PLASTICS RECYCLING - AN OVERVIEW

I. Boustead

Introduction

There is a general climate of opinion at present that recycling is beneficial. A variety of schemes have been devised over the last few years to recover materials as diverse as metals, plastics, glass, paper and board in order that they can be re-used in some way. The act of re-using these secondary materials is, in general, thought to be a 'good thing' but there are relatively few exercises, which monitor existing or proposed recycling schemes to find out if they really produce any environmental benefits. There is, moreover, often some uncertainty on the part of the initiators of such schemes about the precise reason for recycling at all.

This paper examines the general principles underlying recycling processes with a special emphasis on plastics recycling. It is concerned with the physical aspects of materials and energy and is not concerned with the economics of the processes.

The environmental effects of industrial processes

All industrial processes take in a supply of raw materials and energy to produce some useful product or service and in the course of materials processing give out solid, liquid and gaseous wastes. From an environmental and conservation viewpoint there are therefore five main groups of parameters of interest. These are:

1. Raw materials consumption
2. Fuel and energy consumption
3. Emissions to air
4. Emissions to water
5. Solid waste generation

These represent the five main groups of parameters that are currently calculated in life-cycle assessment for extended systems; that is, systems which trace all operations from the extraction of raw materials from the earth through to final disposal at the end of a product's life.

The more efficient processes are those, which minimise the consumption of raw materials and energy and produce the least solid waste and emissions to air and water. Historically engineers have sought to make processes more efficient by improving the performance characteristics of individual processes within a production sequence. However, it has long been recognised that an alternative approach might be to link unit operations in new ways so that, by creating additional paths for materials flows, it may be possible to increase the flow of useful products through the consumer without significantly increasing the environmental burden. This is the principle underpinning recycling.

To understand the implications of recycling processes three examples have been analysed in general terms. These are:

(a) Closed loop recycling when there are no losses in
The recycling loop,

(b) Closed loop recycling when losses occur in the
Recycling loop and

(c) Open loop recycling.

Materials flows in loss-free closed-loop recycling

Probably the simplest form of recycling is closed loop recycling. This is illustrated schematically in Figure1. Figure1(a) shows a simple linear production sequence consisting of three unit operations labelled 1, 2 and 3. Figure 1(b) shows the same production system but a recycling loop has been included in which essentially some of the waste materials are extracted from the system, re-processed and fed back into the same production sequence to displace virgin raw materials.

It is not difficult to calculate the saving in raw materials that will occur. Suppose that all of the operations operate without materials losses and further suppose that the consumer is located somewhere in operation 2.

In the absence of recycling (Figure 1(a)), if a mass of raw materials is fed into the system, then a mass m of product will be experienced by the consumer.

Now suppose that a recycling loop is incorporated into the system (Figure 1(b)) and further suppose that it takes a fraction f of the waste products leaving operation 2, reprocesses them without materials loss and returns them to the main production sequence. The mass flows, for a flow m through operation 2 will now appear as in Figure 1(b).

The important feature of Figure 1(b) is that although the consumer in operation 2 will still see a product of mass m flowing past, the raw materials input to operation 1 has been reduced from m to (1-f) m and the solid waste entering operation 3 has also been reduced from m to (1-f)m. Therefore as a consequence of introducing the recycling loop, the demand for raw materials has been reduced and the solid waste generated has also been reduced. Even if an allowance is made for materials losses in all of the operations, the same general conclusion will apply.

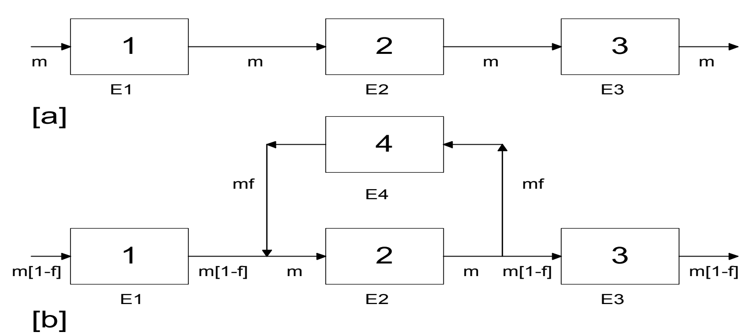

Fig.1
[a] Simple linear production sequence with no recycling.
[b] The same production sequence with recycling loop incorporated see text for explanation

An alternative way of viewing this effect is to suppose that a single mass m is fed into operation 1 in Figure1 (b) and then monitor the quantity of product that will pass the consumer, as some fraction of this initial mass is repeatedly recycled.

On the first pass, the product mass will be m. After the first recycle, the mass will be mf. At the second recycle it will be mf2 and so on. Thus after an infinite number of recycles, the consumer will have experienced a total mass M of product passing through where

$$M = m + mf + mf2 + mf3 + mf4 + ….$$

And summing this series gives

$$M = m/(1-f) \qquad (1)$$

Thus if there is no recycling, f will be zero and M = m which corresponds to the situation shown in Figure 1(a). On the other hand, if 50% of the materials leaving operation 2 are recycled, f = 0.5 and M = 2 so that for an input of 1 kg of materials, the consumer will experience 2 kg of products. Similarly, with 90%recycling, f = 0.1 and M = 10 so that an input of 1 kg of raw materials will lead to the passage of 10 kg of product. In all of these cases, the amount of solid waste generated will remain at 1 kg.

Thus if the aim of recycling is to minimize raw materials consumption and solid waste generation, then the aim should be to aim for the highest recycling rate possible.

Energy flows in closed loop recycling

The energy needed to drive the systems shown in Figure 1 presents a more complicated picture than the raw materials flows. To evaluate these energies suppose that the energy requirement per unit output for each of the unit operations 1 to 4 is E1, E2, E3 and E4 respectively; thus E1 is the energy required by operation 1 to give an output of 1 kg from operation 1, and so on.

For the system of Figure 1(a), where no recycling occurs, the system energy, Es, is given by

$$Es = m.E1 + m.E2 + m.E3$$

$$= m(E1 + E2 + E3) \qquad (1)$$

For the recycling system in Figure 1(b), the energy will be Es' where

$$Es' = (1-f)mE1 + mE2 + (1-f)mE3 + fmE4$$

And this rearranges to:

$$Es' = m(E1 + E2 + E3) + fm(E4 - E1 - E3) \qquad (2)$$

Using equation (1), this can be rewritten as:

$$Es' = Es + fm(E4 - E1 - E3) \qquad (3)$$

If the energy change introduced as a result of incorporating the recycling loop is written as ΔEs, where

$$\Delta Es = Es - Es'$$

Then from equation (3)

$$\Delta Es = fm(E1 + E3 - E4) \qquad (4)$$

If the right hand side of this equation is positive, then there will be energy saving. If, on the other hand, the term is negative, then the introduction of the recycling loop will have incurred a net expenditure of additional energy. The critical condition, which determines whether energy will be saved or lost in recycling, is the value of E4 relative to the sum of E1 and E3.

For the recycling of post-consumer waste, operation 1 in Figure 1(b) will represent all processes starting with the extraction of raw materials from the earth through to the production and delivery of a material at the converter. Operation 3 will represent all materials handling operations that occur after the consumer has finished with the product at the end of its useful life and in most systems represents the collection and disposal of waste. In general, the energy associated with operation 3 will be small compared with the energy associated with operation 1. Consequently, provided that the materials can be collected, reprocessed and delivered to the converter with an energy requirement less than that needed to produce virgin materials via operation 1, then an energy saving will occur.

One important consequence flows from this conclusion. As the production of virgin materials is made increasingly more energy efficient by improved manufacturing techniques, the scope for energy saving by recycling is gradually diminished because the parameter E1 in equation (4) is decreased relative to E4.

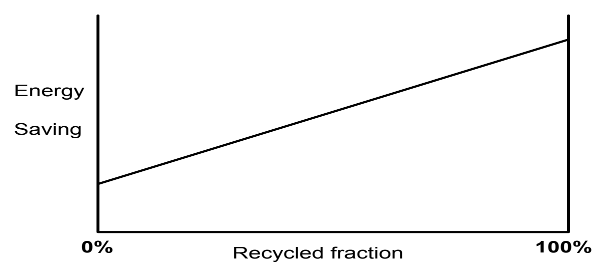

Fig.2. Energy saving as a function of recycled fraction if energy terms are constant

A further important factor to be borne in mind is the effect of recycled fraction on the energy saving. In most analyses of recycling, it is assumed that the parameters E1, E3 and E4 in equation (4) are constant.

As a consequence, the energy saving, ΔEs, is a linear function of f. Therefore on this scenario, if an energy saving occurs when the recycling scheme is initially implemented, the magnitude of the saving can be increased by simply increasing the recycling fraction because energy saving should follow the graph shown in Figure 2.

However, the assumption that the energy terms in equation (4) are constant is not correct and to understand why, it is necessary to examine the nature of the energy use in the recycling loop (E4 in Figure 1(b)). E4 is a composite value made up of the energy used to recover the waste materials from the consumer, to transport them to the re-processing plant, to re-process them and finally to deliver them to the converter. All of these elements are likely to be variables for the following reasons.

Recovering waste materials

Irrespective of the method used to acquire the waste materials, transport plays a significant part in this operation. Initially materials will be recovered from large population centres but as recovery fraction increases, transport distances and consequently energy will increase. If consumer-aided recovery is used there is a need to include a proportion of the consumer's transport energy in the recovery system

Processing waste

At low recycling fractions, the processing plant will be operating below capacity and the base load of energy will be spread over the relatively low volume of throughput. As recycling fraction increases, the plant will exhibit improved performance until it is full loaded. If additional plants are brought on stream, they too will suffer the same effect.

Delivering reprocessed materials

As with the collection of the waste, as the amount of reprocessed materials increases and the number of users increase, they will become increasingly scattered and so the final delivery energy will change.

Of these, the recovery of post-consumer waste and its delivery to the re-processing plant is probably the most important because of the very scattered nature of post-consumer waste. For example, at low recycling fractions, the recovery of waste from urban communities can probably be made sufficiently efficient for energy savings to occur, as over the initial portion of the
Line in Figure 2.

However, consider the other extreme of trying to recover the last 5% when the recovery rate is already 95%. Such a proposal would require that every last container, including those taken away by overseas holidaymakers, be recovered. Clearly such a proposition is impractical but it underlines the fact that at very high recovery rates, the recovery energy would certainly be increasing steeply. As a consequence, the actual relationship between energy saving and recycled fraction will be a curve such as that shown in Figure 3.

The precise form of the curve in Figure 3 will vary from one material to another but the general form indicates two very important points.

First, if the recycling process is not to use more energy than the process without recycling, then the recycled fraction should not increase above f1 in Figure 3; that is, until the energy reaches its initial value.

Secondly, if the primary purpose of recycling is to save energy, then recycling should be practised only until the energy saving curve reaches the minimum of Figure 3; that is, until the recycling fraction reaches f2.

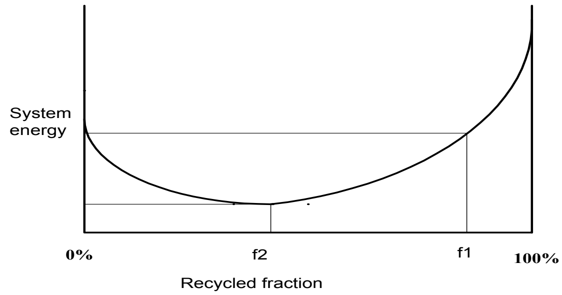

Fig.3
Energy savings as a function of recycled fraction if energy terms are not constant

Materials flows in closed-loop recycling with losses

One objection to the simplified analysis is the assumption that the recovery and reprocessing loop causes no loss of materials. This assumption leads to the unrealistic conclusion that if f=1 (100% recycling) then the system is self sustaining and no further raw materials must be fed to the production process. In fact this problem can be resolved by setting up the equivalent system, but including a loss stream in the sequence as shown in Figure 4.

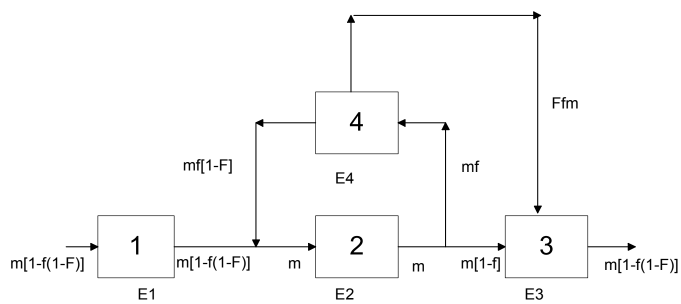

Fig. 4. Simple closed loop recycling when the reprocessing stage, 4, produces waste materials

If a single mass of 1 kg were now to be fed into this system, then a 1 kg of product will pass the consumer at the first pass. If a fraction f of the material leaving the consumer is now fed into the recycling loop and if the recycling loop is responsible for a loss of a fraction F of the material passing through the reprocessing stage 4, then the material returned to the main production sequence will be of mass mf (1-F) and this is the mass of product that will pass the consumer after the first recycle. After a second recycle, the mass of product will be reduced to mf2 (1-F) 2. If the material is continually recycled under the same conditions, then after a large number of cycles, the total mass of product that will have passed the consumer will be S, given by

$$S = m + mf(1-F) + mf^2(1-F)^2 + mf^3(1-f)^3 + ...$$

Summing this equation and assuming that there are an infinite number of terms gives

$$S = m/(1-f(1-F)) \qquad (5)$$

This equation is of the same form as equation (1) but the main physical difference is that the factor f is always reduced by the multiplying factor (1-F). Thus if there is 50% recycling, equation (1) predicts that the consumer will experience 2 kg of product for every 1 kg of raw materials fed into the system. If however, there is a loss of 20% of the recycled materials, then this product flow is reduced to 1.7 kg. Clearly then, there should ideally be as small a loss in the recycling loop as possible if raw materials demand is to be maximized.

This effect is shown up in Figure 4. If a mass m of product is to be maintained at the consumer in operation 2, the raw materials consumption increases from m(1-f) in the loss-free case of Figure 1 to m[1-f(1-F)] in Figure 4. At the same time, the mass of solid waste generated increases from m(1-f) in the loss-free case of Figure 1 to m[1-f(1+F)]in Figure 4.

Energy flows in closed-loop recycling with losses

The energy used in the system of Figure 4 can be calculated in exactly the same manner as that for Figure 1. Suppose that the energy requirements per unit output from each of the component unit operations 1, 2,3 and 4 are E1, E2, E3 and E4 respectively, then with mass flows as shown in Figure 4, the energy requirement of the overall system, Es" is simply the product of the unit energy requirements and the mass flows. Hence

$$Es'' = E1m(1-f(1-F)) + E2m + E3m(1-f(1-F)) + E4mf(1-F)$$

And this simplifies to:

$$Es'' = \underbrace{\{m(E1+E2+E3)\}}_{A} + \underbrace{\{mf(E4-E1-E3)\}}_{B} - \underbrace{\{mfF(E4-E1-E3)\}}_{C}$$

Although the form of this final equation looks complicated it is, in fact, only necessary to realize that the right hand side consists of three terms labelled A, B and C. Term A is simply the energy requirement of the system when no recycling is practised. Term B is the recycling term that occurs when the loss-free loop is introduced (see equation 3). Term C is a new term occurring in the recycling loop; the E4 part arises because materials are being processed but then lost, the E1 part arises because more virgin raw materials are having to be supplied from operation 1 to make up the losses and the E3 part reflects the increased solid waste generated as a result of the losses.

In general, therefore, although the occurrence of losses in the closed loop system follow the same general form as when no losses occur, it is expected that the energy saving will be reduced as a consequence of the losses.

Materials flows in open loop recycling

Open loop recycling occurs when the material from one production sequence is recovered, reprocessed and fed into a different, and often unrelated production sequence. An example of open loop recycling would be the recovery of post-consumer waste PET bottles, which are then fed to fibre production.

To examine the effect of such recycling, it is first necessary to consider the pair of production sequences involved before and after the recycling operation is introduced. Figure 5 shows such a pair. Suppose that, in both instances, the materials are processed without loss. For the sequence employing operation 1-2-3 I Figure 6, the mass flow through the consumer is m and for the sequence employing operation 4-5-6 in Figure 6, the mass flow is M.

The total demand for raw materials is therefore the sum of the input masses to the two systems, m+M and the solid waste produced is also m+M.

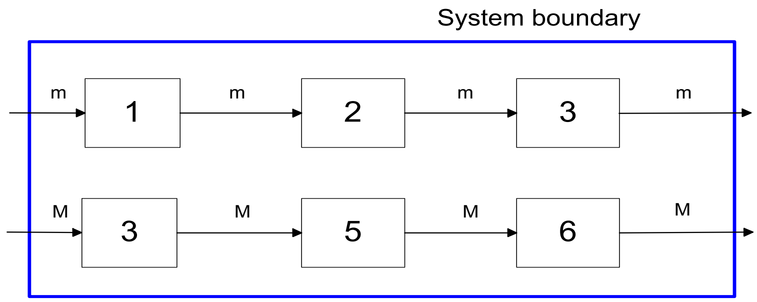

Fig.5. Schematic diagram showing a pair of unrelated production sequences

Now suppose that the two production sequences are linked together by a recycling operation as shown in Figure 6. A fraction f of the post-consumer waste from one sequence is recovered, re-processed and fed into the second sequence. Assume that during the recovery and reprocessing operation a fraction F of the material is lost as solid waste. This waste is fed into operation 3 for disposal along with all other waste from the first production process.

The mass flows will be as shown in Figure 6 and, as cane seen, the demand for input materials is now

$$m + M - fm(1-F)$$

This represents a decrease of fm (1-F) over the situation before recycling is implemented; that is, the raw materials demand of the overall system is reduced by the amount of material recovered by the recycling operation less the waste generated by the recycling operation.

The mass of solid waste generated is when recycling is practised is

$$M + m(1-f) + Ffm$$

This represents a decrease of mf(1-F) compared with the situation in the absence of recycling (Figure 5); that is, the waste is decreased by the mass of material recovered by the recycling loop less the waste generated by the recycling operation.

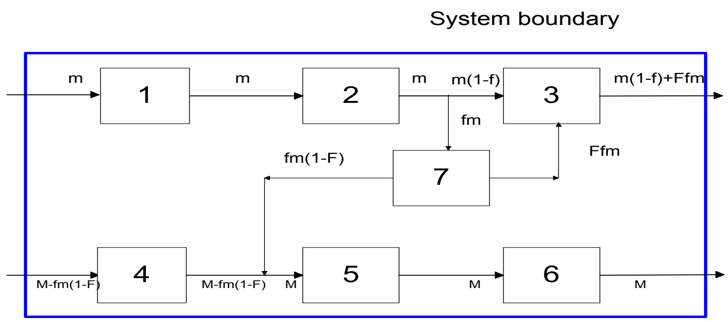

Fig. 6 Schematic diagram showing open loop recycling. See text for explanation

Energy flows in open-loop recycling

The effect of open-loop recycling on energy requirements can be determined by writing E1 for the energy per unit output from operation 1, E2 for the energy associated with unit output from operation 2, and so on.

For the combined system of Figure 5, in the absence of recycling, the total system energy, Es, is given by the sum of the products of unit energy and mass, so that:

$$Es = m(E1 + E2 + E3) + M(E4 + E5 + E6) \qquad (6)$$

This represents the energy against which any changes must be judged.

For the combined system with recycling shown in Figure 6, the system energy, Es', will again be given by the sum of the products of unit energy and mass, so that:

$$Es' = mE1 + mE2 + (m(1-f) + Ffm)E3 + fm(1-F)E7 + (M - fm(1-F))E4 + ME5 + ME6$$

This equation can be rearranged to the form:

$$Es' = \underbrace{[m(E1+E2+E3)+M(E4+E5+E6)]}_{A} - \underbrace{[fm(E3+E4-E7)]}_{B} + \underbrace{[Ffm(E3+E4+E7)]}_{C}$$

As with the closed loop recycling, the energy equation consists essentially of three terms, labelled A, B and C. Term A is identical to the energy term when no recycling is practised (see equation (6)). Term B corresponds to the energy change that will occur when recycling is practised but when there are no losses in the recycling operation. Term C is the energy change introduced when the recycling operation produces waste.

Although the specific contributions are different, it is clear that the general form of the equations for open loop recycling are the similar to those for closed loop recycling. The energy change in the overall system, ΔEs, when there is no waste produced in the recycling operation is of the form

$$\Delta Es = fm\ (E3+E4-E7)$$

The main practical difference, however, is that ΔEs now relies on the energy associated with the recycling operation, E7, as for closed loop recycling, but also on the energy from one operation in the first production sequence, E3, and on the energy from one operation in the second production sequence, E4. This dependence on energies from different production sequences leads to two important discussion points.

First, the energy change can readily be calculated for the overall system. However, since the system now contains two products, it is impossible to identify which of the products is responsible for the energy saving. Much argument has taken place in the past over who should get the 'credit' for recycling. The operators of the first production sequence 1-2-3 in Figure 6 often claim that their production sequence should get the benefit because they are supplying the raw materials for the second production sequence 4-5-6 in Figure 6. Equally vociferous are the operators of the second production sequence 4-5-6 in Figure 6 who claim that they should get the 'credit' because they are taking the waste from the first production sequence. There is, in fact, not scientific way in which the energy change of the overall system can b partitioned between the product flows m and M; all that can be calculated is the change in the system energy.

The second important point to note is that the two production sequences are interlinked and, although they may be operated independently, they cannot be operated in isolation from each other if recycling is to be practised in an efficient manner. A simple example illustrates this point. Suppose that the production sequence 1-2-3 in Figure 6 is responsible for producing PET bottles and the second production sequence 4-5-6 in Figure 6 is responsible for producing PET fibre.

If sequence 1-2-3 in Figure 6 is operated in isolation, the aim of the operators will be to maximize the efficiency of their process. In general this will mean light-weighting the bottles. Provided that the bottles are made solely of PET, there is no great difficulty in recycling them. However, as the bottle mass decreases there eventually comes a point where the wall thickness is such that the bottles will no longer hold a carbonated beverage.The problem can be overcome by introducing a barrier layer so that further light weighting becomes possible. However, once the barrier layer is introduced, the bottles are no longer recyclable. Thus in order to promote recycling, the operators of the first production sequence 1-2-3 in Figure 6 must deliberately refrain from making their process as efficient as it could be. Given that the bottle maker will usually be completely divorced commercially from the fibre producer, it would open a new chapter in industrial processing to ask one producer to remain inefficient in order to benefit the common good.

Fuels and feedstocks

In all of the above analysis, materials flows have been examined separately from energy flows and the final consequences of recycling are shown to be different for these two different parameters. In general, recycling will always result in a reduction in raw materials consumption and solid waste generation per unit product at the consumer. For energy, however, there is no guarantee that savings will occur when recycling is practised.The energy changes resulting from recycling are governed by a number of different parameters and only when certain well-defined conditions are satisfied will energy savings occur.

For products manufactured from inorganic materials, raw materials consumption is invariably kept separate from the consumption of fuels. The units in which they are measured are different and there is therefore no temptation to try and combine the two.

For polymers, however, the raw materials input, measured as the feedstock energy,is usually expressed in the same units as the fuel energy. Consequently there is frequently the desire to combine the two contributions into a single parameter for simplicity. This, however, should not be done. The effect of recycling on feedstock energy follows the treatment given earlier for materials flows whereas the treatment for fuel energy follows that given for energy and, as noted earlier, they are different.

Why recycle?

Recycling is a mechanism. It is a mechanism for achieving some environmental goal. It is not a goal in its own right.

Therefore, before any recycling scheme in introduced, it is essential that the ultimate goal be specified. If the goal is not specified, then it is impossible to judge whether the recycling scheme has achieved its purpose or to judge whether an alternative mechanism might not be better in achieving the goal

Within the areas of materials and energy flows considered in this paper there are three possible goals.

(a) Reduce the consumption of raw materials (feedstock).

(b) Reduce the consumption of fuels, especially fossil fuels.

(c) Reduce the generation of solid waste.

If the goal is to reduce raw materials (feedstock) consumption and there are no other constraints, then recycling should always be practised.

If the goal is to reduce the generation of solid waste and there are no other constraints, then recycling should always be practised.

If there is an energy constraint then the individual process must be examined very carefully.

It is also important to distinguish between two different types of recycling processes for plastics; mechanical recycling and energy recovery. Mechanical recycling is the recovery of plastics for further use as materials. This form of recycling is available to all other materials.

Energy recovery is the recovery of plastics for their fuel value. This option is available to relatively few materials; plastics and wood products are the most obvious examples. These two options are complementary; they are not mutually exclusive options.

Energy constraints on mechanical recycling

From the earlier analysis, the energy change, ΔE, occurring as a result of implementing recycling can be written as

$$\Delta E = Evirgin + Edisposal - Erecovery - Ereprocessing$$

where

Evirgin = the energy to produce virgin material from raw materials in the earth. (Evirgin corresponds to energy E1 in equation 4)

Edisposal = the energy to dispose of the material if it were not recycled. (Edisposal corresponds to E3 in equation 4)

Erecovery = the energy to recover the material from the post-consumer stream and deliver it to reprocessing

Ereprocessing = the energy associated with reprocessing the recovered material until it is in a form that it can displace virgin material. (The sum of Erecovery and Ereprocessing corresponds to E4 in equation 4).

Suppose now that the recycling scheme should be designed and operated in such a manner that the energy requirement per unit product should not increase. This implies that $\Delta E = 0$ and therefore

Virgin + Disposal = Erecovery + Ereprocessing

Since Evirgin and Edisposal are both known from the system before recycling is implemented, it is possible to determine the maximum energy that can be used in the recycling process before the process incurs an excess energy demand.

Thus in the case of polyethylene, where the production energy (excluding feedstock) is of the order of 30 MJ kg-1 and the disposal energy is less than 1 MJ kg-1, the recovery and reprocessing of 1 kg of polyethylene can use up to about 30 MJ before it incurs an energy penalty provided that there are no materials losses. If, however, there are materials losses in the recycling process, then the maximum energy will be reduced. For example, if there is a 20% loss of material during polyethylene reprocessing, the maximum energy that can be employed is the recycling process is reduced to 0.8 x 30 = 24 MJ kg-1.

It is important to recognize that since the maximum energy that can be used in the recycling process is usually dependent almost entirely on the energy to produce the virgin material, the more energy efficient the virgin process, the lower will be the energy available to the recycling process and as production processes become more energy efficient with time, recycling as an option which saves energy becomes less favourable.

It is also important to recognize that the recovery energy depends on the method used to recover the material. Consumer-aided recovery, in which the consumer is expected to take the used product to some collection point, can be very energy intensive. (The energy consumption of a car is approximately 2 MJ/km). It is widely assumed that the consumer will not make any special trips to such a collection point but will only visit them as an incidental to performing other tasks. However, if the standard logic of partitioning consumer energy over all functions performed, a portion of the energy associated with a visit to a collection point must be added to the recovery total.

Recovery by separate collection with the consumer being given separate sacks for different materials will also incur an additional energy penalty associated with the production of sacks. If a low density polyethylene sack is of mass 50 g, then the energy associated with the sack will be of the order of 4 MJ if made from virgin material and somewhat less if made from recycled material. If such a sack were collected when it held 5kg of waste, the energy associated with 1 kg of waste would be 0.8 MJ.

Within both the recovery stage and the reprocessing stage, transport is involved; the collected product has to be transported to the reprocessing site and the reprocessed material must be transported to the converter where it re-enters the production sequence. It is possible to assign notional values to this transport. A 10 tonne payload truck uses energy at the rate of approximately 20 MJ per vehicle-km. If is assumed that the degree of compaction of the load is such that the volume limit of the truck is reached before the mass limit so that the load carried is only 50% of the maximum payload and if the truck makes an empty return trip, then the energy associated with the delivery of 1 kg over 1 km is 0.007 MJ. Per 100 km, the delivery energy will be 0.7 MJ/kg.

It is impossible to calculate any accurate energy for recycling without knowing the precise mechanisms used. However, a set of notional data can be calculated byway of an example. Suppose that polyethylene with production energy of 30 MJ/kg is usually disposed of using disposal energy of 1 MJ/kg. If instead, the polymer is collected into sacks which are collected and transported about 100 km to the reprocessing site where 20% is lost and the reprocessed product is transported a further 100 km for use, then the 'balance sheet' for the process is of the form:

		MJ
Produce 1 kg of virgin polyethylene		30
Dispose of 1 kg polyethylene		1
	Total for no recycling	31
Recovery in sacks		1
	Total	30
Transport to reprocessing		1
	Total	29
Loss during reprocessing		6
	Total	23
Transport to converter		1
Maximum energy available for reprocessing		***22***

Energy constraints on recycling for energy recovery

The recovery of plastics for use as a fuel is an attractive proposition and one that has often been proposed as a means of disposing of plastics. Because plastics are based on oil and gas, they possess an intrinsic calorific value. For polyethylene, this calorific value is similar to that of crude oil (about 45 MJ kg-1).

In principle, all of this calorific value can be realized by burning but in practice the maximum recovered useful energy is limited by a number of factors.

For example, suppose that polyethylene is recovered and burned with minimal treatment to generate steam for export either to a district-heating scheme or for industrial use. The gross calorific value (CV) must first be reduced to the net calorific value to account for the way in which the incineration plant might be operated. It is expected that there will be some contamination of the polymer say with 5% water and 5%other contaminants. Heat recovery within the incinerator might typically be 80%. The steam distribution line would result in further losses. Finally there is the use that is made of the steam at the delivery point. In the case of a district-heating scheme, there would probably be a high take-up of delivered heat in winter but a low take-up in the summer.

Taking all of these factors into account, it is possible to draw up a 'balance sheet' of the process per kg of polyethylene: -

	MJ
Gross CV = maximum energy available	45.00
Less loss to net CV	4.50

	40.50
Less 5% water contamination @ 3 MJ/kg	0.15

	40.35
Less 5% other contaminants @ 3 MJ/kg	0.15

	40.20
Less boiler losses	8.04

	32.16
Less distribution loss @ 10% of input	3.22

	28.94
Less unused steam (50% utilization)	14.47

	14.47

Thus of the original 45 MJ of energy in the input polymer only about 32% is used usefully. From this must be subtracted the energy needed to recover the polymer and carry out any initial processing.

The situation is little different if the polymer is used to produce electricity rather than steam. Such a process eliminates the distribution and utilization losses but incurs the inefficiencies of converting from heat to electricity. The balance sheet for the electricity example would now appear:

	MJ
Gross CV = maximum energy available	45.00
Less loss to net CV	4.50

	40.50
Less 5% water contamination @ 3 MJ/kg	0.15

	40.35
Less 5% other contaminants @ 3 MJ/kg	0.15

	40.20
Less boiler losses	8.04

	32.16
Less conversion loss to electricity	21.55

	10.61

Thus of the original 45 MJ input only 24% is eventually recovered as usable electrical energy. Again the recovery and reprocessing energy must be subtracted from this total.

Energy constraints on recycling back to feedstock

An alternative form of recycling, sometimes known as tertiary recycling, that has received considerable attention is reprocessing used polymer back to monomer. In this process the waste plastic would be recovered by one of the routes proposed for other forms of recycling. However, instead of simply cleaning, flaking and possibly extruding to granules, the polymer will be chemically treated and fed back to the production process before the polymerisation stage.

The fact that the materials are returned to the system before the polymerisation step is critical in determining the energy behaviour of the system because the term E1 in equation 4 does not now refer to the production of the polymer but to the production of the monomer. Since monomer production from raw materials in the earth, requires less energy than polymer production, the maximum energy that can be used in the reprocessing of the waste is reduced.

Thus in the case of polyethylene with a polymer production energy of 30 MJ kg-1, the energy required to produce the monomer is only about 20 MJ kg-1. It was shown earlier, that by making some simple assumptions about recovery method, the energy available for reprocessing recovered polyethylene was about 22 MJ kg-1 If reprocessing back to monomer is to be accomplished, then this energy must be reduced by 10 MJ to 12 MJ kg-1 as the maximum energy available before the process become energetically unfavourable. The exact energy required to effect the conversion back to monomer will obviously depend upon the amount and sophistication of the processing required but it is perhaps worth noting that the energy associated with steam cracking is of the order of 15 to 20 MJ kg-1.