THE ImpEE PROJECT

UNIVERSITY OF CAMBRIDGE

The Cambridge-MIT Institute

Energy balance in recycling one PET bottle

Title: Energy balance calculation in recycling one PET bottle: Estimation and Qualitative Analysis

Background: In the related ImpEE resource on the Recycling of Plastics[1], it is suggested that of the 3 million tonnes of waste plastic produced in the UK each year, only 7% gets recycled. Aside from issues of land-filling and non-renewable petrochemicals which are the raw materials for plastics, significant energy goes into actually producing these products, a portion of which can be recovered by recycling.

Overview and motivation for this exercise: This examples question prompts the student to calculate the approximate energy that goes into recycling a typical Polyethylene Terepthalate (PET) drink bottle. This will involve not only practicing specific technical skills (materials, thermodynamics, physics, A-level chemistry) but also transferable skills (estimation and qualitative analysis, modelling, analysis with uncertainty, system thinking, and independent research). When put into context, quantifying the amount of energy that can be saved from recycling one such bottle will help the students to develop ESD awareness (impact of engineering on society, developing a global perspective, awareness of ESD issues, role of engineerings in making our society sustainable).

General and Specific Resources: The ImpEE resource on the Recycling of Plastics[1] can provide the general background for setting this problem into a larger context. It also describes the recycling process which involves transport, shredding, and melting

The student is expected to have a knowledge of A-Level chemistry and First-year Materials.

The energy required to make a PET bottle from scratch is 8.42 MJ. This can be calculated from the formation enthalpy of polyethylene from naptha. The calculation[2] is shown on the DoITPoMS website.

The main parameters required for completing the question are given. Optionally, the lecturer can withhold some or all of these to encourage the student to engage in their own independent research.

This examples paper was based on the work of the DoITPoMS TLP[3] available online.

Links:

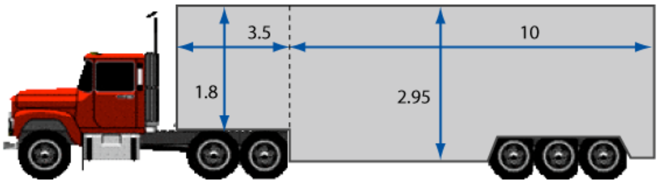
1. "Recycling of Plastics", ImpEE Resource, http://www-g.eng.cam.ac.uk/impee/paul?section=topics&topic=RecyclePlastics
2. "Calculating the formation enthalpy of polyethylene from naptha", DoITPoMS TLP, http://www.doitpoms.ac.uk/tlplib/recycling-polymers/formation_enthalpy.php
3. "Calculation of energy to recycle one PET bottle", DoITPoMS TLP, http://www.doitpoms.ac.uk/msm-impee-dev/recycling-polymers/energy_recycle.php

Example Question:

Estimate the amount of energy required to recycle a single PET bottle. Include all stages of the recycling process from transport and shredding to melting. Compare this approximate energy expenditure to the energy required to make the PET bottle in the first place which is 8.42 MJ. Attempt to quantify the potential energy savings in everyday terms. How much would this be if we increased our national plastic recycling rate from 7% to 30%? What are some of the problems associated with recycling PET bottles?

You need to know the following: the density of PET is around 1345 kg m^{-3}, a typical lorry has a fuel economy of 7.8 miles per gallon, the energy density of diesel is 34.62 MJ per litre, a typical bottle washer runs at 110W and can process 60 bottles per minute, a bottle shredder uses a 7.5 kW motor and outputs 150 kg/h, the specific heat, Cp, of PET is around 1446 kg^{-1} K^{-1} and its melting point is around 512 K.

Example Solution:



We are told to account for energy expenditure throughout the recycling process. The bottles first need to be transported to the recycling factory. A typical transporter lorry is shown above, with dimensions in metres, and it has a maximum payload of 26,089 kg. Assuming the width is approximately 2m, the volume of the hold is:

$$\text{Volume} = (1.8 \times 3.5 \times 2) + (2.95 \times 10 \times 2) = 71.6m^3$$

Considering the density of PET (1345 kg m^{-3}) the plastic needs only be compacted to around 28% to fill the truck to its maximum load (26, 089kg) which is reasonable.

Assuming that the distance the plastic would have to travel to the recycling plant is 100km, we can calculate the energy required to transport one plastic bottle. At a fuel economy of 7.8 miles per US gallon, it would take 30.3 litres of fuel to travel 100 km. If a single plastic bottle has a mass of 0.1 kg then the payload could take 260,890 bottles. There are 34.62 MJ in a litre of diesel, so the energy required to transport one bottle to the recycling centre is:

$$E_{transport} = \frac{30.3 \times (34.62 \times 10^6)}{260890} \approx 4kJ$$

Once at the recycling facility, the bottles must first be washed in an automatic bottle washer, which runs at a power of 110 W and can process 60 bottles per minute:

$$E_{washing} = 110 \text{ J/s} \times \tfrac{60}{60} \text{ Bottles/seconds} = 110 \text{ J}$$

After washing, the bottles are shredded by a machine operating a 7.5kW motor and an output of 150kg/h. The energy used by the machine is thus 27MJ/h and it processes 1500 bottles per hour:

2.3 System Thinking

$$E_{shredding} = 27 \text{ MJ}/1500 \text{ bottles} \approx 18kJ$$

We can also calculate the energy required to melt down one plastic bottle. The specific heat, Cp, of PET is around is around 1446 kg^{-1} K^{-1} and its melting point is around 512 K. Therefore the energy to heat one PET bottle to its melting temperature would be:

$$E_{melting} = \Delta T \times C_P \times m = 219 \times 1446 \times 0.1 = 31.7 \text{ kJ}$$

The heat of melting one bottle is 125 J so the total energy to melt down one PET bottle is:

$$E_{melting} = 31700 + 125 = 31.8 \text{ kJ}$$

Thus, the **total energy** used in recycling the bottle into pellet form is:

$$E_{recycling} \approx 4000 + 110 + 18000 + 31800 \approx 53.91 \text{ kJ}$$

2.1.4 Analysis with Uncertainty

In comparison, the energy required to make an equivalent bottle, 8.42 MJ, is on the order of 100 times as great! In other words, recycling reduced the energy expenditure of a PET bottle to around 1%.

To put the energy saving into context, a 60 W lightbulb consumes around 216 kJ per hour. Thus, recycling just one PET bottle saves enough electricity to power a lightbulb for almost 38 hours!

Impact of Engineering on the Environment

We are told that annually about 9.2 billion PET bottles are consumed around the world, of which only 7% are recycled. If this were increased to 30%, this would be an additional 2 billion bottles that are recycled instead of manufactured. If each recycled bottle saved around 8 MJ, that would a total global energy savings of around 1.7×10^{16} J. This is the entire annual production of a typical 600MWe nuclear power station!

The biggest disadvantage of recycling PET is that the process is intolerant of impurities which typically means that a PET bottle can only be recycled once. Other disadvantages are that the sorting and recycling process is rather labour intensive, and that the market for recycled plastics is not fully developed.

Developing a novel material and/or recycling solution to replace PET bottles would have a dramatic impact on the global environment.

Transferable Skills:

Estimation and qualitative analysis (2.1.3)/Analysis with Uncertainty (2.1.4) In this calculation, the students are expected to make estimations to come up with approximate answers. Although this is reflective of the real world, it is quite different from what is done in the standard curriculum so many students feel uncomfortable. The lecturer should stress to the students that the objective of the question is to qualify the relative impact of recycling a PET bottle, not to get an exact scientific value for the energy involved. This concept is embodied in the concluding answer "The energy required to recycle a PET bottle is in the tens of kilojoules, but the energy to make one from scratch is several megajoules." This difference of several orders of magnitude should reassure the student that any estimation errors are likely to have no impact. For example, if the distance required to transport the bottles was instead 500km, the extra 16 kJ expended would would not change the conclusion in any qualitative sense whatsoever.

System Thinking (2.3) A perceptive student might notice that the energy required to shred the bottles is the same order of magnitude as the energy required to melt the bottles. Since the energy expended on shredding the bottles mostly becomes waste heat energy dumped into the system, this would suggest that the bottles come close to melting during the shredding process. Indeed, this is a real world problem with the shredding stage of the recycling process; the plastic starts melting and gumming up the shredding equipment. This is a good example of "broad-perspective systems thinking".

ESD Skills Developed:

Awareness of ESD Issues. The students is made aware of some of the issues involved in recycling PET. For example, most people consider the recycling process to be one about reusing materials, but clearly it is just as much about reducing energy use.

Impact of Engineering on the Environment. The amount of energy saved in recycling one PET bottle was calculated to be the order of several Megajoules. To place this otherwise abstract value into context, the students are asked to relate this to the operation of a lightbulb. This helps them to appreciate the scale of the energy saved. Finally, they are made aware that only 7% of bottles are recycled and what impact it would be if this were increased to 30%.

The labels used to describe the transferable skills refer to the CDIO Syllabus. See www.cdio.org for more details.