, the second product virgin supply chain category 1 energy is credited with the 22 MJ nre/kg PET bottles, regardless of where it is used because that is a fossil fuel "credit." The cumulative energy for two PET bottle cycles is 89 MJ nre/kg PET bottles +2.5 MJ nre/kg grinding plus (89-22) MJ nre/ kg PET bottles or 160 MJ nre/2 kg PET bottles or 80 MJ nre/kg PET bottles (2.8 kg CO_{2eq}/kg PET bottles), Figure 6. Even if grinding can be avoided this would shift this value to 89 + [89-22] = 156 MJ nre/2 kg PET bottles or 78 MJ nre/kg PET bottles. Continuing this scenario to bottle three, we have 229 MJ nre/3 kg PET bottles or 76 MJ nre/kg PET bottles (3.1 kg CO_{2eq}/kg PET bottles), a 120% improvement. Extending this scenario to 100 cycles (10 000 PET bottles combusted), reaches a limit of just 70 MJ nre/kg PET bottles. With the fuel value of crude oil and natural gas at 45 and 53.5 MJ/kg, respectively, the use of PET as a fuel (22 MJ/kg PET) is much smaller because it is 39% oxygen, while crude oil is 1%-3% non-carbon and hydrogen, and natural gas is nearly zero. PET is just a less desirable fuel energy source. Even polymers with higher fuel value like polyethylene or polypropylene, only offset more of the category 1 energy leaving the category 2a energy of the whole supply chain to make the polymer required for subsequent bottle cycles.

3.6 | Scenario 6: Varying recycled content of products

Using any recycling technology yields a material that can be reincorporated into the same or similar product or into different products, thus producing a product with a post-industrial or post-consumer recycled content. We developed an equation that determines the environmental benefit of producing successive product(s) while factoring in the type of recycling technology, the polymer, and the amount of recycled content. It can also be used for any other recycling technology, at any percent recycled content, for any plastic or other material, and for any life cycle metric, like energy, global warming potential, human health, and so forth.

With the environmental genome energy and other life cycle metric data on the primary product (product A) and the incremental energy to produce the same product by

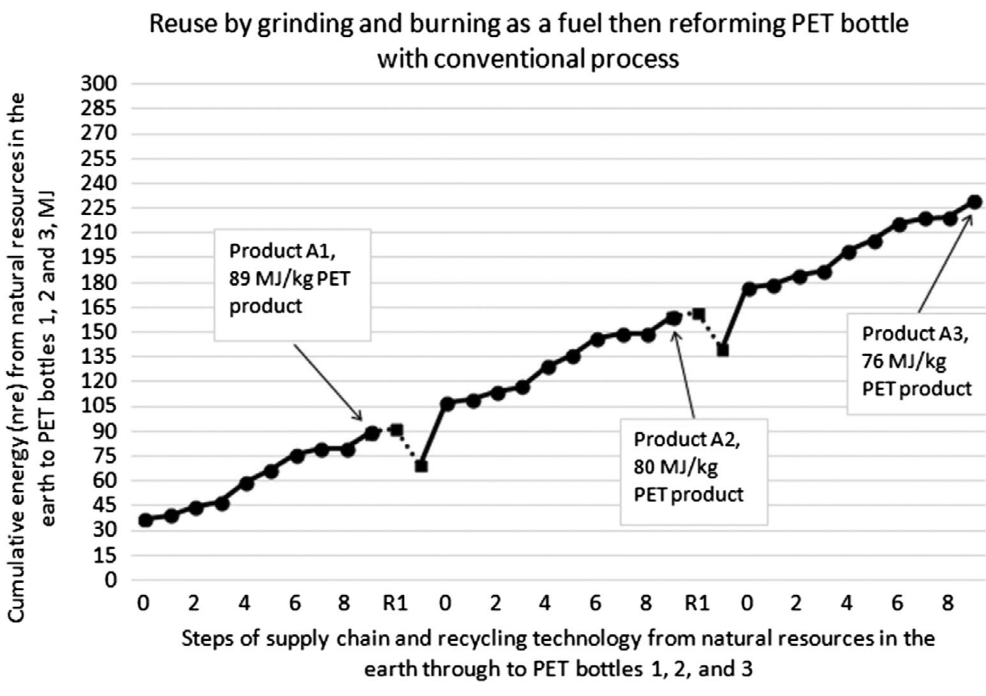

FIGURE 6 Reuse as a solid fuel

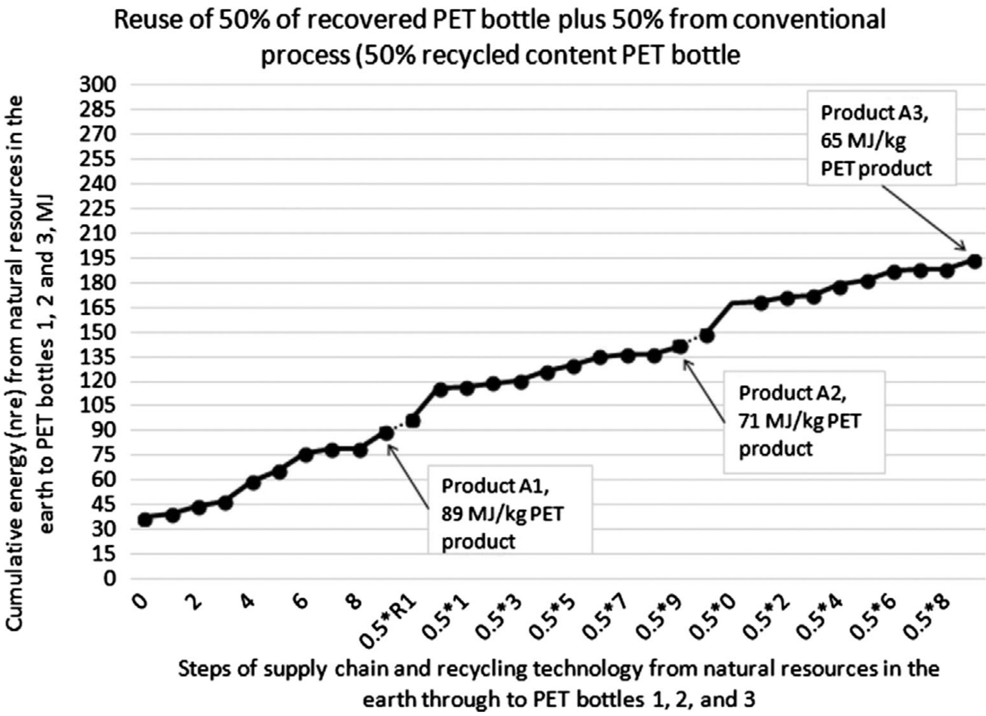

FIGURE 7 Reuse of 50% of recovered PET bottle material (from mechanical process of grinding, extrusion, pelletizing, and injection molding) plus 50% from conventional virgin PET process (ie, a 50% recycled content PET bottle). PET, polyethylene terephthalate

any recycling technology from waste materials we can now determine the benefits of increasing recycle content (Equation 1).

$$\text{ERC (MJ/kg product A)} = \text{PPE}/n + [\text{PPE}*(1 - f) + \text{RTE}*f]*[(n-1)/n] \quad (1)$$

Where ERC = energy of recycled content product after the first virgin manufacturing, calculated as the cumulative energy needed for n products divided by n. PPE = virgin product energy, MJ/kg recycled product A. In the Figures of this article, PPE is the energy segment illustrated with solid lines. RTE = recycling technology energy to convert waste product into the recycled product A. In the Figures of this article, RTE is the energy segment illustrated with dotted lines. f = fraction of product A that is recycled content (0 to 1). n = number of successive products (n = 1 is the virgin manufacturing of product A).

This equation allows one to scale any recycling technology and any polymer to explore the benefit of recycling and incorporating recycled material into products. It is more detailed than Geyer,[6] thus making it clear why recycling some polymers is better, even if the recycling technologies employ the same amount of energy. It also includes the effect of multiple loops. Note: by writing two equations for a "two-product" system and solving these simultaneously, Equation (1) can be used for any open loop regardless of whether the recycled product is downscaled or upscaled. The lifecycle metric of nre is used here, but in this method, any life cycle impact assessment metric can be calculated with Equation (1). Thus, with this approach of comparing technologies, it is neither difficult to add different products of PET nor to change the material being displaced by the recycled PET, hence it applies to open and closed loop systems.

Recent publications of LCA-based analyses[12] asserting that increasing recycled content does not necessarily confer environmental benefits have missed the impact of category 1 energy. The process energy for incorporating recycled content does not change since both virgin and secondary chemicals are processed under the same conditions (ie, polymerization or injection molding). If recycled content has a positive environmental benefit at any level, then a disadvantage of increased recycled content would only occur if the product manufacturing process somehow required substantially greater energy as secondary sources are increased (virgin sources decrease). The authors know of no wide-spread incidence in which this is true.

As an example, using mechanical recycling to produce material to be added as recycled content, and a 50% recycled content in successive PET bottles, we can see from Equation 1 the second bottle is 71.5 MJ nre/kg PET bottle. Figure 7 depicts the use of recycled PET content derived from the mechanical recycling technology, Figure 4. After the first product, the mechanical recycled PET is shown as 7.4 MJ nre/kg (the delta energy between product 1 and 2 in Figure 4, R1 to R4 times 50% to get MJ

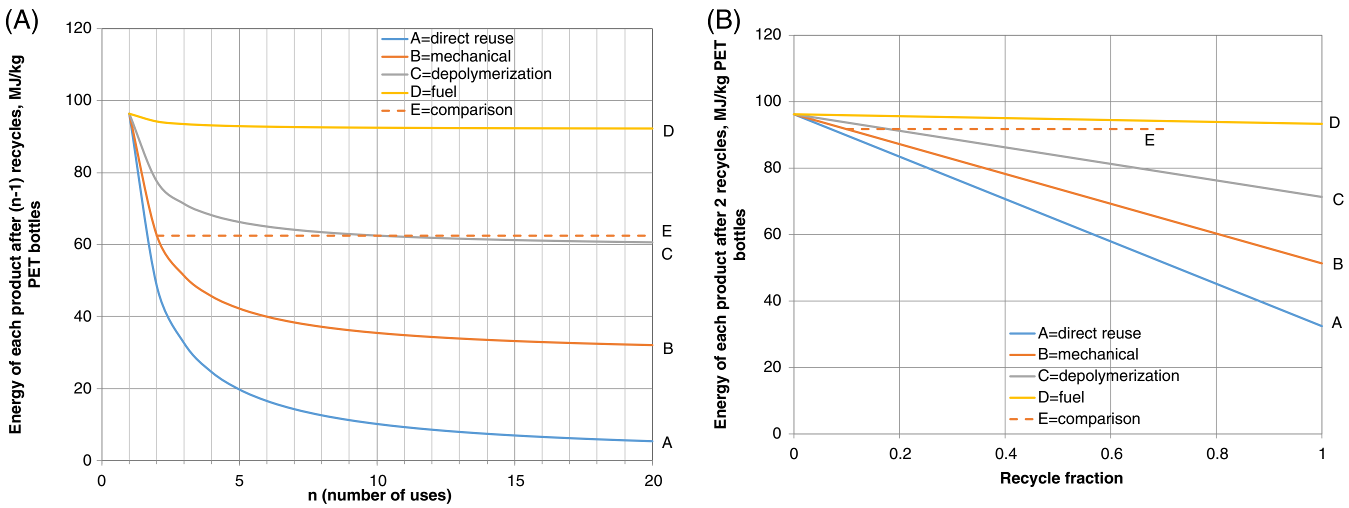

FIGURE 8 Influence of number of recycling loops, A, and recycled content, B, on recycling technology energy for 1 kg PET bottles. PET, polyethylene terephthalate

nre/0.5 kg PET). The other 50% of the PET is from the virgin supply chain, also multiplied by 50% to get MJ nre/0.5 kg virgin PET. On the X-axis of Figure 7 the notation is R1*0.5 and each of the nine stages of the virgin supply chain are given as Z*0.5. These graphics are used to describe that this second bottles is half-recycled PET and half-virgin PET. As a result, the second bottle is an average of 71 MJ nre/kg PET bottle (2.9 kg CO_{2eq}/kg PET bottles). The third bottle is a cumulative energy of 138 MJ nre/kg PET bottle which is an average of 65 MJ nre/kg PET bottle (2.8 kg CO_{2eq}/kg PET bottles). If we increase to 70% recycled content, the third bottle is an average of 55 MJ nre/kg PET bottle (vs 65 MJ nre/kg PET bottle with 50% recycled content). These cases show that both increasing the number of recycling loops and increasing the recycled content give continued energy improvement in making PET bottles.

Equation (1) helps explore the environmental benefits of recycle content and the number of recycle loops, Figure 8. In Figure 8A we see that there is a consistent continuum of energy benefit when each technology is used across multiple recycle loops. However, if mechanical recycling is used for one cycle (line E) and depolymerization is used for nine recycle lops, there is little difference in the energy benefit of these two technologies. It is thus clear that multiple loops are fundamentally better for energy improvement, but the magnitude of improvement depends on the recycling technology.

Recycle technologies are located in relatively few and dispersed locations across the U.S., where the availability of waste PET may vary. This can lead to limits on the supply of recycled content for one technology due to location vs another technology in a different location can have higher availability of recycled materials. This variation in recycled content can lead to localized shifts in the better environmental benefits when comparing technologies. In Figure 8B, mechanical recycling at 10% recycled content has a higher energy/kg PET bottles than depolymerization at 30% recycled content, despite the consistent energy difference patterns of these two technologies when compared at equal recycled contents (Figures 4 and 5). Therefore, it is critical to factor in the varying product recycle content when evaluating the energy benefit of recycling technologies.

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is critical to factor in variations of recycled content of products (the varying product recycle content) when evaluating the energy benefit of recycling technologies.

4 | METHODS

Five recycling scenarios representing the common categories of plastics recycling are examined. These are based on PET polymer in the form of a beverage bottle as the product. However, PET for the window washer fluid container in an automobile is also used as an example for one scenario as it is easier to illustrate this first recycling concept. The functional unit is 1 kg of PET bottle product (~100 single-serve 0.5 L water bottles). For all five scenarios, the first product is made from virgin inputs and the energy for the first bottle is the same across all scenarios. The next bottle begins with one of the recycling technologies and continues until a second bottle is made. The cumulative energy at the second bottle stage is the sum of the first and second bottles, which is two bottles for X total MJ, which then is X/2 per bottle. To learn from the progression involving the energy in categories 1 and 2, the third product is made with the same scenario. The cumulative energy at the end of the third bottle is Y total MJ, which then is Y/3 per bottle. Further, the energy used is given as the nre, which accounts for the full energy needed in all the manufacturing and recycling processes as described in Table 1. Most of the data are from the environmental genome initiative (www.environmentalgenome.org) and Environmental Clarity, Inc. database[9] and described in Appendix 1. It is neither difficult to add different products from the recycled PET nor to change the material being displaced by the recycled PET by following this method. This is done by writing two equations for a two product systems and solving these simultaneously. Equation 1 can thus be used for any open loop regardless of whether the recycled product is downscaled or upscaled. Thus, this equation applies to and compares open and closed loops. However, to get a more basic comparison of these secondary technology issues the approach used must also be transparent.

5 | DISCUSSION OF FUTURE ANALYSIS GOALS

Based on this preliminary study, improved explanation and energy use information of these five scenarios and variants thereof will strengthen the credibility of recycling decision-making. At present, all of these alternatives are better than landfilling and should be accepted by society as improvements. It must be emphasized that these results attempt to quantify the environmental benefits of recycling on cumulative energy use and do not attempt to address other critically important aspects such as toxicity or economic impacts.

The supply of waste material varies across the country, so in one location more of plastics A may be available than plastics B, thus leading to potentially different amounts of recycled content of end products. From Equation (1), this can change the relative benefit of one recycling technology (with higher recycled content) compared to another technology (with lower recycled content). Thus, waste-limited cases cannot be easily compared as this factor overrides the actual technology energy improvement performance.

TABLE 2 Comparative summary of MJ nre energy per kg PET bottles (about 100 single-serve 0.5 Liter water bottles) for various recycling technologies

Scenario	PET bottle 1	PET bottle 2	PET bottle 3
Direct PET bottle reuse with only transport or simple process to next user	89	45	30
Reuse by grinding, extruding, pelletizing, and injection molding to bottle	89	52	36
Reuse by grinding, depolymerizing to terephthalic acid and ethylene glycol, repolymerizing to pellets, and injection molding to bottle	89	67	60
50% recycle of PET from grinding, extruding, pelletizing, and injection molding to bottle and 50% virgin PET	89	71	65
Reuse by grinding and burning as a fuel then reforming PET bottle with the conventional virgin process	89	80	76
Non-recycle PET product with bottle to landfill and virgin supply chain for successive bottles	89	89	89

Abbreviation: PET, polyethylene terephthalate.

Another vital but currently missing body of information is the number of recycling loops a plastic can undergo before some factor forces it into lower material quality uses where the performance requirements are less stringent, or it is converted into recovered energy or liquid fuel sources. These cycle limits can further shift the environmental benefit of any technology as Table 2 shows the energy profile improves with higher number of loops. This article illustrates loops one and two only. This is a degradation factor that could be studied by just looping immediately to discover this limiting factor value. For example, mechanical recycling may degrade the PET polymer and thus have fewer cycle loops as a bottle, while depolymerization to monomers and purification may extend the life of the polymer substantially. If this degradation limit to the number of recycling loops for PET recycling for these and other technologies can be estimated, then analysis herein can be modified by inserting a virgin product at this recycle limit and then continuing as shown in the current Figures. Additionally, if some recycling technologies do not need cleaned polymers, the benefit of reduced energy in the collection and processing stages can be added to those technologies.

6 | CONCLUSIONS

Table 2 captures the continuum of recycling or circularity benefits for these representative scenarios for PET and shows consistently that more recycling loops provide lower product impact. The data are assembled from the greatest benefit expressed in energy per kg PET bottles (about 100 single-serve 0.5 L water bottles), listed first, and the base case of landfill listed last. From Appendix 1, there are ranges in values of the process energies on the order of 1-3 MJ nre/kg PET. This variation does not significantly change the relative energy use for these technologies. All cases, except solid fuel, use injection molding of the bottle and these larger variations in Appendix 1 are thus the same for all technologies examined herein and likewise do not alter the comparisons. Thus, one can conclude all the circularity scenarios lead to an improvement over landfilling or littering of PET bottles. For some technologies like direct reuse, the energy improves significantly with the third and higher product recycling loops, while others such as solid fuel use show smaller incremental improvement. This successive improvement demonstrates the long term goal of these reuse or recycling scenarios. The data shown here describe the kind of analysis and level of transparency that are required for each polymer or chemical considered for recycling in order to quantitatively define the energy reduction benefit, and hence to form a science-based comparative methodology for more plastics recycling technologies. The environmental genome (www.environmentalgenome.org) can facilitate these calculations as it contains the polymers and whole supply chains for such evaluations.

ACKNOWLEDGMENTS

Elizabeth Ritch of GreenBlue has selflessly helped us with the graphing challenges in this article and as an external evaluator.

CONFLICT OF INTEREST

This engineering-based analysis was undertaken with no conflict of interests or direct funding support.

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How to cite this article: Overcash MR, Ewell JH, Griffing EM. Life cycle energy comparison of different polymer recycling processes. *J Adv Manuf Process*. 2020;2:e10034. https://doi.org/10.1002/amp2.10034

APPENDIX 1

References and data used in plastics recycling technology comparisons

Polyethylene terephthalate (PET) recycling technologies	Source	Value	Value judged as representative
Virgin supply chain energy	Category 1, fossil natural resources in PET	790 kg crude oil*45 MJ/kg crude oil +30.2 kg ng *53.5 MJ/kg ng = 37 160/1000 kg	37.2 MJ/kg PET
	Category 2, supply chain energy in PET, see this article Figure 1		52.2 MJ/kg PET
	Total supply chain		**89.4 MJ/kg PET**
Granulating or Grinding of Plastics	Polyretec[13]	5.2 MJnre/kg	**2.5 MJ nre/kg PET**
	Polyretec[13]	2.5 MJnre/kg	
	Paradise distribution and recycling[14]	2.0 MJnre/kg	
	Dupont Teijin study[15]	1.7 MJnre/kg	
Transport	Belzer, US DOE 2014 single compartment trucks[16]	0.0025 MJ nre/kg km	**0.003 MJ nre/kg km**
	Belzer, US DOE 2014 dual compartment trucks[16]	0.0055 MJ nre/kg km	
	Ecoinvent operation, roads, maintenance, manufacture[17]	0.0018 MJ nre/kg km	
	Wang, 1999 p. A-72[18]	0.0055 MJ nre/kg km	
	Thiriez, 2006[19]	0.0019 MJ nre/kg km	
Pelletizing	Dupont Teijin study[15]	0.19 MJ nre/kg	**0.18 MJ nre/kg PET**
	Pelletizer heuristic[20]	0.12-0.19 MJ nre/kg	
	Thiriez, 2006[19]	0.16 MJ nre/kg	
Extrusion	Dupont Teijin study[15]	1.7 MJ nre/kg PET	**2.2 MJ nre/kg PET**
	Thiriez, 2006[19]	1.8-5 MJ nre/kg	

(Continues)

Polyethylene terephthalate (PET) recycling technologies	Source	Value	Value judged as representative
	Extruder heuristic[21]	2.7 MJ nre/kg PET	
	Paradise distribution and recycling[14]	2.0 MJ/kg	
Injection Molding	Thiriez, 2006[19]	3-8 MJ nre/kg	**10 MJ nre/kg PET**
		4-70 MJ nre/kg	
		2-15 MJ nre/kg	
	Ecoinvent[17]	21 MJ nre/kg	

Note: Significance of bold is for numbers judged as representative where there are multiple values cited.