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A life cycle assessment of the closed-loop recycling and thermal recovery of post-consumer PET

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ABSTRACT

Waste polyethylene terephthalate (PET) bottles collected by source-segregation recycling schemes can be treated by mechanical and chemical means to remove any contaminants. The cleaned PET can then be melted and formed into pellets with the same physical properties as virgin PET. Full-scale trials have shown that this reprocessed material can be used with virgin PET to make new bottles. An alternative recovery option is to collect the waste PET with the non-recyclable waste and burn it in an energy-from-waste plant. A life cycle inventory was produced for these two recovery options to compare the atmospheric emissions of key pollutants and the overall environmental impacts. The recycling option resulted in an overall reduction in the emission of each key pollutant and in the overall environmental impact. This was due to the reduction in emissions from displacing virgin PET. The energy-from-waste route also leads to a reduction in the emissions of several of the pollutants, depending on the assumptions made about the thermal efficiency of the process and the pollutants generated by burning the PET.

1. Introduction

Polyethylene terephthalate (PET) is widely used to make containers for carbonated and non-carbonated soft drinks. It has several advantages over glass, such as consumer safety when dropped and weight savings which benefit customers and reduce the cost and environmental impacts of transport.

In the year 2007/2008, the UK produced 31.8 million tonnes of municipal waste. Based on a compositional survey undertaken in Wales (Burnley et al., 2007), 1.7% of this consisted of dense plastic bottles. Recoup (2003) estimated that 42% of waste plastic bottles are made from PET, which suggests that the UK generates 227,000 tonnes a year of PET in its municipal waste. This compares with a value of 300,000 tonnes per year for PET bottle production in the UK in 2007 (WRAP, 2007).

One of the requirements of the EU Packaging Directive (European Commission, 1994) requires member states to recycle specified proportions of different packaging materials. In addition, under the Waste Framework Directive (European Commission, 2008), member states are required to work towards the long-term target of recycling 50% of their household waste. Both these measures are encouraging public and private sector waste management organisations to develop ways of recycling plastics, including PET.

However, it is more difficult to recover PET through "closed-loop" recycling (incorporating material from used containers in new containers) than through "down-cycling" in lower grade applications such as garden furniture. Closed-loop recycling demands higher quality materials so extensive processing and cleaning are required before post-consumer PET can be blended with virgin polymer and incorporated into new containers. Awaja and Pavel (2005) highlighted a range of contaminants that would make closed-loop recycling of PET impossible. These contaminants include water, other polymers (from bottle caps and labels), colourants, acetaldehyde, metals and the previous content of bottles (detergents, pesticides, etc.).

Furthermore, the physical and chemical properties of the recycled PET (particle size, degree of crystallinity, molecular mass, etc.) must be the same as the virgin material. Recent research carried out by the main author (Chilton, 2009) at a full-scale bottle manufacturing plant found that, even when using clean in-house PET scrap, the maximum proportion of recycled material that could be used was 5%. Further trials conducted with post-consumer recycled PET resulted in the production of bottles that contained specks of black material which was unacceptable to the beverage manufacturers that intended to use the bottles. Similar findings were also reported by Rogers (2006).

Preliminary trials carried out as part of this research have indicated that post-consumer PET can be incorporated into new bottles if the waste PET is processed to remove physical contaminants (coloured PET, other polymers from bottle labels and caps and non-plastic materials) and then treated with sodium hydroxide to

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remove the potentially contaminated surface layer of the particles. Finally, the clean PET has to be melted and formed into pellets with the same physical dimensions and degree of crystallinity as virgin PET (Chilton, 2009).

Alternatively, waste PET can be recovered by collecting it with the non-recyclable household waste followed by burning it in an energy-from-waste incineration plant. This process has the advantage that there are no issues over the PET composition or quality and there is a ready market for the power (and possibly the heat) generated. The need for separate collection, intermediate transport and processing of the PET is avoided with corresponding environmental and financial savings.

The aim of this research was to compile a life cycle assessment (LCA) inventory to quantify and compare the environmental emissions from recovering value from post-consumer PET by the recycling and thermal recovery routes.

2. Previous studies

Song et al. (1999) derived a mathematical model to produce an LCA inventory for waste PET management. This theoretical model assumed that, for most processes or activities, the environmental burdens were directly proportional to the mass of material treated. However, in the case of post-consumer bottle collections a non-linear relationship was adopted which assumed that the resources needed to collect 100% of the bottles would be almost infinite. The model considered six recovery options; recycling into new bottles, recycling into carpet manufacture, chemical recycling to feedstocks, pyrolysis, incineration and landfill. The environmental burdens considered were atmospheric emissions of CO_2, NO_x, SO_2 and the quantity of waste generated. The authors concluded that the model could be used to optimise the PET management system to minimise any given environmental burden.

In a related study, Song and Hyun (1999) used the model to derive an overall optimum solution for post-consumer PET management. In terms of energy conservation, the optimum solution consisted of collecting 80–90% of the waste PET for closed-loop recycling and incinerating the bottles that were not collected for recycling. The worst option was to treat the separately collected bottles by pyrolysis and landfill the remaining bottles. These findings also applied to NO_x and SO_2 emissions, but the lowest CO_2 emissions were achieved when around 85% of the bottles were collected for closed-loop recycling with the remaining bottles sent to landfill. This reflects that landfill represents a "sink" for CO_2 when considering non-degradable wastes such as PET.

Taylor Nelson Sofres (2000) reviewed previous studies on the energy implications of waste plastic management and concluded that the optimum solution was dependant on the thermal efficiency of the energy recovery process. For PET recovery, the review concluded that incineration in a high efficiency, combined heat and power (CHP) plant and recycling were equally beneficial, but the balance favoured recycling for lower efficiency (power only) incinerators. This study also suggested that transport-related emissions had only a minor impact on the energy balance.

Tukker (2002) compared mechanical recycling, incineration and feedstock recycling of waste plastics, and concluded that mechanical recycling of plastics was the most energy-advantageous recovery process, but only if a "high quality" use could be found for the recovered product. Otherwise, thermal recovery and feedstock recycling were equally advantageous when considering energy. In terms of the overall environmental impact, landfill had the greatest impact (the least beneficial option), followed by incineration (due to the low thermal efficiency of the power generation aspects) and energy recovery in cement kilns. Mechanical recycling was the most environmentally beneficial option providing that there was a market for the recovered PET. However, Tukker's review ignored the energy implications of the separate collection and mechanical processing required by the recycling option.

Arena et al. (2003) carried out an LCA of PET and polyethylene (PE) container recovery using operational data from Italian kerbside collection and bring recycling schemes and from bottle sorting, baling and polymer processing (grinding, washing, etc.) operations. They investigated the energy implications of six scenarios using combinations of recycling, incineration and landfill. The conclusion was that, in all cases, recycling gave the lowest environmental burdens. In terms of greenhouse gas emissions, like Song and Hyun (1999), the conclusion was that recycling plus landfill of the remaining PET was the best option whilst in terms of energy and atmospheric emissions (organic species, dust and metals) recycling with incineration of the remaining PET resulted in the lowest environmental impacts.

Perugini et al. (2005) undertook a similar LCA study of collected PET and PE waste management, but also considered the options of energy recovery by pyrolysis and by hydrocracking to produce hydrocarbon feedstocks. They concluded that mechanical recycling with incineration of the process waste resulted in the lowest burdens in terms of greenhouse gas emissions, organic compound emissions, waste generation and water consumption. However, in terms of energy conservation and crude oil consumption, recycling with hydrocracking of the process waste PET was the best option.

WRAP (2006) published a review of 10 LCA studies on waste plastic management that incorporated 60 scenarios. However, only 10 of these scenarios related to PET. To be included in the review, a study had to use an LCA or "LCA-like" methodology and provide a comparison of at least two different management options. When comparing recycling with incineration, the results suggested that, in terms of the energy balance and greenhouse gas emissions, recycling is generally the better option, but not if recycling only allowed the substitution of virgin material on a 1:0.5 basis. Furthermore, in cases where the plastic required washing as part of the recycling process, incineration was generally the better option.

In summary, the literature indicates that recycling is generally the best option for managing post-consumer PET wastes. However, whilst the majority of the studies are robust in LCA terms, there are a number of omissions in terms of waste management aspects. For example:

- the research only considered a limited range of environmental burdens (Song et al.,1999; Song and Hyun, 1999; Taylor Nelson Sofres, 2000; Tukker, 2002);
- the waste collection burdens are not considered (Tukker, 2002) or are based on purely theoretical assumptions (Song et al., 1999; Song and Hyun, 1999);
- the burdens associated with bottle cleaning are not stated (Song et al., 1999; Song and Hyun, 1999; Taylor Nelson Sofres, 2000; Tukker, 2002).

The research described below was designed to address these issues by carrying out an LCA of closed-loop PET recycling using operation data on waste collection, transport and processing technologies, PET bottle manufacturing and incinerator performance.

3. Life cycle assessment study

This research used the SimaPro Version 7.1 (SimaPro, 2009) LCA package, and considers two scenarios for recovering value from post-consumer PET soft drink bottles:

- kerbside collection, followed by reprocessing and closed-loop recycling (i.e. incorporation into new soft drink bottles); and